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| 16. Abstract<br>The report examines the movements and stresses which accompany underground mining and which may be used to characterize the subsidence process. The major applications of subsidence monitoring are reviewed and for each, the relevant data measurements for a cost-effective monitoring program are identified. Seven sets of measurements are repeatedly encountered and these are formalized as individual measurement systems. Specifications for each of the measurements in each system are developed in the report. To identify capable instrumentation for the measurement systems, basic properties such as availability, cost, and ease of use are listed for over 100 instruments potentially useful for subsidence monitoring. The instrument properties are quantified and rated with respect to the specifications developed for each instrument in each measurement system. The most effective instrument for each measurement is selected from among those with the highest scores. For each instrument selected, detailed information is provided on installation and operation procedures. Finally, the measurement systems, with their associated instrumentation, are ranked according to cost and time limitations, versatility of the component equipment, and previous service experience by users. |                                          |                                                 |           |
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## FOREWORD

This report was prepared by Woodward-Clyde Consultants, Western Region, San Francisco under USBM Contract Number J0265027. The contract was initiated under the Advancing Mining Technology; Coal Mining, Environmental Protection for Surface Areas Program. It was administered under the technical direction of Denver Mining Research Center with Mr. W. F. Eichfeld acting as the Technical Project Officer. Mr. W. P. Battle was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period July 1976 to October 1977. This report was submitted by the authors on October 17, 1977.

The authors wish to acknowledge the program direction and constructive review of this report by Dr. Ulrich Luscher, Woodward-Clyde Consultant's Principal-in-Charge for this project, as well as the yeoman assistance of Dante Tolosa, draftsman, and Anita Davy, technical typist.

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## EXECUTIVE SUMMARY

### Overview

Underground mining frequently causes downward movement of the strata overlying the mine, called subsidence. The subsidence process is generally characterized by a trough shaped depression at the surface and bending or collapse of the overlying strata into the mined-out void. Such subsidence is detrimental to utilization of the surface and may present a hazard at mine level. Monitoring of subsidence phenomena is the first step toward understanding and controlling subsidence.

The objective of the contract was to develop and evaluate the economic and technical feasibility of several subsidence monitoring systems which fulfill the needs for acquisition of subsidence data by regulatory agencies, mine operators and surface resource consumers.

The objective of this report is to present the results of our extensive study of subsidence monitoring instrumentation made pursuant to the contract. Accordingly, the report examines the mine subsidence problem in the United States and identifies and evaluates seven instrument systems and thirteen specific instruments to be used for monitoring subsidence phenomena.

### Summary

Subsidence depends on many physical factors including mining method (including measures taken to control subsidence), geologic conditions and terrain features. Phenomena which accompany underground mining and which may be monitored to characterize the subsidence process include:

|                                            |                                   |
|--------------------------------------------|-----------------------------------|
| Ground Surface Vertical Settlement         | Subsurface Vertical Deformation   |
| Ground Surface Horizontal Strain           | Subsurface Horizontal Deformation |
| Ground Surface Tilt                        | Extent of Subsurface Fracturing   |
| Ground Surface Crack Movement              |                                   |
| Ground Surface Visual Appearance           | Mine Level Pillar Stress          |
|                                            | Mine Level Support Stress         |
| Structure Differential Vertical Settlement | Mine Level Roof Sag               |
| Structure Strain                           | Mine Level Roof Strata Separation |
| Structure Crack Movement                   | Mine Level Convergence            |
| Structure Visual Appearance                | Mine Level Rock Noise             |
|                                            | Mine Level Visual Appearance      |

There are many reasons for careful monitoring of subsidence movements. Generally, there are no present laws which specifically require subsidence monitoring, but at locations where strict subsidence control legislation is in force or where the surface owner is entitled to support, monitoring may minimize litigation. The most pressing argument for monitoring is believed to be economic - to help protect the value of existing surface facilities, to ensure growth and development in undermined communities, and to prevent damage to the mine plant and underground facilities. Further, monitoring can contribute to the performance and economy of both mine and surface engineering projects by providing an understanding of the influence of mining methods, mine filling techniques and geology on subsidence.

Monitoring for each of these reasons will emphasize somewhat different instrumentation. The measurements needed to monitor a building on the surface will be different from those needed to monitor a barrier pillar separating two mines. After the measurements useful for a variety of monitoring needs were tabulated, seven measurement systems were identified:

- System A: Subsidence Detection
- System B: Structure Performance
- System C: Mine Stability
- System D: Performance of Supported Structures
- System E: Performance of Caving Systems
- System F: Performance of Filled Mines
- System G: Visual Documentation

Measurement specifications have been developed for each of the systems; see Section 5.0 of the report.

To identify instruments most effective for the measurements required in the seven measurement systems, over 200 instruments were reviewed initially. Basic properties such as availability, cost, and ease of use are described in the report for over 100 instruments. To simplify instrument selection, the instrument properties were quantified and rated in light of the specifications developed for each measurement system. In this way the most effective instruments for each measurement system were identified as the ones with the highest total ratings. A combination of the total ratings and engineering judgment was then used to select preferred instruments for subsidence monitoring from among the top-rated instruments. The thirteen selected instruments, listed below, are described and their installation and operating details given in Section 8 of the report.

|                                         |                                      |
|-----------------------------------------|--------------------------------------|
| Precision Level                         | Rod Extensometer with tensioned      |
| Steel Tape Extensometer                 | vibrating wire in telescoping casing |
| Rod Extensometer with Micrometer        | Multiple Point Borehole Extensometer |
| Dial Indicator Strain Gauge             | Rod Type with Dial Gauge             |
| Full Profile Borehole Extensometer      | Hydraulic Load Cell                  |
| with Electromagnetic Torpedo            | Elastic Disc Load Cell               |
| Full Profile Borehole Inclinator        | USBM Borehole Deformation Gauge      |
| with Servo Accelerometer Torpedo        | Encapsulated Flat Borehole Pressure  |
| Microseismic Detectors, with headphones | Cell                                 |

The relationship among measurement systems, measurements, and selected instruments is summarized in the attached table.

Finally the measurement systems were ranked with respect to technical and economic features, to assist the person planning a subsidence monitoring program to decide how complex a system he should choose initially. Practical decisions for implementation of monitoring programs often must take into account cost and time limitations, versatility of the equipment, and previous experience by other users. These factors were assessed for each system, using very simple prototype installations for evaluating the cost and time variables.

The results, presented in Table 9.5 of the report, indicate that where it is sufficient for immediate needs, the most cost effective system is also technically the simplest. More elaborate systems, suited to more complicated subsidence problems, require an increased scope of measurements with an accompanying increase in cost and installation time, and acquisition of less versatile equipment.

TABLE  
INSTRUMENTS SELECTED FOR MEASUREMENT SYSTEMS

| MEASUREMENT SYSTEM<br>MEASUREMENT            | SYSTEM A:<br>SUBSIDENCE<br>DETECTION | SYSTEM B:<br>STRUCTURE<br>PERFORMANCE | SYSTEM C:<br>MINE STABILITY   | SYSTEM D:<br>PERFORMANCE OF<br>SUPPORTED SYSTEMS     | SYSTEM E:<br>PERFORMANCE OF<br>CAVING SYSTEMS        | SYSTEM F:<br>PERFORMANCE OF<br>FILLED MINES           |
|----------------------------------------------|--------------------------------------|---------------------------------------|-------------------------------|------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------|
| Ground Surface Vertical Settlement           | Precision Level                      | -                                     | -                             | Precision Level                                      | Precision Level                                      | Precision Level                                       |
| Ground Surface Horizontal Strain (Lines)     | -                                    | -                                     | -                             | Steel Tape Extensometer                              | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Horizontal Strain (Triangles) | -                                    | -                                     | -                             | Steel Tape Extensometer                              | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Crack Movement                | -                                    | -                                     | -                             | -                                                    | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Tilt                          | -                                    | -                                     | -                             | Precision Level With Steel Tape or Tape Extensometer | Precision Level With Steel Tape or Tape Extensometer | -                                                     |
| Structure Differential Vertical Settlement   | -                                    | Precision Level                       | -                             | -                                                    | -                                                    | -                                                     |
| Structure Strain                             | -                                    | Rod Extensometer with Micrometer      | -                             | -                                                    | -                                                    | -                                                     |
| Structure Crack Movement                     | -                                    | Dial Indicator Strain Gauge           | -                             | -                                                    | -                                                    | -                                                     |
| Subsurface Vertical Deformation              | -                                    | -                                     | -                             | FPBX with Electro-magnetic Torpedo                   | FPBX with Electro-magnetic Torpedo                   | FPBX with Electro-magnetic Torpedo                    |
| Subsurface Horizontal Deformation            | -                                    | -                                     | -                             | FPBI with Servo Accelerometer Torpedo                | FPBI with Servo Accelerometer Torpedo                | -                                                     |
| Extent of Subsurface Fracturing              | -                                    | -                                     | -                             | -                                                    | Microseismic, with headphones                        | -                                                     |
| Mine Level Roof Sag                          | -                                    | -                                     | Precision Level               | Precision Level                                      | -                                                    | -                                                     |
| Mine Level Convergence                       | -                                    | -                                     | Steel Tape Extensometer       | Steel Tape Extensometer                              | Steel Tape Extensometer                              | Rod Extensometer with Spring tensioned vibrating wire |
| Mine Level Roof Strata Separation            | -                                    | -                                     | -                             | MPBX, Rod Type, with Dial Gauge                      | -                                                    | -                                                     |
| Mine Level Prop Load                         | -                                    | -                                     | Hydraulic Load Cell           | Hydraulic Load Cell                                  | Hydraulic Load Cell                                  | -                                                     |
| Mine Level Rock Bolt Load                    | -                                    | -                                     | Elastic Disc Load Cell        | Elastic Disc Load Cell                               | Elastic Disc Load Cell                               | -                                                     |
| Mine Level Pillar Stress (Absolute)          | -                                    | -                                     | -                             | USBM Borehole Deformation Gauge                      | USBM Borehole Deformation Gauge                      | -                                                     |
| Mine Level Pillar Stress (Relative)          | -                                    | -                                     | -                             | Encapsulated Flat Borehole Pressure Cell             | Encapsulated Flat Borehole Pressure Cell             | -                                                     |
| Mine Level Rock Noise                        | -                                    | -                                     | Microseismic, with headphones | -                                                    | -                                                    | -                                                     |

KEY: FPBX = Full Profile Borehole Extensometer; MPBX = Multi-Point Borehole Extensometer; FPBI = Full Profile Borehole Inclinator

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## 1.0 INTRODUCTION

Ground subsidence due to mining has long been recognized and evaluated on a qualitative basis. However, the environmental and economic consequences of ground subsidence have only recently been given major attention and consideration in the United States. Past mining activities have largely been in areas that were undeveloped and thinly populated. As suburban population centers extended out into areas that were being mined, the effects and problems of mining subsidence escalated (Vandale, 1967).

Historically, subsidence has occurred not only in rural but also in urban areas. As early as 1912, Griffith and Conner did a comprehensive survey of mining conditions in Scranton, Pennsylvania, prompted by mine subsidence damage to an area and a local school of that city. In 1927, Herbert and Rutledge commented that "American mine operations have seldom anticipated the effects of subsidence...(Disregard of the rights of surface owners)...has led to legal judgments against mining companies that involve large sums of money or to severe restrictions on account of the obligation to leave pillars of valuable mineral." However it was not until 1966 that the first restrictive subsidence legislation was passed (Pennsylvania, 1966). Therefore, it is probably reasonable to attribute the current interest in mining subsidence to the increased social responsibility spawned in the '60's rather than to the expansion of the population into mining areas.

A recent survey in the United States has disclosed that practically all mining subsidence in developed areas results from coal mining (HRB-Singer, 1977). Thus, the character of coal mining subsidence will be of primary concern in this report.

In the next section, the basic characteristics of surface subsidence due to underground mining are reviewed. In succeeding sections, the loads and deformations which accompany subsidence movements are detailed. Legal, economic and engineering needs for measurements and applications of these measurements are then discussed. Specifications are developed for several multiple-measurement systems to monitor the stresses and deformations appropriate to the intended application of each system. An extensive list of instruments are evaluated against each set of system specifications. The instruments that collectively meet each set of specifications form application systems, which are described in greater detail in a following section of the report.

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100.

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## 2.0 THE SUBSIDENCE PHENOMENON

### 2.1 DEFINITIONS AND PARAMETERS

When an underground mineral is removed, the overlying strata may settle into the resulting void. This phenomenon is called subsidence. A two-dimensional model, as shown on Figure 2.1, is commonly used to illustrate the basic characteristics of subsidence.

The model consists of a horizontal coal seam through which a strip of coal or other mineral has been extracted. The coal seam and mined-out area ("goaf" or "stope") extend for a long distance perpendicular to the figure. This two-dimensional characterization then assumes a trough-shaped subsidence pattern (General Analytics, 1974).

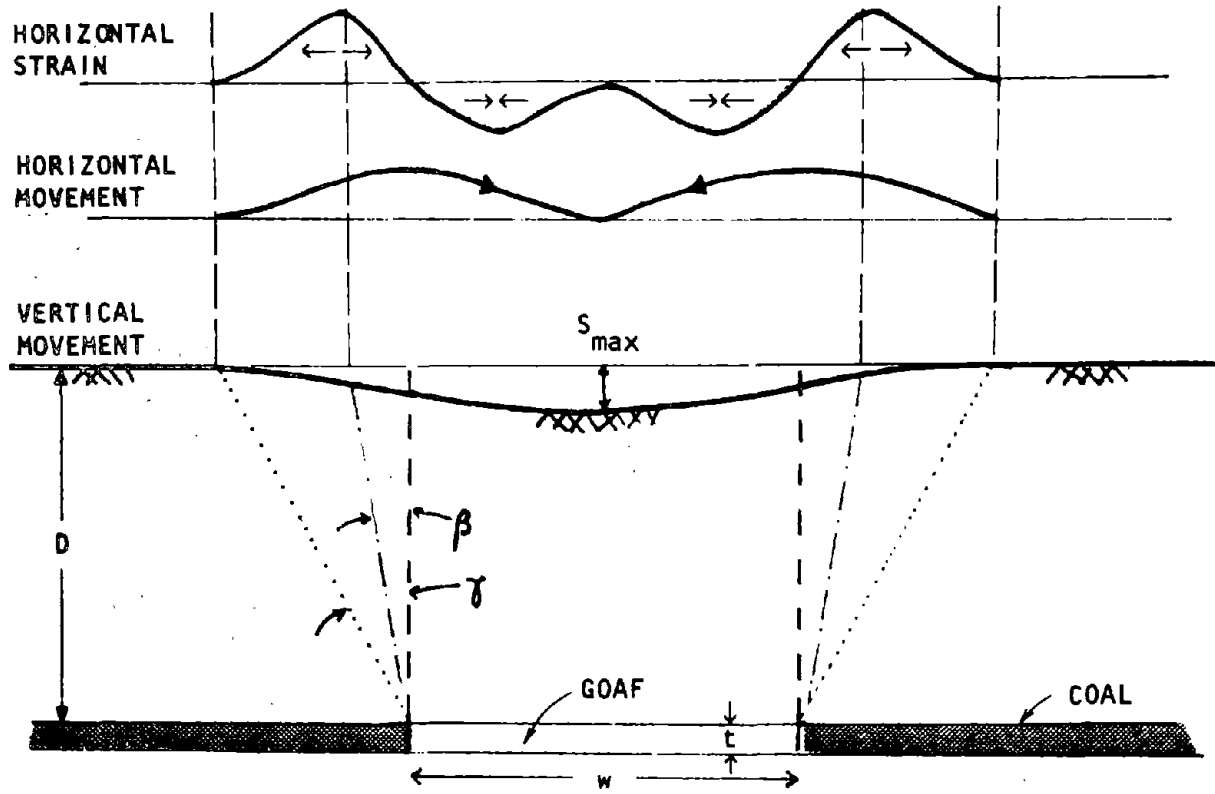
The subsidence trough is commonly described in terms of the angle of draw  $\gamma$ , angle of break  $\beta$ , seam thickness extracted  $t$ , depth of the seam  $D$ , and width of the goaf  $w$ . The angle of draw is defined as the angle from the vertical of a line projected upward from the edge of the goaf to the edge of the subsidence trough. Similarly, a line may be extended from the edge of the goaf to the point of maximum curvature of the subsidence trough; the angle which this line makes with the vertical is called the angle of break. The seam thickness  $t$ , depth to the seam  $D$  and width of the goaf  $w$  are all illustrated in Figure 2.1. Care must be taken in reading the literature because the angle of draw is sometimes taken as the angle to the horizontal rather than vertical.

Experience has shown that the vertical deflection at the center of the subsidence trough  $S$ , expressed as a percentage of the seam thickness  $t$ , increases with the width of the mined area. The value of  $S/t$  is called the subsidence ratio. However, a critical width is reached at which the maximum vertical subsidence at the center of the trough no longer increases, but remains constant at  $S_{max}$ . The critical width can be determined by projecting two lines at the angle of draw from a point on the surface down to the coal seam. The width of mineral between the two lines is the critical width, shown in Figure 2.2. Thus, the critical width in nearly horizontal bedded stratigraphy is

$$w_{crit} = 2D \tan \gamma$$

If the mined-out void is of supercritical width, i.e. wider than the critical width, the subsidence trough is characterized by a flat area at the center of the trough which has settled  $S_{max}$ . For subcritical width, the maximum subsidence at the center of the trough will be less than  $S_{max}$ .

In addition to vertical subsidence, underground mining also produces a net horizontal displacement of points on the ground surface toward the center of the mined area. Differential horizontal displacement between adjacent points produces horizontal strains in the ground surface. Both tensile and compressive strains develop. The transition point between tensile and compressive strain is generally assumed to be directly above the edge of the



KEY :

- $S_{max}$  : Maximum possible vertical subsidence given thickness of extracted seam
- $t$  : Thickness of extracted seam
- $D$  : Depth to coal seam from surface
- $w$  : Width of goaf
- $\gamma$  : Angle of draw
- $\beta$  : Angle of break

Figure 2.1 - TWO DIMENSIONAL MODEL OF SUBSIDENCE  
(Shown for Goaf of Critical Width)

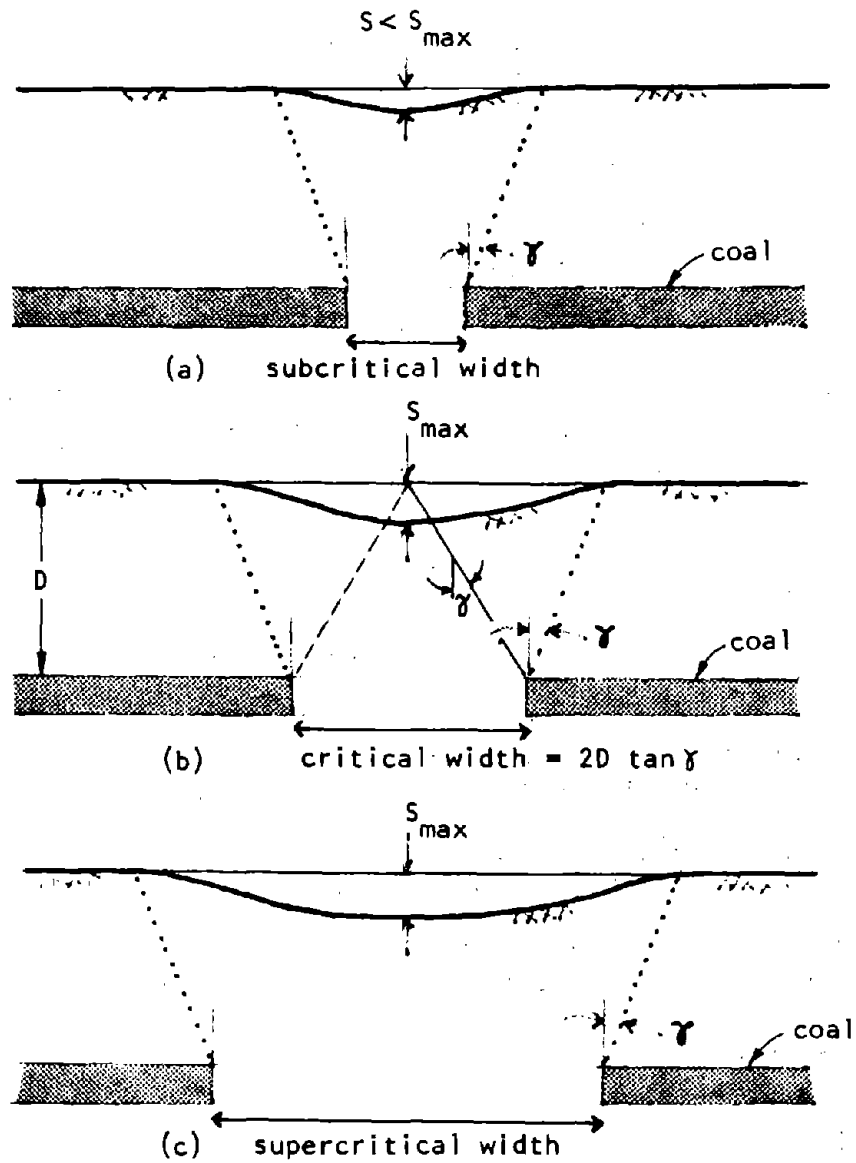


Figure 2.2 - EFFECT OF WIDTH OF GOAF ON SUBSIDENCE

goaf, but its location depends on the strength of the rock formation. For stopes of subcritical width, the center of the trough undergoes horizontal compressive strain. At critical width, the center point of the subsidence trough is strain-free. The strain-free portion of the trough is expanded if an area of supercritical width is mined.

The two-dimensional model shown in Figure 2.2(b) or 2.2(c) can also be interpreted as a panel in which the direction of face advance is parallel to the page. Using this interpretation, it can be seen that subsidence movement precedes the face. In fact, these "travelling" displacements may be somewhat closer to the face than the static displacements.

The two-dimensional model discussed highlights the important characteristics of subsidence deformations. In fact, the subsidence process is more complex than this model suggests. However, the model provides a basis for describing subsidence experience.

Before continuing to Section 2.2, the reader is referred to Figures 2.3, 2.4 and 2.5 where several of the basic mining methods and related terminology are illustrated.

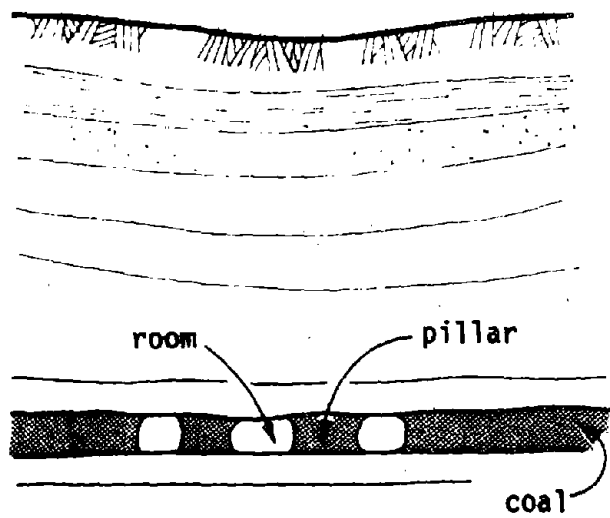
## 2.2 MINING CONDITIONS AND SUBSIDENCE EXPERIENCE IN U.S. AND FOREIGN PRACTICE

### 2.2.1 Relative European and U.S. Mining Conditions

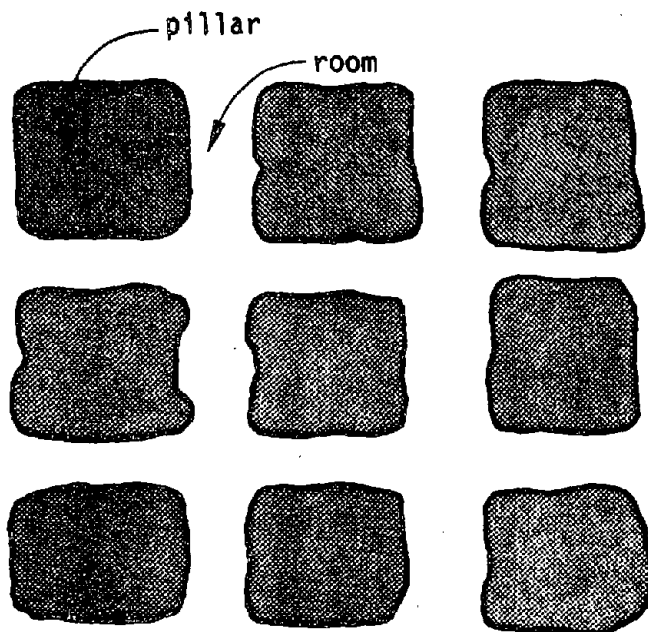
The European and British subsidence experience is well documented. Most of the literature deals with coal mining, although deformations due to salt mining have also been described in the literature.

The essential differences between American and European coal mining practice and geology were summarized by Lewis and Clark (1964):

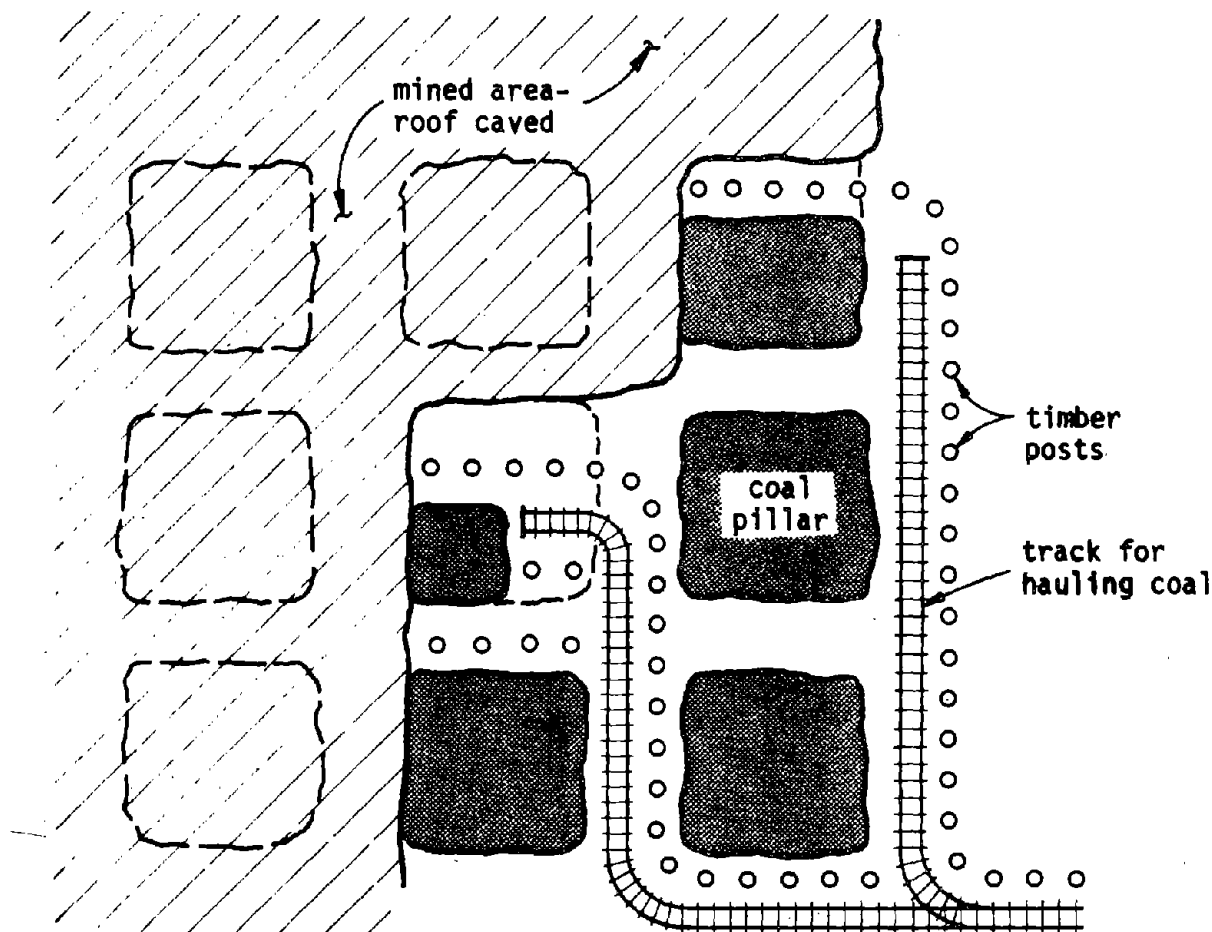
"In comparing European and domestic coal mining, it is interesting to note that European coal fields are characterized in the main by relatively small-sized coal basins, great concentration of coal in the strata and much folding and faulting of strata. In the United States the coal beds are fewer in number, more regular in occurrence, and have a flatter dip, being practically horizontal over large areas. The average depth of hoisting shafts is less than 500 ft as compared with about 1000 ft in England, about 1500 ft in France and Germany and about 2000 ft in Belgium, though the deepest shafts extend to more than 3500 ft below the surface. Thickness of seams worked in Europe may be as little as 16 in., with 36 in. as the average. However, the total thickness of all seams in a vertical section may be 120 to 150 ft, and as many as 12 seams may be worked simultaneously. In this country, it is seldom that more than one seam is worked at a time, and the minimum thickness of coal seams worked is about 30 to 40 in., with 40 to 60 in. as the average.



a) "FIRST MINING" - ELEVATION

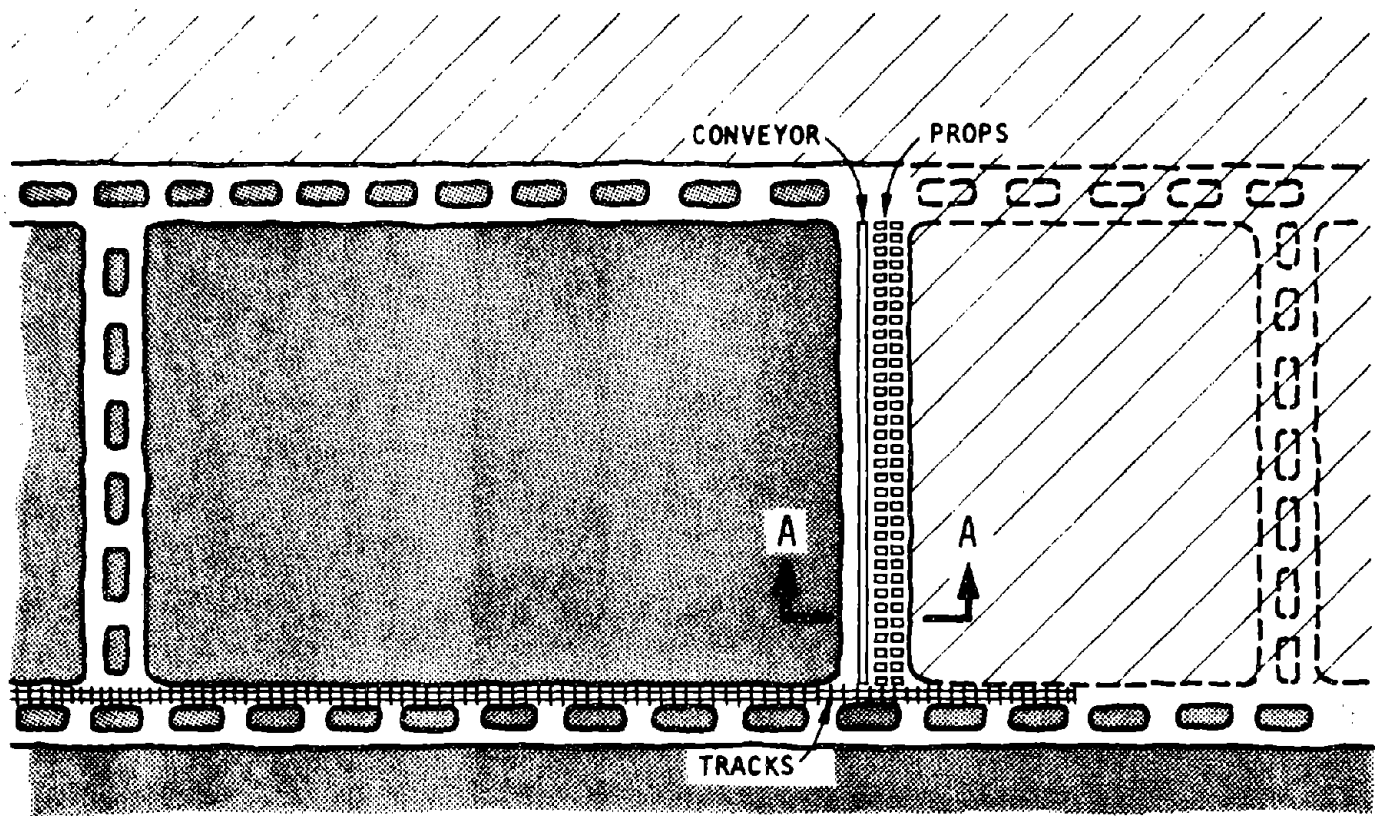


b) "FIRST MINING" - PLAN VIEW



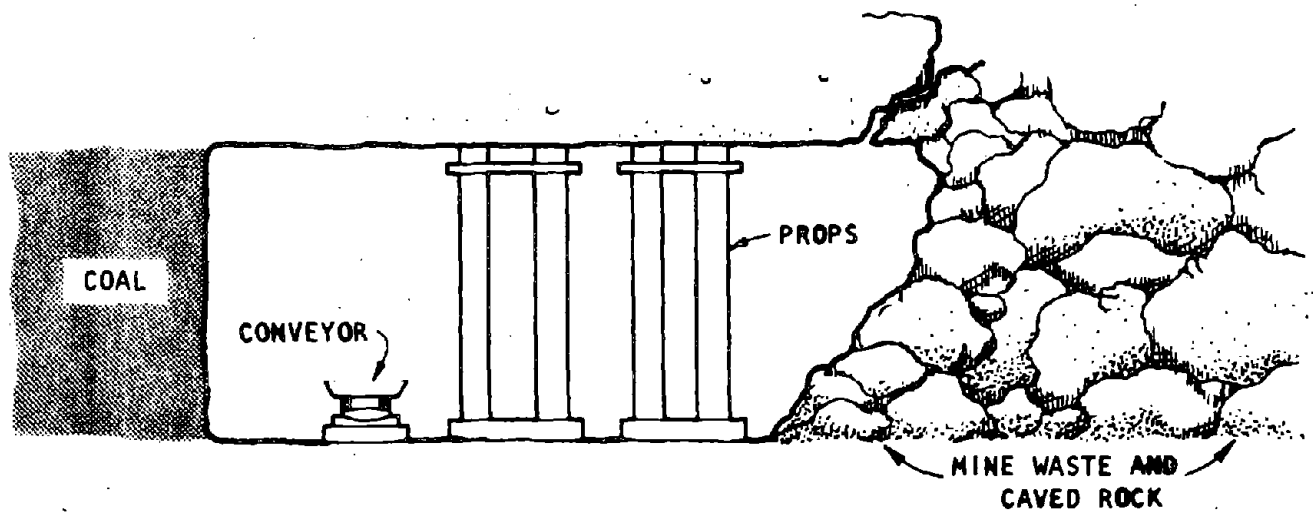
c) PILLAR EXTRACTION - PLAN VIEW

Figure 2.3 - ROOM AND PILLAR MINING



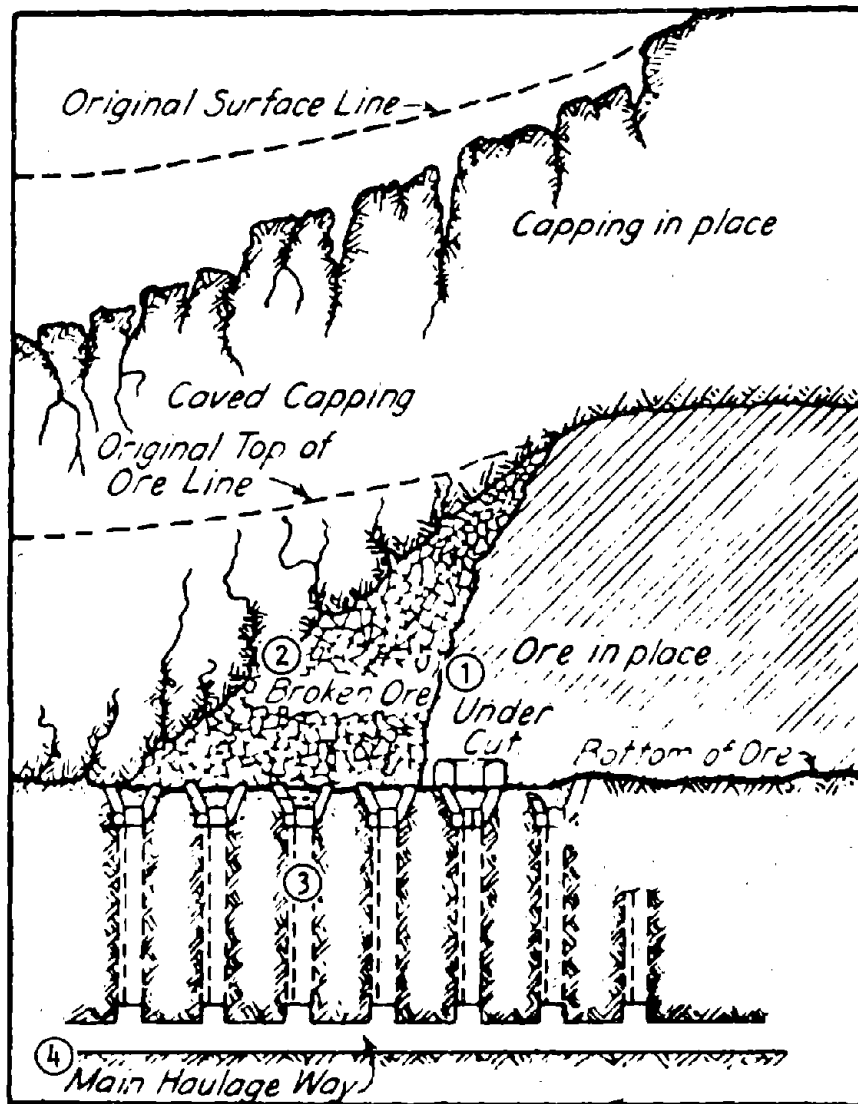
-  UNMINED COAL
-  MINED-OUT AREA WITH  
CAVED ROOF

P L A N



SECTION A - A

Figure 2.4 - LONGWALL MINING SYSTEM  
(after Lewis & Clark, 1964)



KEY :

- 1 Ore is undercut
- 2 The weight of the capping breaks up the ore
- 3 The ore falls down the chutes
- 4 The ore is removed

Figure 2.5 - B L O C K    C A V I N G  
(Lewis and Clark, 1964)

The long life of European mines and the fact that all workable seams will be mined leads to the construction of elaborate and permanent surface plants of brick, steel and concrete. Buildings are of pleasing appearance and the grounds are fenced and planted with grass and shrubs. Shafts are either round or elliptical, the better to withstand high pressure in soft or water-bearing strata, and are lined with steel, iron tubing or concrete. In the United States wood shafts predominate, though reinforced concrete is used in wet ground. Mining systems in Europe vary with conditions, but complete extraction of seams above a certain minimum thickness is generally required. Advancing longwall with complete backfilling is the most adaptable method and is well suited for insuring a maximum recovery of coal and for minimizing subsidence at the surface. Room-and-pillar mining is adaptable to most mining conditions, though from 20% to 30% of the coal is lost in pillars, and much damage may be done to the surface. It is the method most commonly used in the United States."

#### 2.2.2 European Subsidence Experience

The National Coal Board (U.K.) publishes the Subsidence Engineers' Handbook which synthesizes deformations from hundreds of case histories. Other Britons have extensively documented the British subsidence phenomenon.

From the numerous subsidence records analyzed by the NCB in Great Britain (National Coal Board, 1966), it was shown that undermining causes a trough shaped depression approximated by the two-dimensional model presented in Section 2.1. The subsidence factor can be as high as  $S/t = 0.9$  for complete mineral extraction with caving. The subsidence factor  $S/t$  was shown to increase with the ratio of width to depth of the mined-out void, levelling off when  $w/D$  equalled 1.2. This ratio,  $w/D = 1.2$ , defined the critical width of extraction for British coal mining operations and corresponded to an angle of draw of 30 degrees.

More recent research in Great Britain has indicated that the subsidence factor  $S/t$  depends not only on the ratio of width to depth, but also increases with depth for a constant  $w/D$  ratio. Note, however, that for mines of constant width, the subsidence ratio decreases with depth (National Coal Board, 1976). The subsidence factor can be reduced as much as 50% (all other factors being equal) by use of solid stowing.

Subsidence data from coal fields in several European countries (Brauner, 1973) indicate maximum subsidence factors,  $S_{max}/t$ , in the range of 0.6 to 0.9, where the range in values reflects the variations in geologic conditions in the coal fields studied. Also, in the European subsidence experience, observation of a rise in ground surface elevation or heave on the order of 0.4 inch was not uncommon before vertical downward subsidence was detected.

The other components of ground surface movement, slope and strain, have been shown to be a function of the width to depth ratio in England. Typical values for the maximum strain and slope are presented on Figure 2.6, as a function of seam thickness, mine width and depth to the seam.



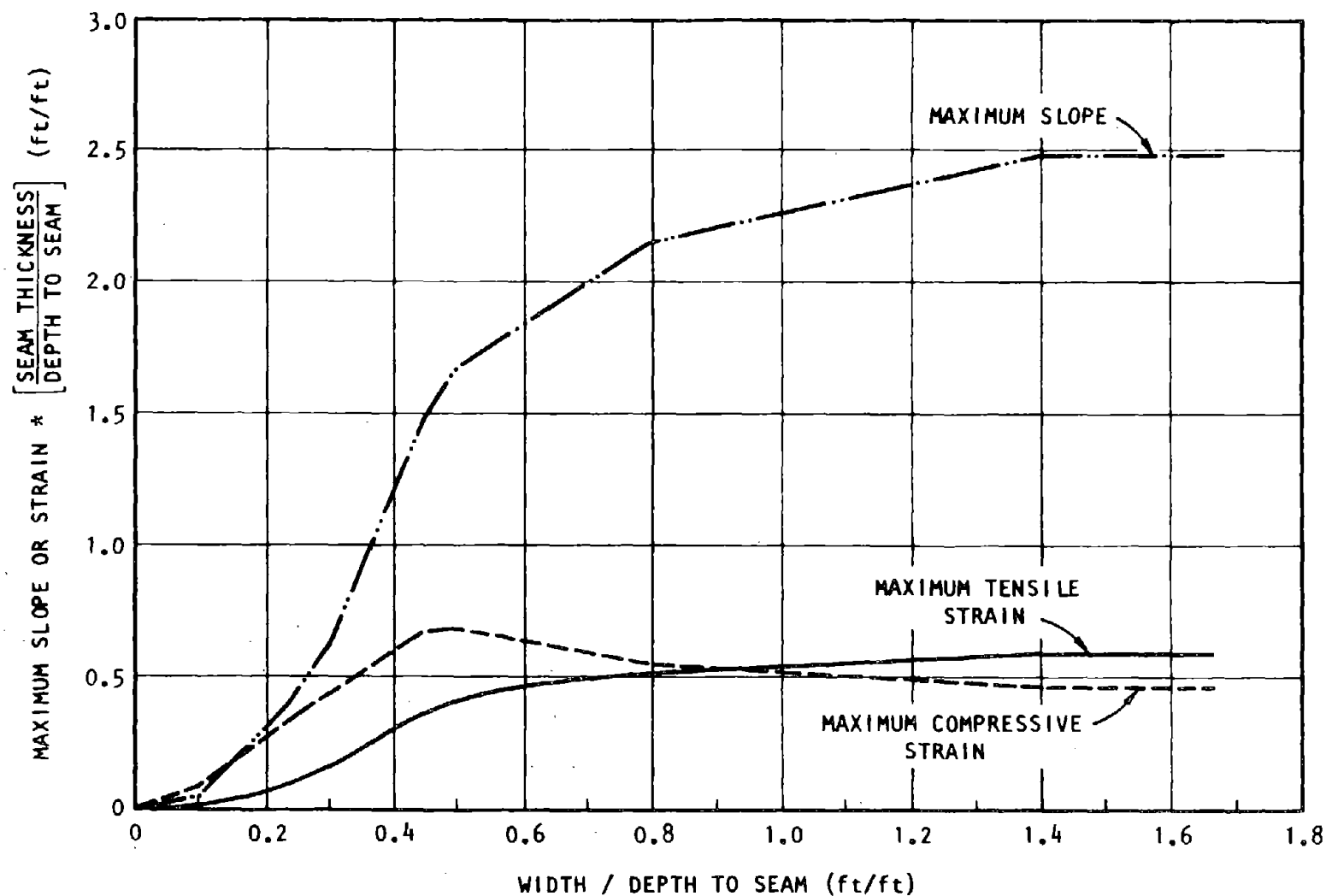


Figure 2.6 - TYPICAL MAXIMUM SLOPE AND STRAINS AS FUNCTIONS OF MINE DIMENSIONS (Based on Fig. 15, NCB, 1976 and Fig. 2, Voight, 1970)

NOTE: Values are for single seam longwall workings without solid stowing in Great Britain

### 2.2.3 Asian and Australian Subsidence Experience

In Japanese coal mining subsidence experience, the angle of draw ranges from 30 to 60 degrees and depends on the thickness of the overburden, the surface soil, the type of rock formation and ground water location (Kaneshige, 1970).

In a well-documented report on subsidence over longwall operations in India (Kumar and Singh, 1973), the travelling angle of draw was observed to be negative at -15 to -22 degrees and was attributed to hard sandstone comprising most of the overlying strata. The final angle of draw was 16 to 17 degrees.

In Australia, subsidence has been documented above the Southern Coalfields since 1965 and above the Northern Coalfields since 1969. Subsidence ratios varied from 0.05 to 0.61 and with as much as 1.9 ft of subsidence occurring with 1,400 ft of cover (King and Green, 1973).

### 2.2.4 United States Subsidence Experience

A recent survey of the literature of mine subsidence concluded that very little documented United States experience exists (General Analytics, 1974). Consequently, an intensive effort was made to collect and synthesize available American subsidence literature to determine ranges and average values of variables, such as subsidence factor, for various mining conditions.

2.2.4.1 Subsidence over Coal Mines - Most of the American literature deals with subsidence due to coal mines. However, the available published case histories of American coal mining subsidence experiences often were not sufficiently documented to be useful.

Pertinent case history data, where the mine width was at least the critical width, show the maximum subsidence to be generally in the range of 0.5 to 0.6 of the seam thickness, but with isolated cases showing a maximum ratio of 0.72 (refer to Table 2.1). In these case histories, the angle of draw ranges from 7 to 35 degrees. Additional unpublished cases of monitored subsidence over room and pillar mining followed by pillar extraction reported maximum vertical subsidence in the range of 0.55 to 0.65 of the extraction thickness (Cortis, 1977). In these cases, the pillar robbing after room and pillar mining did not necessarily remove all of the coal; the total extraction ratios were generally in the range of 85 to 95 percent.

Some additional case histories of United States subsidence experience are available in which subcritical widths of coal have been extracted. Dahl and Choi (1974, 1975) documented the mining of a six to seven foot thickness of coal in southwestern Pennsylvania and northern West Virginia. The coal was mined at two locations, one by room and pillar methods followed by pillar extraction and the other by longwall procedures. The resulting maximum subsidence factor ranged from 0.31 to 0.37. Young (1916) reported on subsidence in Illinois due to room and pillar mining followed

TABLE 2.1 SELECTED UNITED STATES SUBSIDENCE CASES

| LOCATION             | MINING METHOD                             | SEAM<br>THICKNESS,<br>FT | SEAM<br>DEPTH<br>FT | MAXIMUM<br>VERTICAL<br>SUBSIDENCE,<br>FT | $S_{MAX}/t$     | REFERENCE                   |
|----------------------|-------------------------------------------|--------------------------|---------------------|------------------------------------------|-----------------|-----------------------------|
| Western Pennsylvania | Room and Pillar with<br>Pillar Extraction | 7.1                      | 318                 | 3.90                                     | 0.55            | Newhall and Plein (1936)    |
| Western Pennsylvania | As Above                                  | 6.2                      | 533                 | 3.21                                     | 0.52            | Maize and Greenwald (1941)  |
| Western Pennsylvania | As Above                                  | 6.0                      |                     | 4.31                                     | 0.72            | Rayburn (1930)              |
| Illinois             | As Above                                  | 8.0                      | 450                 | 4.0                                      | 0.5             | Young (1916)                |
| Illinois             | Longwall                                  |                          | <200                |                                          | 0.55            | As Above                    |
| Illinois             | As Above                                  |                          | 200-400             |                                          | 0.5             | As Above                    |
| Illinois             | Longwall                                  | 3.5                      | 430                 | 2.16                                     | 0.62            | Herbert and Rutledge (1927) |
| Illinois             | As Above                                  | 3.5                      | 590                 | 1.94                                     | 0.55            | Auchmuty (1931)             |
| New Mexico           | Longwall                                  | 10.0                     | 350                 | 5.1 to<br>7.1                            | 0.51 to<br>0.71 | Gentry (1976)               |

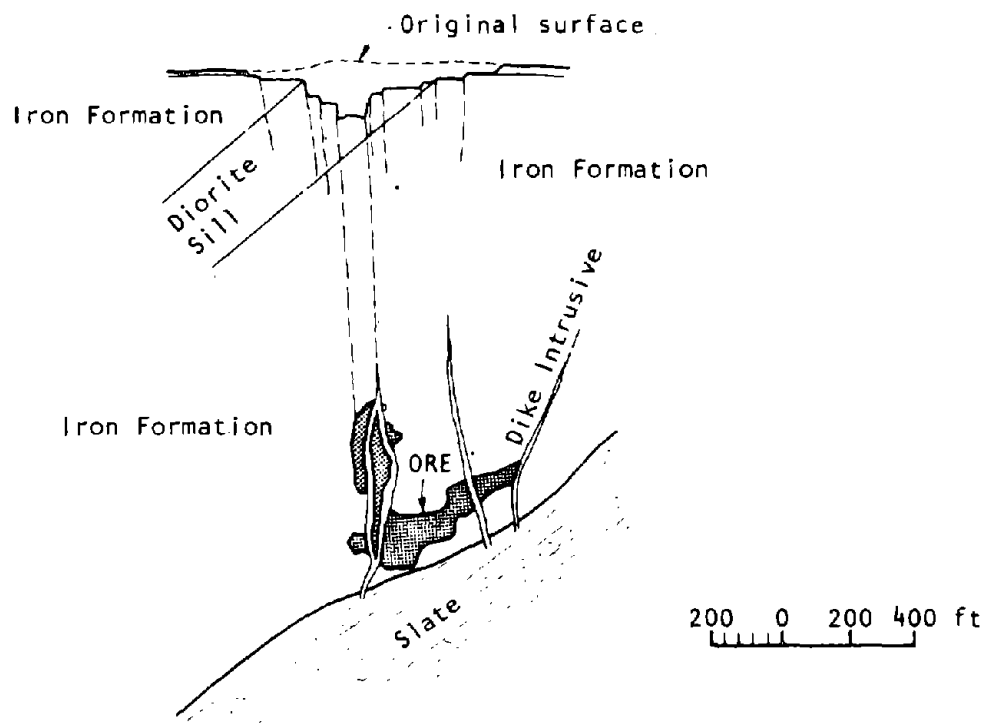
Note: Goaf greater than or equal to critical width.

by partial pillar extraction. The areas of the caved zones were generally small (i.e. of subcritical width) because pillar extraction was suspended when the area being worked began to squeeze. As a result, both the mining conditions and net extraction percentages varied within the mine. The observed subsidence was generally in the range of 0.1 to 0.6 of the seam thickness and the subsidence factor  $S/t$  generally decreased with increasing depth for mines of constant width. Montz (1928) documented subsidence events from mining conditions in the northern anthracite field of Pennsylvania. The coal was worked by room and pillar methods and then flushed with silt before extracting the pillars. Pillar robbing increased the extraction ratio to 86% over much of the mine. Survey measurements indicated a maximum subsidence factor of about 0.57 after pillar extraction.

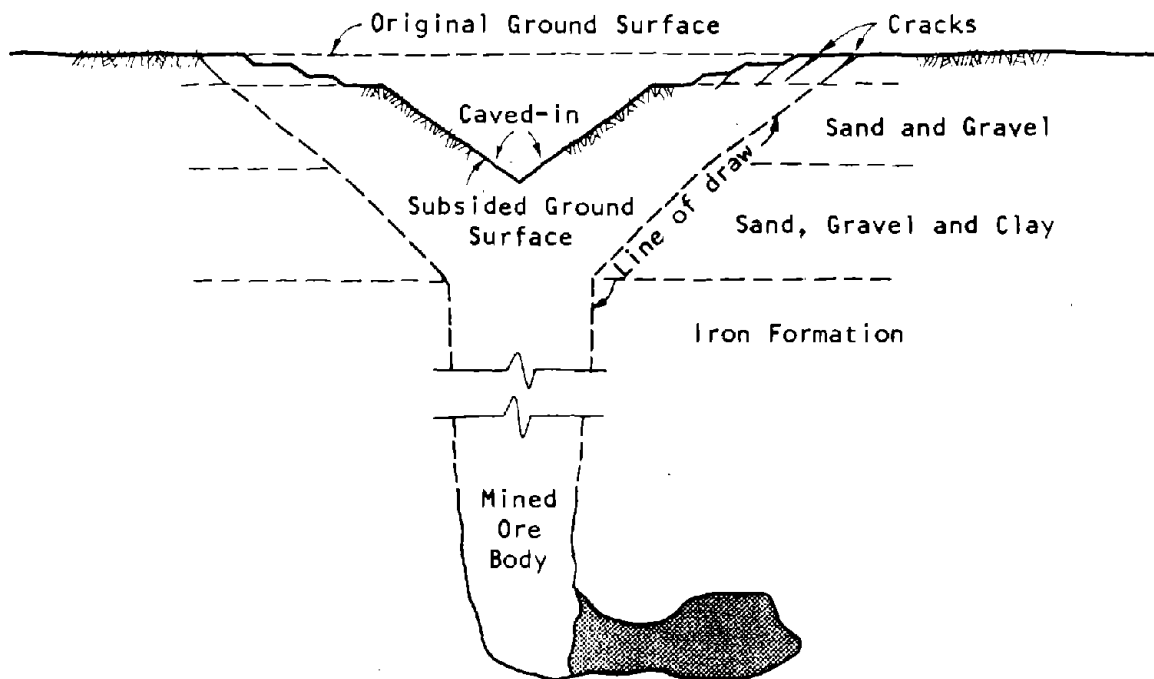
Throughout these case histories of U.S. coal mining, the ground subsidence was observed to develop the general trough or dish-shaped profile consistent with the British and European experience. For this reason, the present study assumes that foreign subsidence data are relevant to predicting ranges of subsidence characteristics to be expected for American mining, where sufficient American experience data are not available. However, caution must be used when applying European experience to U.S. coal mining conditions. For example, the subsidence ratio throughout the U.S. appears to be consistently less than in the foreign experience. The coal measures in the United States are typically of higher strength and greater competence than those in Europe and Great Britain. Also, most of the British data are based on longwall operations, while most American underground coal mining until recently has been by room and pillar methods. Even where pillars have been robbed completely on retreat, the time factor may be of significance when comparing end results between the two complete extraction methods.

2.2.4.2 Subsidence over Iron Mines - Case histories of subsidence due to iron mining have been documented in Michigan. Subsidence in the Michigan iron fields is complicated by the dikes, extensive folding and steep dips in the iron formation and by overlying sands and gravels. Crane (1929) observed subsidence troughs often characterized by a cave-in at the center. The subsidence troughs were generally steplike. Boyum (1961) cites similar subsidence patterns at the Cambria Jackson Mine and the Athens mine. The iron mines appear to be characterized by a steep angle of draw through the rock formation, dependent on the dip of the joints, bedding planes and dikes. The angle of draw flattens upon reaching surficial soils to the angle of repose of those materials. These features are shown in Figure 2.7. The steep dip of the ore body and overlying strata in iron ore formations produce subsidence of greater magnitude than coal mines. Also, caves are more common (sometimes intentional) above deep iron mines. Consequently, the monitoring techniques developed in this report may require some modifications for use with iron mines.

2.2.4.3 Subsidence over Copper Mines - Case histories of subsidence due to copper mining have been documented in Michigan and Arizona. The magnitudes of subsidence, often 40 ft to 250 ft, are considerably greater than those encountered with coal mines. Angles of draw have been cited as  $-5^{\circ}$  to  $45^{\circ}$ , although tensile cracking may occur outside this zone. The angle of draw



a) TYPICAL GROUND CONTOURS OVER IRON MINES (after Boyum, 1961)



b) CONTOURS OF SURFICIAL SOILS OVER IRON MINES (after Crane, 1929)

Figure 2.7 - CHARACTER OF SUBSIDENCE OVER IRON MINES

can be altered by the presence of major discontinuities as shown in Figure 2.8. In block caving operations, the fractured zone extends to the ground surface, and the subsidence trough is irregular.

In copper mines, the height of the underground void causing subsidence and the magnitude of the surface movements are much greater than those commonly encountered in U.S. and foreign coal mining experience. It is apparent that a subsidence monitoring program developed for coal mining operations (the focus of this report) may not be fully applicable to copper mining.

2.2.4.4 Subsidence Due to Other Mining Activities - Subsidence has been documented over salt and sulphur ore bodies extracted by solution mining processes. Solution mining of salt can produce large subsurface cavities and may result in sudden cave-ins. Deere (1961) reports that a bowl-shaped subsidence trough developed from solution mining a sulphur deposit 1300-1600 ft deep and several tens of feet thick. Maximum subsidence after 31 months of production was slightly more than 4 feet.

Extraction of groundwater, oil and gas can produce a subsidence basin. Extraction of oil accompanied by water and gas produced up to 29 feet of subsidence in the Wilmington Oil Field in California (Mayuga, 1969). Subsidence due to groundwater withdrawal in the San Joaquin and Santa Clara Valleys in California is well documented, but the subsidence trough typically is much flatter than coal-mining subsidence troughs and extends over tens to hundreds of miles. Because of these gradual contours, damage is far less severe per unit of subsided land than for coal mine induced subsidence.

## 2.3 EFFECTS OF LOCAL CONDITIONS ON SUBSIDENCE

The two dimensional model provides a convenient reference for comparing the subsidence experience of the U.S. and other nations, but subsidence features are not always smooth basins as suggested by the model. They can be marked by cracks, steps and caves and, even if smooth, the contours may be asymmetrical. The characteristics of surface subsidence deformations may be dependent on the local geology, the mining method and subsidence control procedures used, and the terrain features. The effects are briefly outlined below and are described in detail in the later section on measurements.

### 2.3.1 Geologic Conditions

Geologic structural features such as joint systems and faults can have a significant influence upon the mode of propagation of mine collapse to the ground surface (Crane, 1931). Instead of a basin type of subsidence development, major structural features can cause cracks, steps and caves as illustrated on Figure 2.9. Pothole development is noted as a common expression of ground subsidence where coal seams within 150 ft of the ground surface have been mined (Young, 1916; Candeub, 1971).

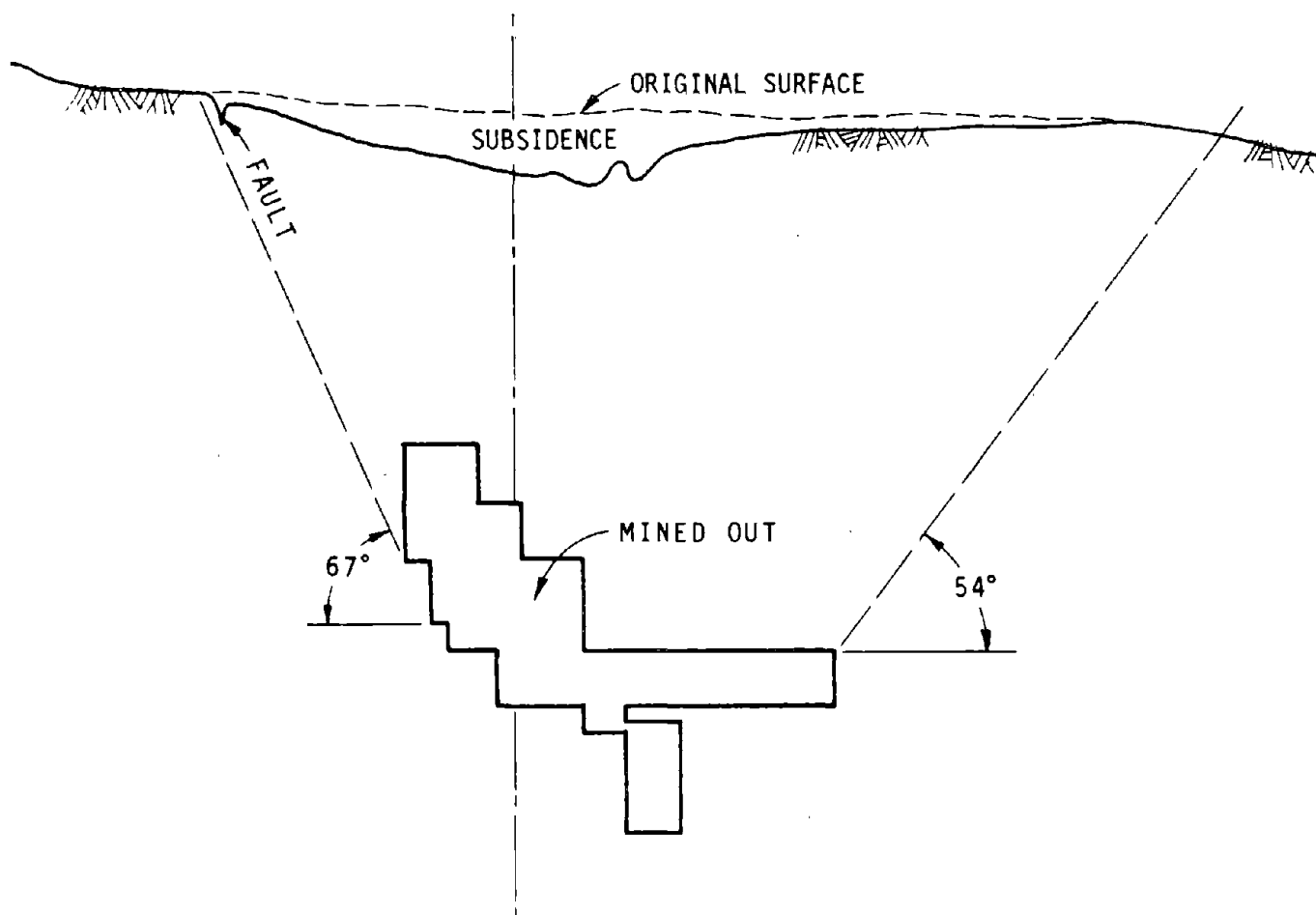


Figure 2.8 - TYPICAL SUBSIDENCE AT COPPER MINE  
(after Lewis & Clark, 1964)

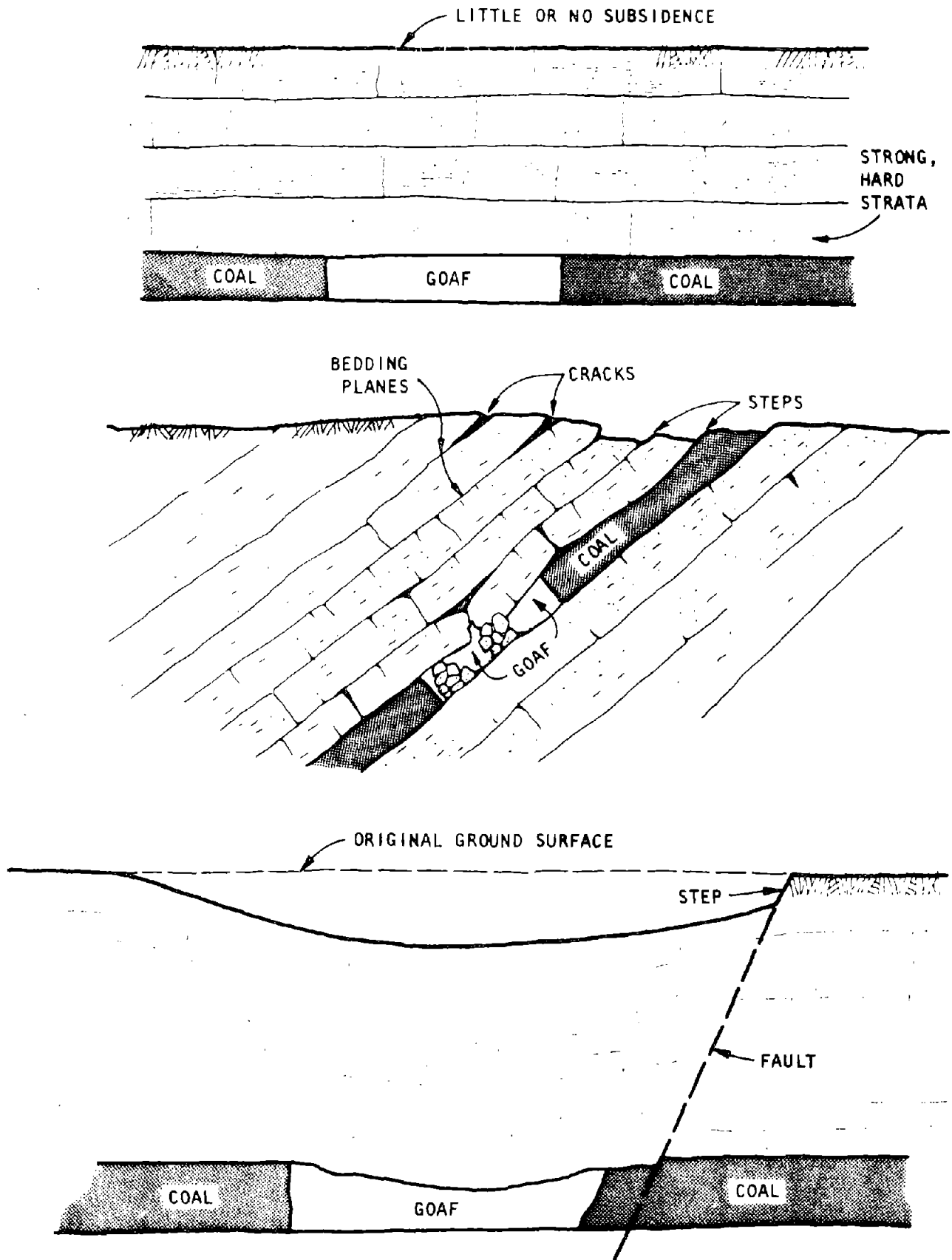


Figure 2.9 - SOME EXAMPLES OF THE INFLUENCE OF GEOLOGY ON SUBSIDENCE



The strength of the capping, the rock strata overlying the mine, is an important parameter in the development of mine subsidence. The coal and overburden rock in the British and some of the European coal fields appear to be of significantly lower strength than commonly encountered in U.S. coal fields (Hardy, 1977; Braunner, 1973). This difference in rock quality may account for the lower subsidence factor observed in American coal mines. Strong capping may reduce the subsidence at the surface by spanning the goaf without sagging appreciably. This phenomenon has been observed in central Pennsylvania (Hardy, 1977; Cortis, 1977).

The competence of the mine roof may dictate the choice of mining method and, in turn, the resulting subsidence. In Illinois, reasonably competent roof conditions were encountered in most mining districts and room and pillar mining was commonly employed. However, poor roof conditions in one district made longwall mining more economical (Young, 1916). Major competent rock strata such as limestone and sandstone overlying a coal seam may bend into the mine workings and, because of their stiffness, heave beyond the workings. The ground surface may heave upward by as much as 0.5 inch (Maize et al., 1941; Auchmuty, 1931; Montz, 1928; Brauner, 1973b; Draper, 1964) before the face advances under the monitored point and downward subsidence is observed.

### 2.3.2 Terrain Features

Ground surface terrain has been shown by measurement and careful observations in a number of cases to have an influence upon the development of mine subsidence. At a longwall mining operation in New Mexico, greater subsidence was observed at the crests of localized ridges than in the intervening draws (Gentry, 1976). Horizontal strain may be greater in the down slope direction of the pre-mining surface contours (Draper, 1964; Ferm, 1977). In Pennsylvania, slopes from 12% to 25% were associated with damage to dwellings using mine design techniques shown adequate for level terrain (Stefanko, 1977). However, other studies of coal mines beneath rugged terrain in southwestern Pennsylvania and northern West Virginia (Dahl and Choi, 1972) suggested that topography played a minor role in subsidence characteristics. The role of terrain needs more study to evaluate its effect on subsidence movements.

### 2.3.3 Mining Methods

In coal mining, the amount of subsidence depends heavily on the level of extraction achieved. Total extraction resulting in collapse of the coal seam roof and overlying strata would be expected to produce the greatest ground subsidence. However, the mining method used to achieve near-total extraction may also affect the amount of subsidence. Room and pillar mining followed by pillar extraction has been observed to produce less subsidence than longwall mining; possibly because the former method removes support more gradually than longwall methods. A possible reason for reduced subsidence might be the development of a compression arch in the overburden strata bridging the mining panel (Dunrud, 1976). Further evidence for the compression arch theory is given by Aynsley and Hewitt (1961), who suggest that maximum subsidence over rapidly advancing faces in longwall mines may be greater than for faces advancing more slowly; i.e., the effect of less ground in

motion at any time offers a better opportunity for arching to develop over the workings. However, if this compression arch theory is correct, the arching action may deteriorate with time, and eventually subsidence similar to that associated with longwall mining may develop.

Where ground subsidence is to be prevented, the common procedure is not to mine the area or to extract only 30 to 60% of the coal with the mining operations (Vandale, 1967; General Analytics, 1974). The success of partial extraction in preventing ground subsidence depends upon the long term stability of the mine pillars, roof and floor.

#### 2.3.4 Abandoned Mines

The previous discussion has been limited to conditions of active mining. Ground subsidence over abandoned mine workings is a significant problem in many areas of the United States and particularly in the western Pennsylvania region where shallow seams were worked by room and pillar mining over the last hundred years (Ackenheil, 1968). Damage to surface facilities has primarily resulted from localized pothole development caused by collapse of rooms in the abandoned mines (Cortis, 1977). Some abandoned mines have created conditions such that tracts of ground have been precluded from economical development, or specialized foundation systems were required at a substantial construction cost premium (General Analytics, 1974; Gray, 1970).

Ground surface subsidence over abandoned workings can result from collapse of the mine roof (Bruhn, 1977) and from squeezing or closure of the abandoned workings (Bates, 1977; Mansur, 1970). Investigations have concluded that this squeezing results from yielding of coal pillars and penetration of the coal pillars into the roof and floor strata.

Ground subsidence due to collapse or squeezing of abandoned coal mines has been reported in Pennsylvania (Mitre, 1972; Martin, 1975), in Wyoming (Donner, 1977) and elsewhere. Where area wide subsidence has been experienced, measurements have shown a bowl or dish-shaped subsidence pattern (Mansur, 1970; Jacobsen, 1975). However, pothole formation may be irregular and unpredictable. Rates of subsidence of about one inch per month (2.5 cm per month) have been reported (Bates, 1977; Jacobsen, 1975) before corrective measures were instituted.

Some land areas that are subsiding due to collapse or squeezing of abandoned mine workings have been stabilized through mine flushing procedures or localized support of the mine roof. (Flushing refers to processes in which the mine is backfilled with a slurry of sand, fly ash, or gravel and water.) Surface monitoring programs over these stabilized areas have indicated varying degrees of success in arresting the subsidence movement (Donner, 1977; Jacobsen, 1975). The state of the art of subsidence control at abandoned mines is rudimentary and additional research is needed to evaluate the effectiveness of mine flushing and other techniques in restoring strata support and arresting land subsidence.

### 3.0 SUBSIDENCE MEASUREMENTS

The nature of subsidence phenomena in the United States was examined in Section 2.0. In this section, the resulting stresses and deformations are examined to determine, for each measurement, the range, sensitivity, layout of monitoring points, and frequency of observation appropriate for a subsidence monitoring program. The important deformations and stresses were identified by a review of published U.S. subsidence experience, supplemented by foreign subsidence data where needed. Additional input was obtained from interviews with coal mining engineers, individuals from regulatory agencies, consulting engineers, university researchers and surface industry owners.

Based on the literature review and the interviews, subsidence measurements were selected that are considered applicable to the present state of the art of mining subsidence engineering and are directly usable by mine operators, regulatory agencies and surface resource consumers. The literature review and interviews were also used to detail the characteristics (e.g., range and accuracy) of the selected measurements.

For this investigation, subsidence movements and related loads have been divided into three categories: surface movements, subsurface movements, and mine level movements and stresses. Further, surface movements have been classified as ground surface movements and structure deformations.

#### 3.1 GROUND SURFACE MEASUREMENTS

On the ground surface, subsidence-related movements consist of three components: 1) vertical movement, 2) horizontal movement, and 3) tilt.

##### 3.1.1 Ground Surface Vertical Settlement

In Section 2.1, the subsidence factor was defined as the ratio of surface vertical settlement to extracted ore thickness. The maximum vertical subsidence factor in the United States for total or near total extraction of the coal, is on the order of 0.5 to 0.6. Since coal mines in the U.S. are generally at a depth of 500 feet and the seam thickness is on the order of 6 feet, the average maximum subsidence due to full extraction mining of a single coal seam with caving is expected to be not greater than about 4.0 feet, although in one case (Gentry, 1976) a maximum settlement of 7.1 feet was obtained. A range of 0 ft to 5 ft should be adequate for vertical settlement measurements over caving systems involving single seams. In cases where multiple seams are being worked simultaneously, the values should be multiplied by the number of seams.

Partial extraction mining by room and pillar methods and longwall mining with solid stowing are two of many methods which can provide support to the mine roof and can reduce subsidence substantially. Large supported

systems are costly, however, and are used only when necessary to keep movements below levels damaging to farmland, roads and railroads, buildings and other surface improvements. Sags on the order of 1 foot can turn farmland into swamps (Earth Satellite Corp., 1975), while settlements as small as 2 inches can cause distress to structures (Grant et al., 1974). A measurement range of 0 to 1 ft should be adequate to monitor damaging movements for vertical settlements over supported systems.

Heave may occur just beyond the rib of the panel being mined and ahead of the face during active mining due to bending of the strata above the mine. Eventually these points will settle, but some permanent heave may occur just outside the limit of the draw. Heave may be as large as 2 to 4 inches where strong strata overly the goafs (Cortis, 1969), and may also occur at the center of the trough in subcritical width mining due to buckling under large compressive stresses (Dunrud, 1976), although this is not generally expected to happen.

Most of the published United States case histories of mine subsidence are based upon level surveys along lines of monuments with accuracies of 0.01 to 0.02 feet. Similarly, most of the people interviewed for this study indicated that their surface vertical surveys were accurate to 0.01 feet. However, this accuracy is not always achievable or practical under certain conditions. One case history (Dahl and Choi, 1974) was based on a vertical measurement accuracy of 0.05 feet in rugged terrain; Deere (1961) reported that level readings to 0.1 foot over a sulphur mine were considered accurate enough in grassy swamp land with movements expected to exceed 5 feet.

Second order surveys are appropriate for subsidence surveys (Moffitt and Bouchard, 1975) on level or moderately sloping ground. Level circuits with a geodetic level and invar scale rod or equivalent should close within  $0.035 \sqrt{M}$  feet where M is the circuit length in miles (Moffitt and Bouchard, 1975). Instruments used to measure elevation should have a relative accuracy of 0.01 ft over a 1000 ft line. In mountainous or swampy areas, third order control may be used with a closure of  $0.052 \sqrt{M}$  ft, or an accuracy of 0.02 ft over a 1000 ft line.

Settlement is usually greatest at the center of the subsidence trough and decreases with distance from the center. The edge of the trough can be practically defined as the point at which downward movement equals at least 0.01 ft. This point then determines the angle of draw. Angles of draw in the United States typically vary from  $70^\circ$  to  $35^\circ$  and may be less, even negative for travelling displacements in the direction of face advance.

Instrumentation over active mines should cover an area defined by an assumed angle of draw of  $35^\circ$  in order to intercept all movements due to the mining operation. Given this angle, instrumentation should extend  $0.7D$  beyond the ribs and face of the panel. This distance,  $0.7D$ , is also recommended by the NCB for British practice (National Coal Board, 1966).

The layout of monitoring points is determined by the type of mining operation. For longwall mining or first mining by room and pillar of flatly

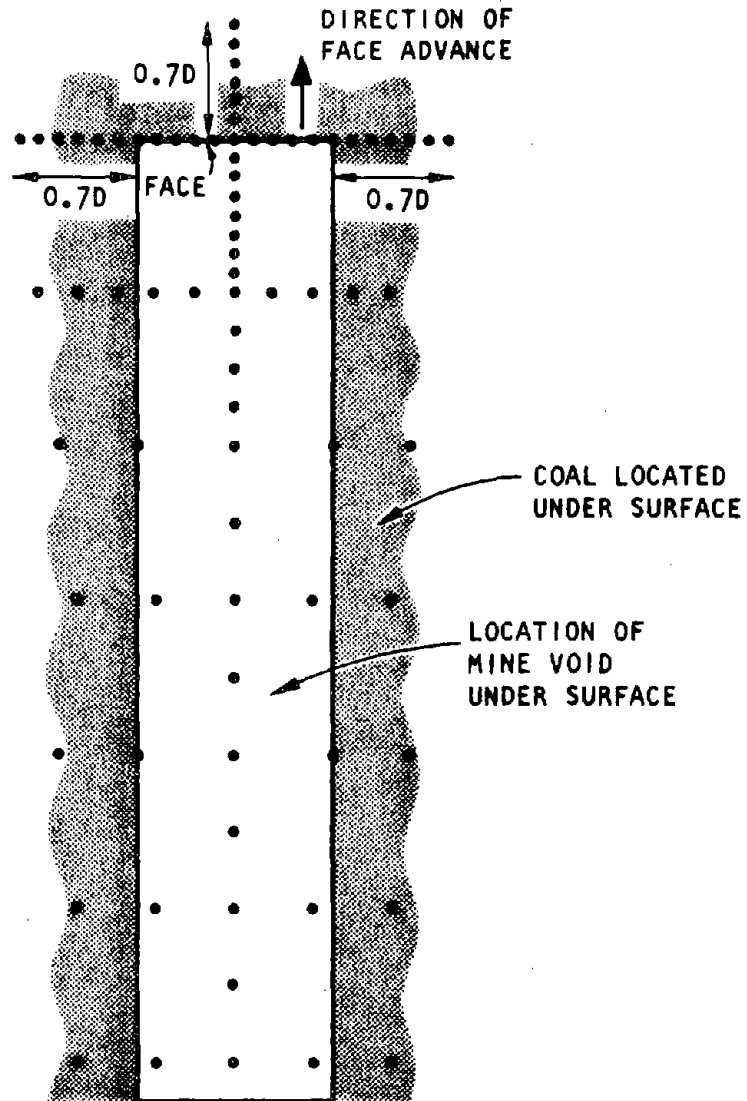
dipping deposits, at least one line of stations should be oriented in the direction of face advance above the center of the goaf. Lines should also be established at 200 ft to 1000 ft spacing (Kumar and Singh, 1973) perpendicular to the direction of advance; a spacing corresponding to the distance typically advanced over two months is recommended. If several panels are worked in an area of relatively constant geology, the perpendicular line spacing can be increased or lines omitted after the first panel is complete. For pillar robbing, solution mining, or mining of steeply dipping deposits, a regular grid above the area expected to be affected may be more appropriate. This area may be defined using an angle of draw of  $35^{\circ}$  from the final limits of the goaf (Deere, 1961).

A close spacing of monuments for vertical subsidence measurement can improve the refinement with which the subsidence profile is determined, but also can increase the cost of the monitoring program. The older subsidence monitoring studies in the United States (Newhall and Plein, 1936; Auchmuty, 1931; Maize et al., 1941; Rayburn, 1930) typically utilized a station spacing of 25 feet. Most of the correspondents to this study favored a 25 foot station spacing and indicated a preference that future monitoring programs should be established with a station spacing of 25 feet. The National Coal Board (1966) recommend a station spacing of 0.05 times the depth to the coal seam. By this criterion, the 25 foot station spacing would be applicable to a coal seam at a depth of 500 feet.

However, station spacings on the order of 75 to 100 feet were used in the more recent U.S. case histories (Dahl, 1972; Dahl and Choi, 1974; Gentry, 1976). One researcher (Deere, 1961) used 200 ft spacings where high accuracy in defining the subsidence profile was not required. In monitoring programs over abandoned mine workings (Donner, 1977; Jacobsen, 1975) station spacings up to 200 feet have been employed to determine ground surface movement. Some subsidence engineers (Choi, 1977; and Gentry, 1977) indicated that the subsidence trough principle was sufficiently well established so that occasional check points were sufficient to verify the general configuration of the subsidence trough. It was felt that even greater station spacings, up to about 0.2 times the seam depth, could be employed in subsidence monitoring programs to minimize time and cost in installation and surveying.

Current monitoring practice suggests that minimum station spacing should be 25 ft or  $0.05D$ , whichever is greater, and maximum spacing should be 200 ft or  $0.2D$ , whichever is less. The varied station spacing cited in the literature and by subsidence engineers suggests that the purpose of the monitoring program should be considered in establishing the optimum spacing. Close station spacings are appropriate for detailed determination of the vertical subsidence profile, while greater station spacings are appropriate for monitoring check points on the subsidence profile in areas where exact determination of the profile is not considered to be vital.

As mentioned earlier, vertical surveys should be tied in to a benchmark outside the subsidence zone. To ensure no movement of the benchmark, it should be located at least a distance  $D$  from the edge of the mine workings



KEY :

- GROUND SURFACE VERTICAL SETTLEMENT MONITORING POINTS

Figure 3.1 - RECOMMENDED SPACING OF GROUND SURFACE VERTICAL SETTLEMENT MONITORING POINTS

where D is the depth to the mine workings (Grobbelaar, 1966). Suggested spacing and layout of monitoring points is illustrated in Figure 3.1.

### 3.1.2 Ground Surface Horizontal Movement including Crack Movement

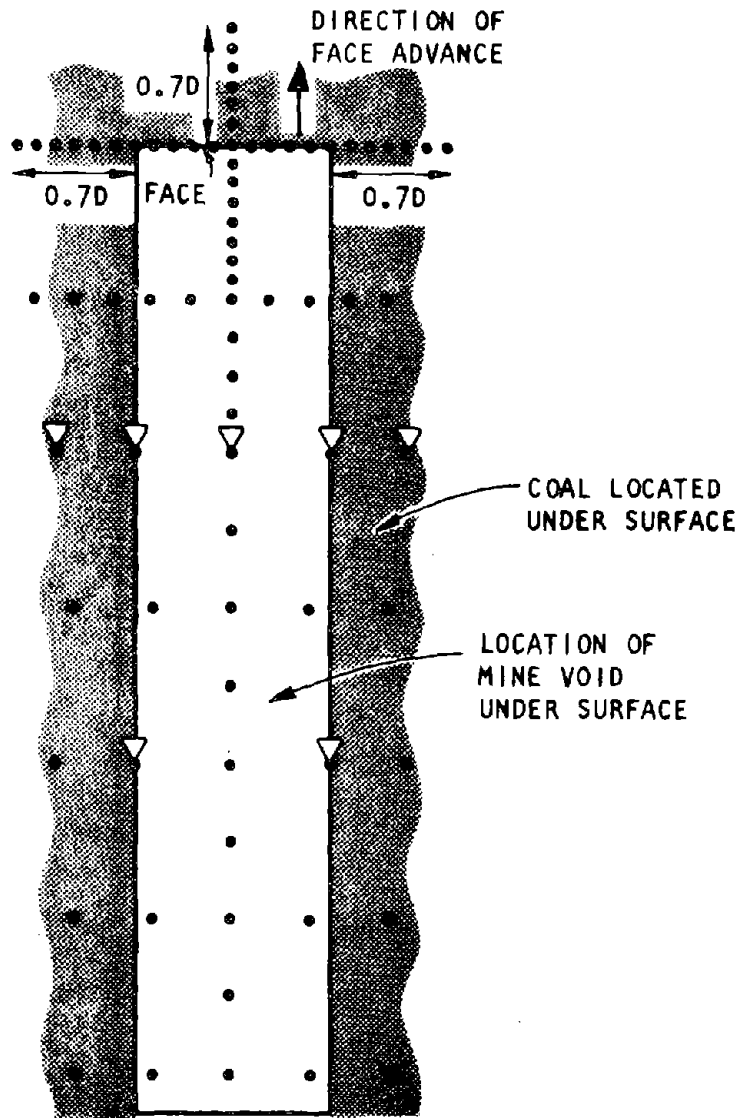
Although the greatest surface deformations are vertical, the most damaging deformations due to mining subsidence may be horizontal (Voight and Pariseau, 1970; Newhall and Plein, 1936). Tension cracks are a common feature of subsidence troughs. The U.S. literature cites horizontal deformations up to 0.7 ft (Newhall and Plein, 1936; Auchmuty, 1931; Draper, 1964; Morgando, 1969); in Colorado tension cracks due to subsidence were observed to open 1.5 to 2 ft (Dunrud, 1976).

There is very little documentation of horizontal movements and of the relationship between horizontal and vertical movement in the United States. In Europe, maximum horizontal displacements were found to be 0.16 to 0.45 of the maximum vertical subsidence, although there was no clear relation between the two parameters (Brauner, 1973a). In fact, most of the people interviewed for this study indicated that horizontal movements were not generally measured because of the time and cost involved. Many researchers consider it adequate to differentiate the vertical subsidence profile to estimate horizontal strains (Mitre Corp., 1972; Hardy, Ripley and Lee, 1961; Lee and Shen, 1969; Dahl, 1972; National Coal Board, 1966 and 1976).

The curves shown in Figure 2.6 suggest that maximum strains associated with full extraction longwall mining in England are approximately 0.6 t/D. Seam thicknesses for longwall operations in the United States vary from 3.5 to 9 feet with 4 to 6 feet most common. The average depth of cover, ranging from 300 ft to 1700 ft, is generally 400 ft to 600 ft (Cummings and Given, 1973). Using these values, maximum strains should typically be no more than 0.4% to 0.9%. Since English prediction methods consistently overestimate vertical settlements due to mining in the United States, the strain predictions are probably too large also. For full-extraction caving longwall systems, a range up to 0.6% strain should be adequate for ground settlement monitoring in the U.S. Since room and pillar mining with pillar extraction causes no more subsidence than longwall operation, a range of 0.6% strain is also adequate for that mining method.

National Coal Board (1975) data suggest that for structures more than 50 feet long, damage may be appreciable to severe for ground strain in excess of 0.2%. Since the purpose of most subsidence control measures is to keep movements below damaging levels, a range up to 0.2% strain should be adequate for partial extraction and backfilled mining methods. In order to detect ground strains before they reach levels damaging to surface facilities, an accuracy of 0.01% strain is recommended.

Horizontal strains occur both parallel and perpendicular to the face (Newhall and Plein, 1936; Auchmuty, 1931; Draper, 1964). Therefore, in order to determine the overall strain pattern, a two-dimensional pattern of monitoring points similar to that suggested for ground surface vertical subsidence is convenient and is recommended (see Figure 3.2). The principal directions of strain, however, are not necessarily perpendicular to the



KEY :

- GROUND SURFACE HORIZONTAL STRAIN MONITORING POINTS
- ▽ GROUND SURFACE STRAIN TRIANGLES (Not to Scale)

Figure 3.2 - RECOMMENDED SPACING OF GROUND SURFACE HORIZONTAL MOVEMENT MONITORING POINTS



edges of the workings. Some evidence (National Coal Board, 1975) suggests that the maximum strain may occur locally in the direction of the maximum ground surface slope. So in addition to lines of strain measurements, strain triangles should be used at selected locations to determine the orientation of the principal strains. Potential locations for strain triangles are shown on Figure 3.2. Five to ten strain triangles per panel should be located at points where large strains are expected. For example, triangles might be situated over the ribs of the panel, at locations where the geology changes and in area of steep ground slopes.

Each strain triangle should be an equilateral triangle. The leg length for the triangles should be short enough so that peak strains are not obscured by averaging the strains over a long gauge length (NCB, 1976). However, a gauge length which is too short may detect atypical strains due to local variations in the soil or rock profile. To satisfy these criteria, the legs of the triangle should be between 6 ft and 25 ft long (Corden and King, 1965). Figure 3.3 shows how maximum strains can be determined from the strain triangle. For triangles which are not equilateral, or where horizontal movements are large, the reader is referred to Figure 3.4.

In addition to strain triangles and lines, cracks should be monitored as they open. Cracks are usually due to tensile stresses caused as the overlying strata bend into the mine. However, cracks may also develop as a result of shear movement on faults (Lee, 1966) or buckling due to compressive forces (Dunrud, 1976).

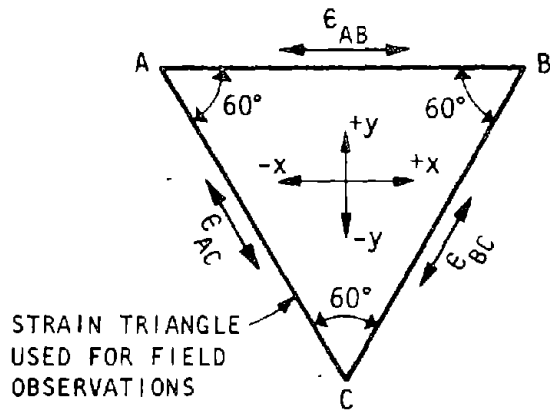
As noted earlier in this Section, reported subsidence cracks typically opened less than 0.7 ft. Therefore, a range of 1 ft and an accuracy of 0.01 ft should be sufficient to document crack behavior. A gauge length of 6 to 25 ft should be adequate to bridge the crack and meet the criteria discussed for gauge length of strain triangles.

Two lines should cross any crack to provide some redundancy in case of damage to the instruments or non-typical local movements. If shear is expected on the crack, it may be advantageous to use a strain triangle over the crack. The range and accuracy for the strain triangle, if used, should meet the specifications given above for measurement of crack movement. The procedure detailed in Figure 3.3 may be used to determine the principal strains. However, if large movements distort the triangle, the procedure shown on Figure 3.4 should be used for analysis.

### 3.1.3 Ground Surface Tilt

Ground surface tilt has been measured directly by a few researchers (Panek, 1966; Corden and King, 1965; Aynsley and Hewitt, 1961), but in general, it is inferred from the subsidence profile. Tilt is a hazard to telephone poles (Young, 1916), smokestacks, transmission towers and other tall narrow structures. It may also affect tall buildings and surface improvements sensitive to gradient change such as railroads, drainage ditches and sewers.

STEP 1:



Calculate the strains  $\epsilon_{AB}$ ,  $\epsilon_{AC}$  and  $\epsilon_{BC}$  between two data readings.

Calculate  $\epsilon_x$ ,  $\epsilon_y$  and  $\gamma_{xy}$  in the arbitrary x-y directions shown. Tensile strain is positive.

$$\epsilon_x = \epsilon_{AB}$$

$$\epsilon_y = (2\epsilon_{BC} + 2\epsilon_{AC} - \epsilon_{AB})/3$$

$$\gamma_{xy} = (2/\sqrt{3}) (\epsilon_{BC} - \epsilon_{AC})$$

(Popov, 1968)

STEP 2:

Draw perpendicular coordinate axes with sign conventions shown below;  $\gamma/2$  is the vertical axis and  $\epsilon$  is the horizontal axis.

Plot point O with coordinates  $((\epsilon_x + \epsilon_y)/2, 0)$

and point N with coordinates  $(\epsilon_x, \gamma_{xy}/2)$

Draw a circle with center at O and radius  $\overline{ON}$

The maximum principal strain is point Q at  $(\epsilon_{max}, 0)$

The minimum principal strain is point R at  $(\epsilon_{min}, 0)$

The maximum shear strain is  $\gamma_{max}$ ; point S is at coordinates  $(0, \gamma_{max}/2)$

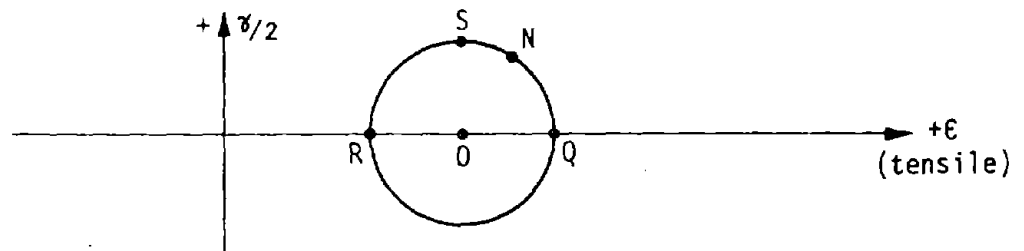
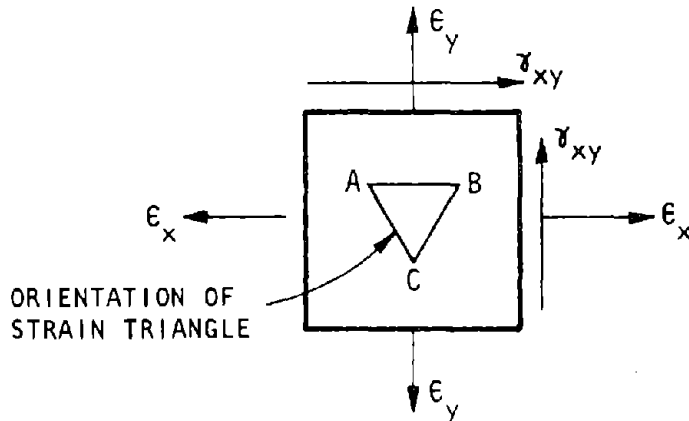


Figure 3.3 - CALCULATION OF MAXIMUM STRAIN FROM STRAIN TRIANGLE

STEP 3:

Draw an imaginary element of soil/rock showing the directions in which strains  $\epsilon_x$ ,  $\epsilon_y$  and  $\gamma_{xy}$  act.



STEP 4:

Draw a line from N parallel to the plane on which the strains  $(\epsilon_x, \gamma_{xy})$  act. This line intersects the circle at the pole P.

Draw line  $\overline{QP}$ .

Measure the angle  $\theta$  between  $\overline{QP}$  and  $\overline{NP}$  on the soil/rock element.

Draw a line at angle  $\theta$  to the plane on which  $(\epsilon_x, \gamma_{xy})$  acts. This is the plane on which the maximum strain  $\epsilon_{max}$  acts.

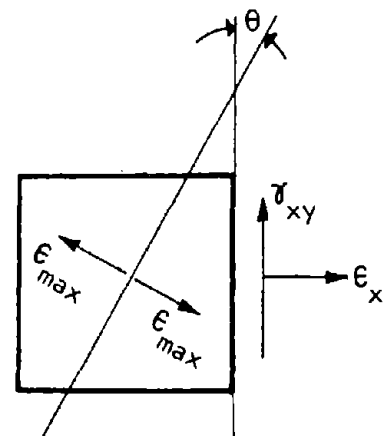
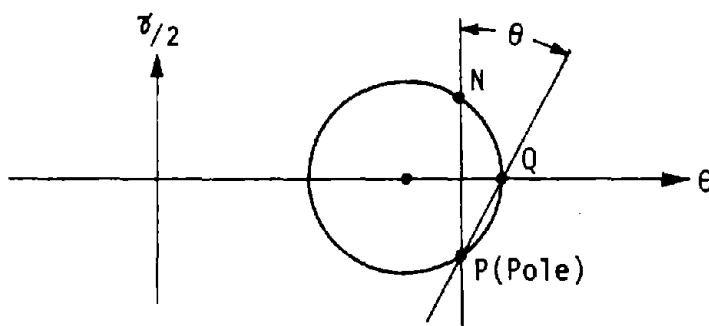
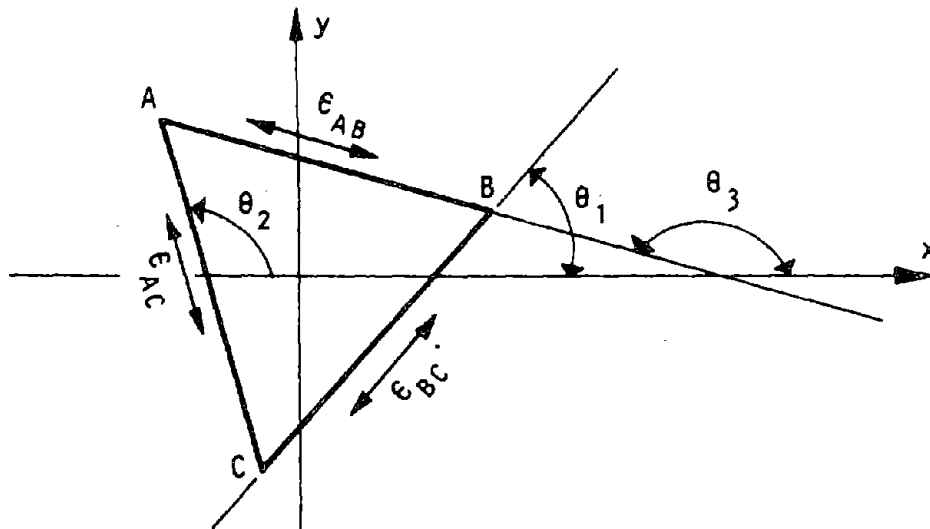


Figure 3.3(Cont'd) - CALCULATION OF MAXIMUM STRAIN FROM STRAIN TRIANGLE



STEP 1:

Calculate the average length of side for  $\overline{AB}$ ,  $\overline{AC}$  and  $\overline{BC}$  between observations of data.

Determine the strain  $\epsilon_{AB}$ ,  $\epsilon_{AC}$  and  $\epsilon_{BC}$  occurring between those two readings.

Draw the triangle.

Calculate  $\epsilon_x$ ,  $\epsilon_y$  and  $\gamma_{xy}$  for the arbitrary x, y axes shown by solving the following simultaneous equations:

$$\epsilon_{BC} = \epsilon_x \cos^2 \theta_1 + \epsilon_y \sin^2 \theta_1 + \gamma_{xy} \sin \theta_1 \cos \theta_1$$

$$\epsilon_{AC} = \epsilon_x \cos^2 \theta_2 + \epsilon_y \sin^2 \theta_2 + \gamma_{xy} \sin \theta_2 \cos \theta_2$$

$$\epsilon_{AB} = \epsilon_x \cos^2 \theta_3 + \epsilon_y \sin^2 \theta_3 + \gamma_{xy} \sin \theta_3 \cos \theta_3$$

(Popov (1968))

STEP 2:

Continue with Step 2 on Figure 3.3

Figure 3.4 - CALCULATION OF MAXIMUM STRAIN FROM STRAIN TRIANGLE SUBJECTED TO LARGE MOVEMENTS

Aynsley and Hewitt (1961) suggest that maximum slope of the subsidence basin may be a better criterion than strain for assessing the potential for damage. Strain measurements near ground fractures, unlike slope measurements, may give abnormally high values. In practice, tilt itself is seldom considered in the design of structures in subsidence areas (Institution of Civil Engineers, 1962) except in the design of drainage facilities (National Coal Board, 1975). Designers do consider differential settlements between adjacent points to be a serious problem where such potentials exist.

The greatest tilt in the idealized subsidence model occurs at the point of inflection between the zones of compressive strains and tensile strains. In Figure 2.6 the maximum slope for British data was given as  $2.5 t/D$  ( $t$  is the seam thickness,  $D$  is the seam depth from the ground surface). Over longwall operations, depths commonly range from 400 to 600 ft and seam thicknesses from 4 to 6 feet. These figures suggest a range of 0.02 to 0.04 ft/ft tilt or approximately 1.2 to 2.3 degrees. Since British prediction methods typically overestimate vertical movements due to mining subsidence in the U.S., it seems reasonable to assume 2 degrees as the upper limit of tilt for this report.

Supported mining systems such as room and pillar mining or longwall with solid stowing are used to prevent damage to surface facilities. Tilts as small as 0.0002 have been shown to affect sensitive machinery, while drainage is not seriously affected until tilt reaches 0.01 to 0.02 (Sowers, 1962). Since the purpose of supported mining methods is to keep tilt well below these levels, a range of 0.02 tilt or approximately 1 degree should be adequate for supported systems.

To detect tilt movements as small as 0.0002 which may be damaging to certain surface facilities, the instrumentation should have an accuracy significantly better than 0.0002 tilt, or approximately 30 seconds.

Tilt is commonly measured as the change in difference of elevation between two adjacent monitoring points. More recently, single point tilt stations are being used to attempt definition of the subsidence trough (Whittaker and Forrester, 1974). The appropriate gauge length or point spacing will be sensitive to local geology as well as to the pertinent subsidence trough parameters, such as  $S/t$ .

Tilt measurements over a long gauge length may not reveal some cases of steep tilt as shown in Figure 3.5. Further, tilt at a point may not be representative of the subsidence profile because of local changes in geology and surface soils. A certain redundancy in quantity of tilt data is appropriate to average out inevitable local anomalies. A gauge length of 25 to 100 ft is recommended for tilt measurements over open land areas. For areas with structures, smaller gauge lengths are appropriate and will be discussed in Section 3.2.1. Single tilt points might be spaced as close as 10 ft on single lines, or up to 100 ft in large grid patterns where flat subsidence troughs are characteristic and where tilt contours might be plotted to smooth out data anomalies. A typical layout for tilt measurements is shown in Figure 3.6.

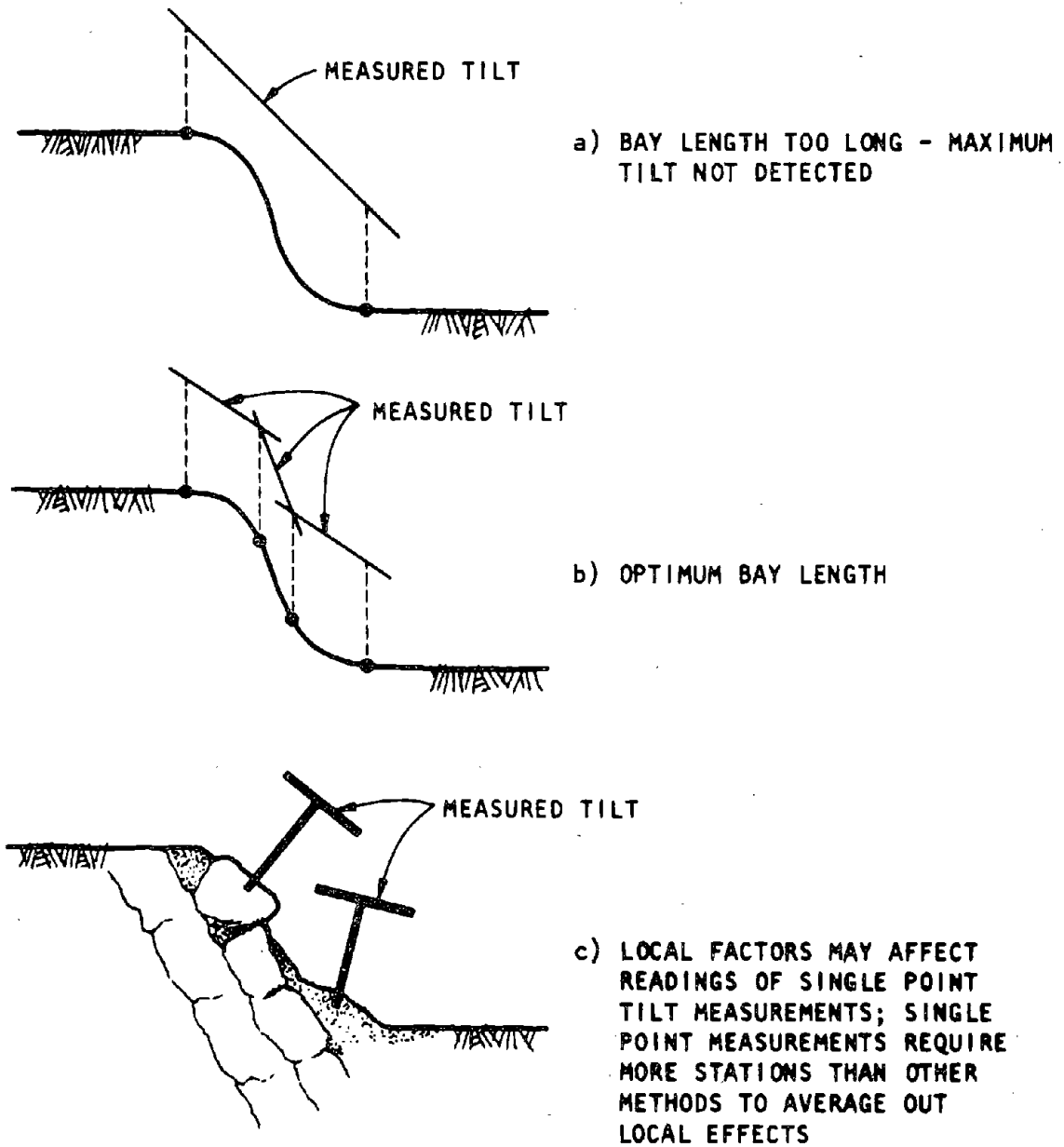
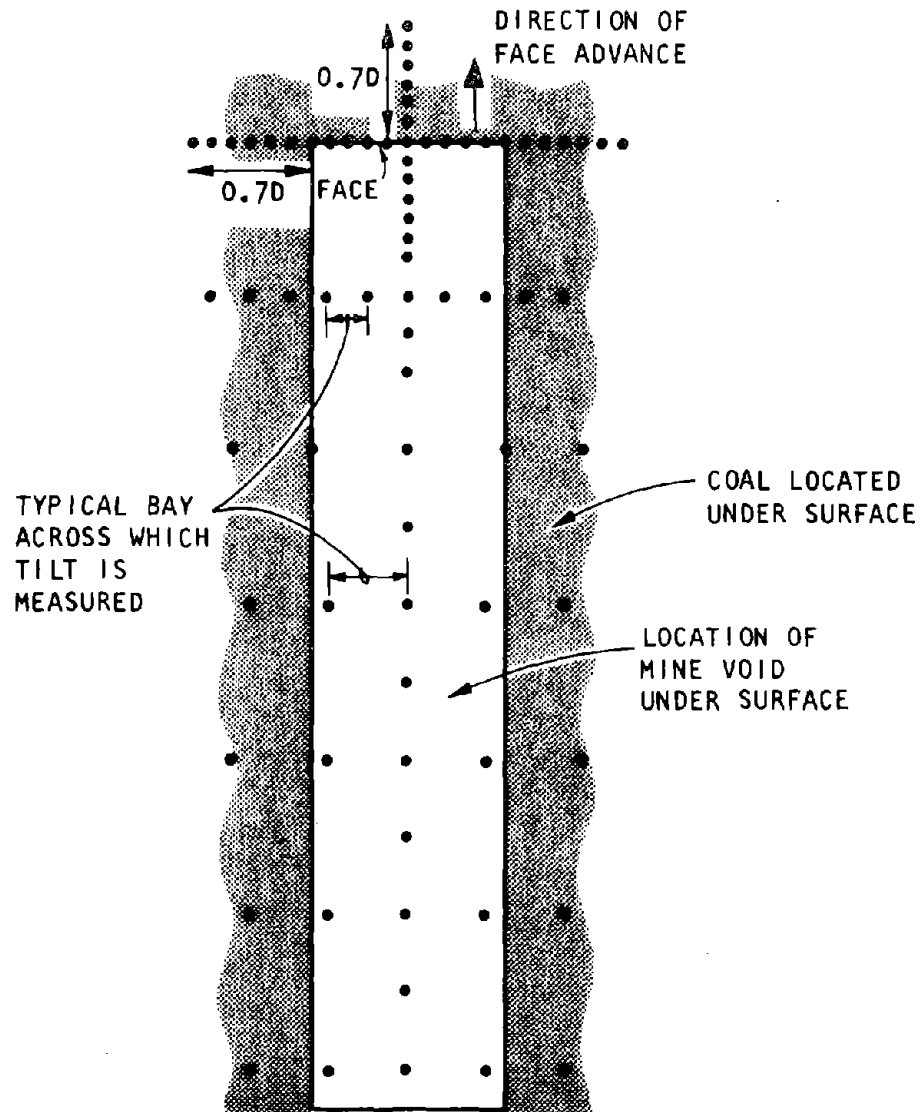


Figure 3.5 - EFFECT OF GAUGE LENGTH ON TILT MEASUREMENTS



KEY :

- GROUND SURFACE TILT MONITORING POINTS

Figure 3.6 - RECOMMENDED SPACING OF GROUND SURFACE TILT MONITORING POINTS

### 3.1.4 Frequency of Ground Surface Measurements

Most movements generally occur within several months over longwall operations in Great Britain although some small movement may continue for several years. Wardell (1969) gave the following relationship for determination of the time during which a part of the surface is subject to movement:

$$T = \frac{2D \tan \gamma}{F} \quad \text{where}$$

$D$  = depth to seam (length)

$\gamma$  = angle of draw (degrees or radians)

$F$  = rate of face advance (length/time)

$T$  = duration of movement (time)

This formula may underestimate  $T$  outside Great Britain.

Surface movement occurred over a 65-week period in an Indian coal mine, although Wardell's equation predicted 12 weeks. Wardell has observed that subsidence occurs concurrently with face advance in Great Britain; however in the Indian mine, 37% of the ultimate subsidence occurred after the panel was complete. In Colorado, subsidence pits in surface soils were first observed 1 1/2 years after coal extraction was completed (Dunrud, 1976).

These examples in Indian and U.S. coal mines suggest that the subsidence process may be much longer than suggested by British data. The Indian coal measures, like those of the United States, are more competent and develop less vertical settlement due to mining than the coal measures in Great Britain. Therefore, it is recommended that surface observations at any monitoring point should continue for at least two years after undermining.

Surface measurements should be made so that at least 0.01 ft of subsidence occurs between readings. Most of the correspondents to this study recommended making subsidence measurements weekly for active mining.

Measurements of surface movement should be made on a weekly basis when the face is within  $0.7D$  of the monitoring point. Once the face is beyond  $0.7D$  of the monitoring point, it is recommended that observations continue on a monthly basis until one year after undermining. At this time, readings could be made two to four times a year until two years after undermining; then if subsidence movements can still be detected, monitoring should continue twice yearly until movement stops. Note, however, that if any sudden increase in movement is detected during the first or second year after undermining, it is recommended that such movements should be monitored at least once or twice a week until a stable condition is achieved.

For room and pillar mining with pillar extraction, monitoring should continue for at least two years after pillar extraction according to the



schedule suggested above. Similarly, for supported systems, monitoring should continue for a minimum of two years after all mining operations are completed below any monitoring point.

When the purpose of the monitoring requires less detail, the monitoring frequency may be less often. For example, over abandoned mines, monthly monitoring, tapering to twice yearly after seasonal movements are established, should be adequate. During flushing operations, however, observations should be made on a weekly basis.

### 3.2 STRUCTURE DEFORMATION MEASUREMENTS

Many of the case histories of United States subsidence cite damage to surface facilities including damage to homes and commercial buildings, mine plant, and pipelines. These facilities may merit intensive monitoring because of their economic and social value. The movements which can damage or restrict the use of surface facilities include differential vertical settlements, strains, tilt and curvature. In most mining studies, structure tilt and curvature are not monitored directly but are calculated from the differential vertical settlements.

Absolute settlement of structures due to mining is seldom a problem (Brauner, 1973a). In fact, in Japan, four dams were undermined and settled up to two feet without cracking or leakage (Kaneshige, 1970). A school building in Illinois experienced net subsidence of 1.6 to 2.0 feet and remained functional, although some cracks opened in the building walls during undermining but subsequently closed (Herbert and Rutledge, 1927).

#### 3.2.1 Structure Differential Vertical Settlement

Differential settlement between two points in a structure may tilt sensitive machinery, distort door frames and window frames, crack plaster and cause structural damage to floors and walls. Data on damaging levels of movement have been measured for both mining and non-mining settlements. The settlements associated with a given level of damage for non-mining conditions are generally higher than those settlements which have produced the same level of damage under mining conditions. Brauner (1973a) explains that horizontal strain generally accompanies differential settlement in proportion to the curvature of the subsidence trough produced by mining. The combination of strain and differential settlement cause more damage than would the differential settlements alone.

Damage due to differential settlements has been reported in the literature in several ways. In its simplest form, reported damage has been related to total differential settlement, i.e., the difference between the change in elevation of any two points in the structure. For a perfectly rigid building, however, uniform tilt can occur from one end of the building to the other without bending deformations. Some investigators deduct from the total differential settlement the rigid body tilt. The remaining value is frequently defined as differential settlement due to curvature. Differential settlements due to tilt and curvature are illustrated in Figure 3.7.



In the mining literature, both tilt and curvature have been reported to cause damage. Damaging levels of differential settlements from numerous sources are listed in Table 3.1. Allowable differential settlements due to tilt and/or curvature vary from  $0.0003\Delta/L$  to  $0.003 /L$ , depending on the building materials, structural system and dimensions. For example, brick walls may be distressed by movements as small as 0.3 inches over a 50 foot wall (Littlejohn, 1975), whereas flexible unitized frame structures designed by the CLASP method (Ward, 1974) can tolerate much larger movements.

Differential settlements due to mining are a problem in two directions: parallel to the face and perpendicular to the face. As a structure is undermined it will experience large differential settlements perpendicular to the face. However, unless the face stops under the structure, the differential settlement perpendicular to the face will gradually decrease. For example, Littlejohn (1975) observed 2 inches of differential settlement over a 45 foot concrete strip footing. Eventually after the face was well past, the differential settlements decreased to about 3/4 inch. The effect of mine layout on differential settlement is illustrated on Figure 3.7.

As the face advances under a structure, the structure may experience both concave and convex curvature and tilt. Instrumentation to measure differential settlement must be able to cope with differential movements which may change in both magnitude and relative direction, as shown in Figure 3.8.

Little data on the magnitude of differential settlements for structures is available. A range of 1 foot for differential settlement should be adequate for most structures. Rigid structures may span the zone of curvature and experience less differential settlement; in structures which have cracks one may find that the differential settlement concentrates at the crack and the two halves of the wall move independently (Gardner and Hibberd, 1961). Differential settlements as great as 1 foot will probably be very damaging. Damage can be expected to occur if the following criteria are met (Brauner, 1973):

$$L(\epsilon + \frac{H}{\rho}) \geq 0.1 \text{ length units}$$

where  $L$  = length of structure (length)

$\epsilon$  = strain (length/length)

$H$  = height of structure (length)

$\rho$  = radius of curvature (length) (Brauner, 1973b)

Based on the NCB data, the maximum radius of curvature resulting from full extraction may be roughly 2400 feet for maximum ground strains of 0.006 (see Section 3.2.2). Then for a 100 foot long building, 50 feet high, the left side of the equation becomes 2.7 feet, so the damage threshold is exceeded.

TABLE 3.1  
ALLOWABLE AND DAMAGING LEVELS OF DIFFERENTIAL SETTLEMENTS

| Reference                                                  | M =<br>Mining<br>N =<br>Non-Mining | Comments                                                                                                                             | $\Delta/L$<br>(or $\rho$ if stated)                                                 |
|------------------------------------------------------------|------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Niemczyk, 1949, cited in Brauner, 1973b                    | M                                  | German; apartment houses; max. allowable:<br>German; cracking of brickwork; limit above which damage occurs:                         | 1 to 2 x 10 <sup>-3</sup> tilt<br>0.6 x 10 <sup>-3</sup> tilt                       |
| Rimant, 1968, cited in Brauner, 1973b                      | M                                  | Poland; level at which slight damage such as hair cracks in plaster occur:<br>Poland; level at which small repairable damages occur: | 2.5 x 10 <sup>-3</sup> tilt<br>5 x 10 <sup>-3</sup> tilt                            |
| VNIMI, 1958, cited in Brauner, 1973b                       | M                                  | USSR - Donets Coalfield, also Karaganda district; maximum allowable:                                                                 | 4 x 10 <sup>-3</sup> tilt up to 10 x 10 <sup>-3</sup> for 1 and 2 storey structures |
| Belygev, 1968 cited in Brauner, 1973b                      | M                                  | USSR; max. allowable for coke batteries:<br>USSR; max. allowable for crane structures:                                               | 3 x 10 <sup>-3</sup> tilt<br>3 to 6 x 10 <sup>-3</sup> tilt                         |
| Grant et al, 1974                                          | N                                  | Analysis of settlements for 193 buildings; limit above which damage occurs:                                                          | 3.3 x 10 <sup>-3</sup> curvature                                                    |
| Thomas, 1953, cited in Gardner and Hibberd, 1961           | N                                  | Racking of brick in filled concrete encased steel frame; limit at which cracking occurs:                                             | 2 to 3 x 10 <sup>-3</sup> tilt                                                      |
| Meyerhoff, 1953 cited in Gardner and Hibberd, 1961         | N                                  | Observation of brick walls of buildings; limit at which cracking occurs:                                                             | 3.5 x 10 <sup>-3</sup> tilt                                                         |
| Sowers and Sowers, 1970                                    | N                                  | Towers, stacks; maximum allowable:                                                                                                   | 4 x 10 <sup>-3</sup> tilt                                                           |
|                                                            | N                                  | Crane rails; maximum allowable:                                                                                                      | 3 x 10 <sup>-3</sup> tilt                                                           |
|                                                            | N                                  | Stacking of goods; maximum allowable:                                                                                                | 10 x 10 <sup>-3</sup> tilt                                                          |
|                                                            | N                                  | Brick walls in buildings; maximum allowable                                                                                          | .5 to 1 x 10 <sup>-1</sup> curvature                                                |
|                                                            | N                                  | Reinforced concrete building frame; maximum allowable                                                                                | 3 x 10 <sup>-3</sup> curvature                                                      |
|                                                            | N                                  | Steel building frame, continuous; maximum allowable:                                                                                 | 2 x 10 <sup>-3</sup> curvature                                                      |
|                                                            | N                                  | Steel building frame, simple; maximum allowable:                                                                                     | 5 x 10 <sup>-3</sup> curvature                                                      |
| VNIMI, 1958, cited in Brauner, 1973b                       | M                                  | USSR - Donets Coalfield; minimum allowable radius of curvature:                                                                      | $\rho = 60,000$ ft to 10,000 ft for 1 and 2 storey structures; curvature            |
| Belygev, 1968, cited in Brauner 1973b                      | M                                  | USSR - coke batteries; minimum allowable radius of curvature:                                                                        | $\rho = 42,000$ ft curvature                                                        |
| Meyerhoff, cited in Gardner and Hibberd, 1961              | N                                  | Evaluation of published work; limit at which cracking occurs:                                                                        | .5 x 10 <sup>-3</sup> curvature                                                     |
| Rigby and Dekoma, 1952, cited in Gardner and Hibberd, 1961 | N                                  | Lightly reinforced brickwork on concrete strip footing; limit at which cracking occurs:                                              | 0.1 x 10 <sup>-3</sup> to 0.02 x 10 <sup>-3</sup> curvature                         |
| Wood, 1952, cited in Gardner and Hibberd, 1961             | N                                  | Brick wall - span of 10-1/2 feet; limit at which cracking occurs:                                                                    | 0.05 x 10 <sup>-3</sup> curvature                                                   |

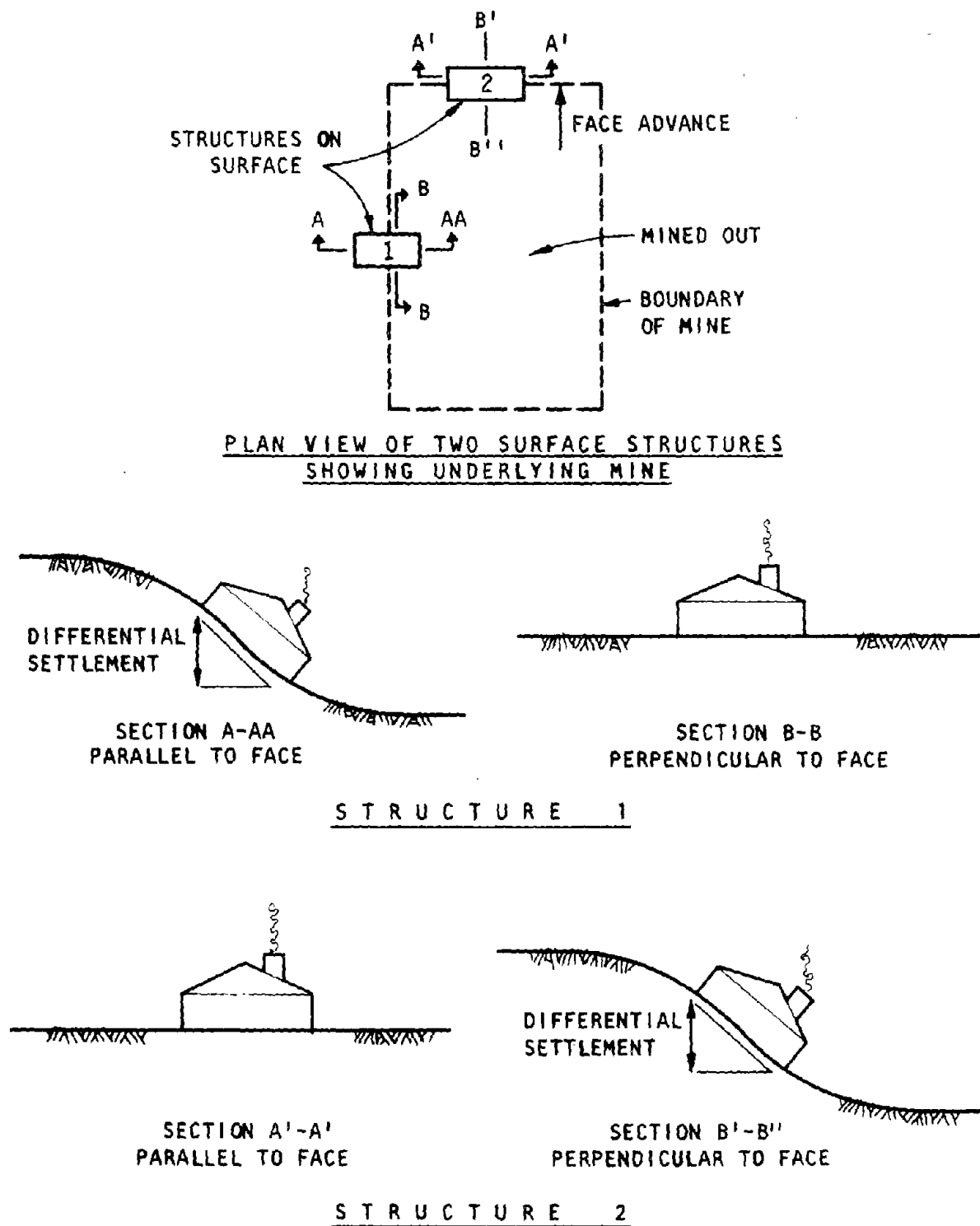


Figure 3.8 - STRUCTURE DIFFERENTIAL SETTLEMENTS PARALLEL AND PERPENDICULAR TO FACE

The structure should have monitoring points along two perpendicular exterior walls at a minimum to detect potential movement in both directions. In order to detect the effect of both curvature and tilt, at least three monitoring points should be used per wall located at each end of the wall and at the center. In Britain a spacing of  $0.05D$  is recommended where  $D$  is the depth to the coal seam (NCB, 1976); this is equivalent roughly to a spacing of 10 to 25 feet between monitoring points. Several ground monitoring points should extend beyond the building to a distance of 100 to 200 ft to assess the effect of differential movements of the soil and rock around the structure on appurtenant pipe and sewer connections.

### 3.2.2 Structure Strains and Crack Movement

Most damage to structures is attributed to horizontal strain when mining subsidence occurs. The NCB (1976) contends that the change in length of the structure is the critical parameter rather than strain. A short brick building can absorb a compressional strain of 0.001 by distributing it over the numerous voids in the brickwork. But for a long structure, say 200 ft, at the same strain level, a shortening of 0.2 ft might concentrate at some weak point. This approach is also used in the USSR; allowable strains decrease with increasing structure dimensions. Some typical allowable levels of strain and movement and damage thresholds for strain and movement are presented in Table 3.2.

Ground strain may not be fully transmitted to structures. In fact, the ground may undergo compressive strains while the structure experiences tensile strain (Littlejohn, 1975). This apparent conflict can be resolved by observing that the percent of ground strain transmitted to the structure may vary during the tension and compression periods. During the tension wave a brick wall, observed by Littlejohn, moved with the ground and slipped only 1/4 inch; however, during the following compression wave, at least 1/2 inch of slip was observed between the wall and the ground.

A range of 0.4% strain should be adequate for most structure monitoring in the United States. Although this is less than the 0.6% suggested for maximum ground strain, this strain level will probably cause appreciable damage to structures longer than 50 feet according to the NCB classification.

Some cracks may open when the strains become this large. When cracks open, the strains will be relieved along most of the structure and concentrate at the cracks. Therefore, a range of 0.4% is probably acceptable for continuous wall or walls with hair cracks. Where cracks open, they should be monitored separately. Cracks opening from 3/4 inches (Littlejohn) to several inches (NCB, 1976) have been observed. A range of 2 in. or 0.2 ft should be adequate for most crack monitoring instrumentation.

Most surveys of structure performance use more accurate measuring techniques than are commonly used for ground movements. Precision leveling (Gardner and Hibberd, 1961; King and Green, 1973) and first order

TABLE 3.2  
ALLOWABLE AND DAMAGING HORIZONTAL MOVEMENTS  
National Coal Board Classification of Mining Damage  
(NCB, 1976)

| Change of length of structure | Class of damage              | Description of typical damage                                                                                                                                                                                                                                                                                                                    |
|-------------------------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Up to 0.1 ft....              | 1. Very slight or negligible | Hair cracks in plaster. Perhaps isolated slight fracture in the building, not visible on outside                                                                                                                                                                                                                                                 |
| 0.1 ft-0.2 ft...              | 2. Slight.....               | Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary.                                                                                                                                                                                                            |
| 0.2 ft-0.4 ft...              | 3. Appreciable...            | Slight fracture showing on outside of building (or one main fracture). Doors and windows sticking; service pipes may fracture.                                                                                                                                                                                                                   |
| 0.4 ft-0.6 ft...              | 4. Severe.....               | Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted; floors sloping noticeably; walls leaning or bulging noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures. |
| More than 0.6 ft              | 5. Very severe...            | As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams lose bearing and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls.                                                                                     |

Allowable Strains in Poland's Mining Districts  
(Rimant, 1968, cited in Brauner, 1973b)

| Allowable strain, $\times 10^{-3}$ | Explanation                                                                           |
|------------------------------------|---------------------------------------------------------------------------------------|
| 1.5                                | Allowable are slight damages such as hair cracks in plaster.                          |
| 3.0                                | Allowable are small reparable damages.                                                |
| 6.0                                | Allowable are damages that do not destroy the building or impair its service.         |
| 9.0                                | Movements are such that completely reinforced structures are required to resist them. |

Allowable Strains in Donets Mining District, USSR  
(VNIMI, 1958, cited in Brauner, 1973b)

| Allowable strain, $\times 10^{-3}$ | Height, m | Number of floors |
|------------------------------------|-----------|------------------|
| 2.5                                | > 15      | Five and more... |
| 3.5                                | 10-15     | Three and four.. |
| 6.0                                | 5-10      | One and two..... |
| 7.5                                | 5-10      | One and two..... |
| 14.0                               | 5         | One.....         |

triangulation (Reynolds and Dearing, 1970) have been used to measure differential structure settlements. An accuracy of 0.002% would be appropriate to detect potentially damaging strains in concrete walls before damage occurs. This accuracy may be somewhat difficult to achieve, but high accuracy is necessary in monitoring deformations in steel or concrete structures.

### 3.2.3 Frequency and Duration of Structure Monitoring

Monitoring should be conducted weekly when the face is within 0.7D of the critical structure. Beyond this time observations should be made on a monthly basis until the end of the first year after undermining and if movement continues twice yearly until the movement stops.

### 3.2.4 Visual Observations of Ground Surface and Structures

In addition to the specific detailed information which is supplied by instrumentation, an overall evaluation of subsidence effects can only be made with a visual examination of an area. Thorough documentation of visual observation prior to mining followed by repeated inspections would indicate the progress of subsidence (Bruhn, 1977). In particular, a chronological log of visual observations, possibly supplemented with a log of mine operations, would make it possible to relate documented visual observations with movements shown by the monitoring records.

Records of visual observations should include notes and selected photographs describing the existing condition of structures, obvious cracks in structures, pavement and the ground, tilting of trees and telephone poles, notable sags or potholes in the ground surface and locations of ponds and swamps.

Visual observations should be made by experienced personnel and they should be assigned to specific areas so that deviations from normal conditions may be detected more readily. The extent of the area covered should be compatible with the damage potential. For example, in an eight-hour workday one man with a vehicle could possibly cover a sparsely populated rural area of ten square miles, but in a densely populated city perhaps only one square mile could be inspected.

## 3.3 SUBSURFACE MEASUREMENTS

As a mine converges or collapses, the movement propagates upward and outward to produce ground surface subsidence. The movement as subsidence propagates upward is a combination of horizontal and vertical subsurface components. Except for research purposes, there has been infrequent monitoring of these movements in connection with mining-induced subsidence although the need to do so is recognized (Dahl, 1976; Choi, 1977; and Bates, 1977). The zone of subsurface movement is generally underlain by a zone of fracturing and, in caving operations, the fracture zone is underlain by the zone of caving. For example, in longwall mining, the zone of



fracturing was observed to extend 3.5 times the seam thickness above the mine in Poland and 8 to 10 times in India (Ropski and Loma, 1973). For block caving, in contrast, the zone of caving may propagate to the surface (Johnson and Soule, 1963), and attempts have been made to monitor the extent of this subsurface fracturing (Obert and Duvall, 1961) over block caving operations.

### 3.3.1 Subsurface Vertical Deformations

As a mining face is advanced, the strata overlying the mine will experience vertical subsidence which eventually will reach a maximum value. Primarily depending upon the local geological conditions, the strata above the mine could subside almost as a unit; or vertical subsidence could propagate upwards gradually, accompanied by sequential opening and closing of bedding planes, joints and faults. Thus, subsurface movements between the ground surface and a point at depth could approach a value equal to the amount of closure of the mine opening.

Therefore, subsurface vertical deformation instrumentation should be able to accommodate 1 to 5 feet of deformation between the surface and the mine roof. In a zone where significant bed separations may occur, instrumentation with limited range could easily be destroyed. In one monitoring program above a coal mine (Dahl and Choi, 1973) subsurface vertical strains were measured in the range of  $2 \times 10^{-3}$  to  $10 \times 10^{-3}$ , or 0.5 ft over a 50-ft gauge length, up to 300 ft above the mine. The available range of vertical movement for subsurface instrumentation should not be less than 0.5 ft to accommodate bed separation. Subsurface instrumentation should be capable of monitoring movements to depths of at least 300 ft (Moebs et al., 1977), and preferably subsurface monitoring points should extend down almost to the mine roof.

Researchers who have made subsurface vertical deformation measurements (Choi, 1977; and Dahl, 1977) reported measurement accuracies on the order of 0.1 to 0.2 feet and indicated satisfaction with this level of accuracy. Other correspondents (Cortis, 1977; and Wade, 1977) expressed a desire to make measurements to within an accuracy of 0.01 feet. In order to attain this measurement accuracy, an instrument accuracy of 0.005 feet over a gauge length between subsurface points of not greater than 50 feet would be appropriate in order to account for system errors such as friction. For monitoring programs where great detail is not desired, a coarser accuracy and longer gauge length may be utilized. Depending on circumstances, it is believed that two to four subsurface monitoring stations should be installed per mining panel.

### 3.3.2 Subsurface Horizontal Deformation

Surface strata above the mine may undergo significant horizontal displacements toward the center of the mine workings (see Figure 2.1). Toward the edges of the subsidence trough, inward movement of the surface strata may be greater than that of the underlying strata. These differential horizontal movements can produce a tilt at the ground surface inward

toward the mine centerline and have been known to shear well casings (Tilton, 1977). Mayauga (1966) observed that horizontal movements in the subsidence basin at the Wilmington Oil Field caused extensive damage to surface and subsurface structures and that many oil wells were "damaged or destroyed by subsurface shearing associated with subsidence." Differential horizontal movements have been monitored in a mine air shaft (Newhall and Plein, 1936), and angular movements on the order of 0.06 to 0.3 degrees were indicated from these measurements. In addition to using subsurface horizontal measurements for active mining, Bates (1977) has proposed that horizontal deformations be monitored to assess the effectiveness of a flushing operation.

Inclinometers are the most practical method for measuring horizontal deformations at depth and further discussion will assume the use of inclinometers. The inclinometer measures tilt between two points separated by a fixed distance. By obtaining a continuous profile of tilt measurements in a borehole, the horizontal displacement of points in the borehole may be calculated.

Little data on the magnitude of horizontal subsurface movements is available. It is reasonable to assume that angular rotation at depth will not exceed the angular rotation at the surface, i.e., the ground surface tilt. Therefore, it is recommended that the range of angular movement for subsurface instrumentation be at least 2 degrees, and should be monitored to depth of at least 300 feet from the ground surface. Borehole inclinometers are currently available which are accurate to 20 seconds of arc and it seems reasonable to specify an instrument accuracy of 30 seconds.

The subsurface horizontal movements indicated are referenced to the initial alignment of the borehole, and the determination of absolute horizontal movement at depth in a subsiding area requires horizontal control at the ground surface or an assumption that at some level the borehole is stationary. It is recognized that substantial costs would be required to install and operate a horizontal subsurface deformation system, and, depending on circumstances, a typical layout would consist of two to four monitoring stations per mine panel.

### 3.3.3 Extent of Subsurface Fracturing

Accompanying the subsurface movements induced by subsidence, caving and fracturing of rock strata may propagate from mine level to the surface. In the case of caving operations, a fracture zone is underlain by the caving zone, and depending on the local geology, this caving zone may or may not stabilize before reaching the ground surface.

A comprehensive monitoring of the propagation of the caving and fracturing zones must consider that the zones encompass large volumes and that they propagate from mine level to the surface over time intervals which may vary from several days to several years. Subsurface fracturing over large areas has been monitored by several researchers. Obert and Duvall (1961) discussed the use of seismic crosshole, microseismic and seismic

reflection methods to detect and delineate subsurface fracturing over a mine in which caving was employed. Lepper and Ruskey (1976) discussed recent developments in improved seismic reflection techniques to monitor conditions over coal seams.

Instrumentation to measure propagation of the caving and fracturing zones over a large area must be able to monitor subsurface conditions to depths of at least 500 feet, a typical depth to coal mines in the United States. The measurement method should detect the areal extent of the subsurface zones undergoing caving and fracturing, and should detect the depth to fracturing within the area. The upper limit of subsurface fracturing can probably be ascertained within 15 feet based on an estimate of accuracies obtainable with current geophysical equipment and procedures. To obtain representative and economical measurements over a large area, measurement methods must accommodate monitoring points in boreholes at least 100 feet apart. Two to four boreholes should be located along the centerline of each mine panel.

#### 3.3.4 Frequency of Subsurface Measurements

Most of the correspondents to this study recommend making measurements weekly during active mining. Measurements of subsurface deformations should be made on a weekly basis when the distance between the mine face and the monitoring point is within 0.7 times the depth to the seam.

Since surface evidence of subsidence may take several months to over a year to develop (Section 3.1.4), it is recommended that observations at any monitoring point should continue for at least two years after undermining. The frequency of observations during the period after active mining should be spaced so that movements larger than the accuracy of the measurements occur between readings and, when possible, boreholes should be checked to determine if (and at what depth) they have collapsed. It is recommended that observations continue on a monthly basis until one year after undermining for monitoring points at a distance of 0.7 times the seam depth beyond the face. During the second year after undermining, readings should be made two to four times a year and, if movement can still be detected, monitoring should continue twice yearly until movement stops. Note, however, that if any sudden increase in movement occurs during the first or second year after undermining, it is recommended that such movements should be monitored at least once or twice weekly until a stable condition is achieved.

When the purpose of the monitoring requires less detail, the monitoring frequency may be reduced. For example, over abandoned mines monthly monitoring, tapering twice yearly after seasonal movements are established should be adequate. During flushing operations, however, monitoring should be maintained on a weekly basis.

### 3.4 MINE LEVEL MEASUREMENTS

Subsidence of the ground surface is a result of changes which have taken place in the underlying strata and, in the case of subsidence due to mining, these changes are initiated at mine level. Therefore, mine level conditions should be monitored not only in the interest of mine stability but also for the purpose of correlating changes in mine conditions with subsidence effects of the ground surface.

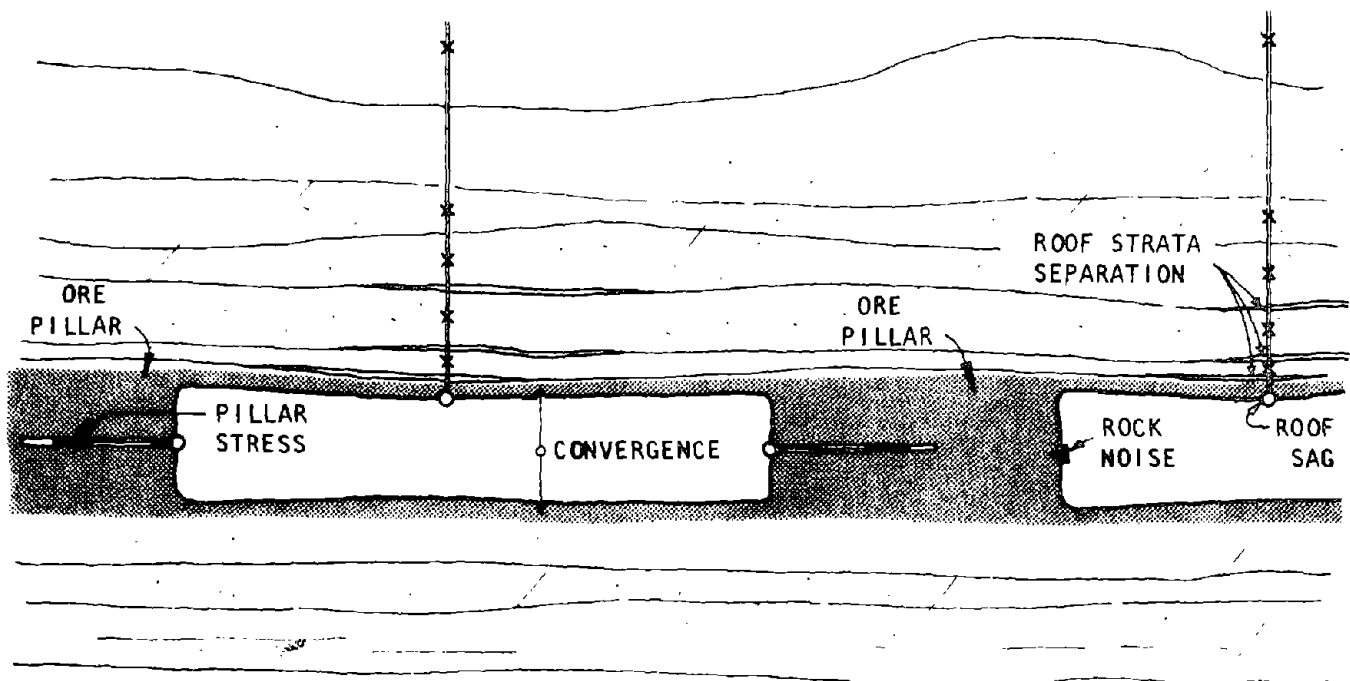
A number of measurements (shown schematically in Figure 3.9) can be made to monitor conditions at mine level but the usefulness of each measurement will depend on the mining method and the reason for monitoring mine conditions. Movement of the exposed surfaces in a mine can be monitored by measuring roof sag and roof-floor convergence, while differential movement in the strata overlying a mine (roof strata separation) requires borehole-type instrumentation. Monitoring of strata movements or mine closure for mines which are not accessible requires surface borehole installations or remote-reading instrumentation. Leads of remote-reading instruments can be brought out through boreholes or routed laterally to the mine entries before the mines are sealed or otherwise become inaccessible. Direct-reading instruments can be used in boreholes which extend from the mine level to the ground surface.

When support is provided at mine level for the purpose of stability and/or to control subsidence, it may be necessary to monitor loads or stresses to determine if additional support is required. For artificial supports, such as rock bolts or props, load cells are appropriate, but for natural supports, such as mine pillars, borehole-type stress cells are required.

#### 3.4.1 Mine Level Roof Sag

The performance of a mine roof may be evaluated by monitoring movement of the roof into the mine. This measurement is most useful in mines with permanent supports. Typically, additional support is installed when roof sag is considered to be of dangerous magnitude. Practical applications of technique depend on the relevant experience of the mine engineer who must determine whether measured deformations are allowable or if additional support is required. One correspondent (Moebs, 1977) reported that two to four inches of roof sag could occur before notice is taken and supplemental support is installed; so a range of movement of 6 inches would be appropriate for instrumentation used to monitor roof sag. Even where instrument ranges are resettable, such operating range is recommended to reduce the possibility to instrument damage due to unexpected movements.

Correspondents who are familiar with roof sag problems (Wade, 1977; Stefanko, 1977; and Hardy, 1977) differed in their opinions of what measurement accuracy would be appropriate for roof sag, stating that values ranging from 0.01 inch to 0.1 inch would be sufficient. In view of these statements and the difficulty in obtaining absolute movements at mine level, a measurement accuracy of 0.01 foot over a line 1000 feet long (or a second order traverse) is considered appropriate for roof sag



KEY :

- LOAD MEASUREMENT DEVICE
- x ANCHOR REFERENCE POINTS OF EXTENSOMETER

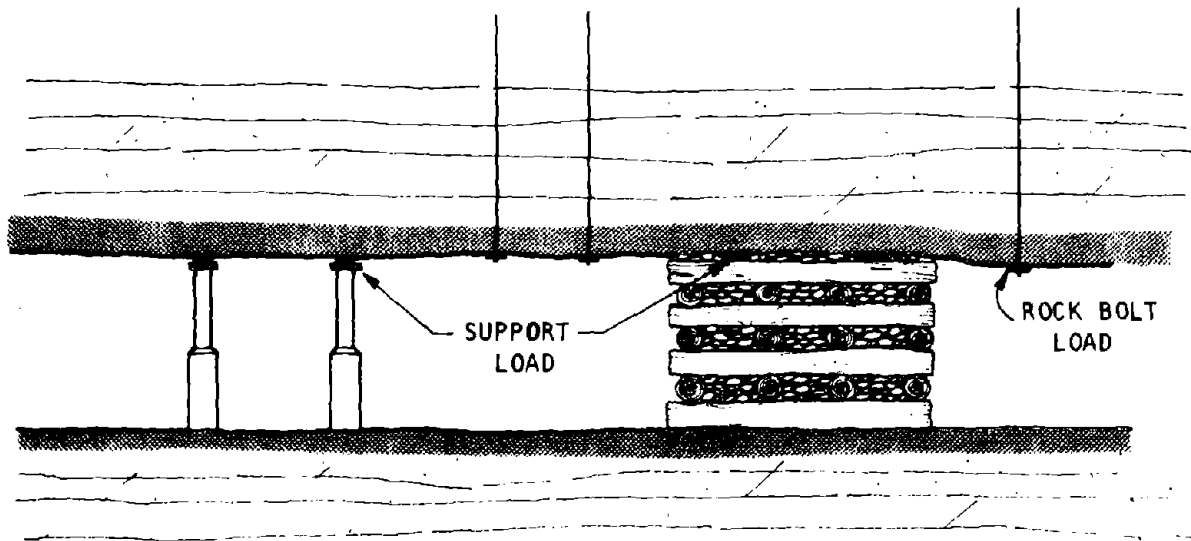


Figure 3.9 - SCHEMATIC DIAGRAM OF MINE LEVEL MEASUREMENTS

measurements. Typical layout may consist of reference points along the mine roof spaced 100 feet apart. Since roof sag monitoring points are easily and inexpensively installed, and measurements are made quickly and relatively inexpensively, 20 to 50 points per panel are recommended for supported mines.

#### 3.4.2 Mine Level Convergence

The convergence of mine openings consists of roof sag plus any floor heave that occurs, and may be accompanied by compression of supporting pillars. Similar to roof sag, mine convergence measurements are easily and inexpensively made but appear to be more extensively employed than roof sag measurements. One European study (Schwartz, 1961) reported convergence approaching three feet and noted that exceedingly soft floor strata were present where frequent maintenance was necessary to maintain access. In contrast, in a study in an American coal mine (Morgan and Still, 1973), room and pillar mining with a low extraction ratio produced a maximum convergence of only 0.1 to 0.2 ft. It was reported during longwall workings of a three-foot seam in Britain that if the rate of convergence exceeds one-half inch per foot of face advance in the supported zone near the face, the roof will start to break up (Panek, 1973). However, in an on-going monitoring program in a United States coal mine (Gentry, 1977), convergence of as much as one inch per foot of face advance in the longwall mining operation is being observed.

It is expected that convergence will occur in coal mines behind an active longwall mining face in the area where temporary support is provided by chocks. Once the chocks are moved, roof strata would be free to collapse. Convergence would be monitored in this situation primarily to determine if additional chocks are needed near the working face. Based upon typical American mining practice (Moebs, and Curth, 1976), it is concluded that maximum convergence in supported mines and near the face in caving operations could be on the order of eight inches. A 12 inch range of range of movement for convergence instrumentation should be adequate for most American supported mines.

As with roof sag measurements, correspondents indicated measurement accuracies ranging from 0.001 ft to 0.01 ft would be desirable, and, in view of the difficulty in obtaining measurements at mine level, an accuracy of 0.01 ft is specified for mine convergence measurements. A typical layout of monitoring would be similar to that for roof sag except that reference points must be installed in the floor as well as the roof of a mine.

To use convergence measurements for determining absolute floor or roof movement a stable reference point is required. Adequate bench marks could be established at the bottom of a drill hole in the mine floor, as long as the hole penetrates through any soft or friable floor materials (Parker and Scott, 1964). These points should be tied into surface bench marks several times per year to detect deep-seated heave. Unstable bench marks could introduce errors of an order of magnitude greater than instrumentation errors.

Consistent with the ease and relatively low cost of installation, it is felt that a large number of convergence monitoring installations should be made. As many as fifty convergence installations within a mining panel and in the adjacent entires may be appropriate.

Convergence measurements may be useful in connection with the filling of abandoned mines. Mine convergence measurements in a flushed seam could be used to evaluate the performance of the fill material. Such measurements will require the use of remote reading equipment installed at mine level, or borehole-type instruments which can be installed and monitored at the ground surface. The cost involved in such instrumentation may only allow for the installation of two to four monitoring points per panel.

#### 3.4.3 Mine Level Roof Strata Separation

Behind an advancing mine face, the strata above the mined-out stope may move downward significantly with respect to the ground surface. To accommodate this movement, separations may occur within the strata near the coal seam (Hardy, 1976; Moebs and Curth, 1976; Gray and Meyers, 1970).

Roof strata separation has been generally monitored for the purpose of roof fall surveillance (McVey, Meyer, and Lewis, 1974), but Potts (1964) described an instrumentation program in a British longwall coal operation which was used to correlate roof strata movements above a lower seam with movements which occurred at a higher seam. In that paper relative movements of 100 inches between the mine roof and reference points 120 feet above the mine roof were reported; in contrast, Stateham (1974) reported relative movements of only 1.4 inches in a U.S. coal mine where reference points were placed 7 feet above the mine roof. Assuming roof strata separations may be on the same order of magnitude as roof sag movements in U.S. mines, a measurement range of 6 inches is desirable. To obtain representative data, two to six reference points should be placed in boreholes and located 5 feet to 50 feet above the mine roof. Five to ten boreholes per panel should be adequate in mines with permanent support.

Correspondents familiar with strata separation measurements felt that a very small amount of roof sag would be necessary to produce strata separation (Moebs, 1977), and that instrument accuracies on the order of 0.0001 foot would be desirable (Hardy, 1977; and Stefanko, 1977). However, with the difficulties inherent in mine level measurements, such accuracy may not be possible and measurement accuracy of 0.001 foot to 0.005 foot may be satisfactory (Moebs, Wade and Curth, 1977).

#### 3.4.4 Mine Level Artificial Support Loads

Roof support systems affect the performance of roof strata both for long term support such as in entries and also for temporary support at the active mining face. Frame-type supports and roof bolts, installed in fairly standardized patterns, are generally used for long term support, whereas temporary support is generally supplied by moveable props and shields.

By monitoring the loads which individual supports carry, it is possible to evaluate the performance of the support system in terms of roof movement control, where the maximum range of such load measurements would be limited by the capacity of the support.

3.4.4.1 Tensioned Rock Bolt Load - The essential feature of a tensioned rock bolt is that it is placed in tension during installation. This distinguishes it from anchor bars which are grouted into holes in rock, but which are not prestressed (Lang, 1961). Rock bolts include ungrouted bolts with mechanical anchors, fully grouted bolts with mechanical anchors, and fully grouted bolts without mechanical anchors. Fully grouted anchor bars are more commonly used in hard-rock mines, whereas fully grouted rock bolts are more commonly used in construction projects. The widespread use of fully grouted rock bolts has not yet taken place in U.S. coal mines on a large scale because of the time and added expense involved (Givens, 1973). As a practical matter, then, consideration is given here only to rock bolts with expanding anchors which are inserted into drillholes and then tightened against bearing plates to keep rock strata from separating.

Hedley (1972) described rock bolts in a Canadian salt mine which were installed at loads of 4,000 pounds to 7,000 pounds and the rock bolt load increased to 9,000 pounds. McVey and Serbausek (1976) described one instrumentation program in a U.S. coal mine where rock bolt loads were monitored using load cells with a range to 30,000 pounds and a repeatability between 1 percent and 5 percent. Installed tensile loads should be about 75 percent of the rock bolt yield strength (Lang, 1975; and Stefanko, 1962), so the tensile load applied to high strength 5/8-inch diameter rock bolts should not exceed 12,000 pounds during installation. Considering this value and the increased load which may be applied to the rock bolt (Hedley, 1972), a loading range up to 20,000 pounds is desirable for rock bolt load cells, and a measurement sensitivity of 100 pounds is possible with load cells that are commercially available.

Since rock bolts are generally installed in high-density groups of approximately one rock bolt per square meter of roof (Givens, 1973), at least ten to twenty rock bolts per mining panel should be instrumented. When the bolting pattern is initially used and when geologic conditions change, rock bolt instrumentation should be more intensive.

3.4.4.2 Frame-Type Support and Moveable Prop Load - In addition to rock bolting, a number of other methods are used for supporting the mine roof and they generally involve materials consisting of timber or steel. Since the strength of wood is less than that of steel, and since a load cell should have a capacity equal to or greater than that of the support, it follows that the load cell requirements will depend on the type of support being used. In particular, steel supports may be yielding or non-yielding and the yield pressure of the hydraulic system being used will limit the load range (Moebs and Curth, 1976). In this case, load measurements may be conveniently made by incorporating a pressure recording system with the hydraulic system.



Sinha, et al (1972) described a monitoring program at a longwall operation in India in which maximum loads of 15 tons for timber props and 21 tons for yielding hydraulic steel props were reported. Potts (1957) reported loads over 40 tons on timber props in a British longwall operation, but excessive convergence due to floor penetration occurred. Givens (1973) reported loads of up to 40 tons for portable yielding steel props and loads of 30 tons to 200 tons for hydraulic steel chocks which are incorporated into longwall mining machinery. For steel sets, which are usually installed in main haulage and longwall entries Proctor and White (1968) indicated that loads of up to 50 tons are allowable for tunnel widths of 17 feet using 4-inch H sections.

Since different support systems may be used in one mining operation, it would be desirable to use load cells which are compatible with the load ranges accepted for timber and steel. Considering the characteristics of load cells commercially available, it is recommended that load cells having a load range of 200 tons and an accuracy of 1 ton be used. Greenwald et al (1937) found that the presence of a load cell will affect the loading conditions for an individual prop as well as neighboring props, and they concluded that all the props over a considerable area should be instrumented in order to obtain representative data. This is usually not economically feasible, and it is recommended that one or two props per 100 feet of active mine face should be instrumented and that ten to fifteen supports per panel should be instrumented.

#### 3.4.5 Mine Level Pillar Stress

Two aspects of mine pillar stress are of interest: the absolute stress and the change in stress with time. These values are generally measured separately. Measurements of the stress in pillars and rock strata are being made to develop a more complete understanding of the strata behavior around a mine operation. Pillar stress may also be evaluated to determine if destressing is required to prevent pillar failure (e.g., rock bursts) (Langstaff, 1976; Reed, 1966).

Absolute pillar stress is a function of local geology (Wade, 1977), pillar size and shape, mine depth, the location of the measuring point relative to the active mine face (Morgan and Still, 1973), and the location of the measuring point in the pillar away from the exposed surface. The upper limit of stress would be the compressive strength of the pillar or the bearing capacity of the floor strata. Holland (1969) reported pillar strengths on the order of 5,000 psi in U.S. coal mines; Hedley et al. (1969) using devices in boreholes 20 feet deep reported maximum stresses of 6,500 psi in a U.S. iron mine and Obert (1962), using devices in boreholes 20 feet deep, indicated that stresses of up to 9,000 psi may be possible in a U.S. limestone mine.

Absolute pillar stress is typically measured by overcoring (Hedley, Soderlund and Coates, 1969). It is most valuable for pillars which are long distances from the active face so that significant stress changes have already taken place or are yet to occur. Lee man (1964) reported that the overcore technique was used in South African coal mine pillars with an instrument capable of measuring stresses over 1,000 psi at depths of over 35 feet into the pillars. Based on these case histories and personal correspondence (Gentry, 1977), it

seems desirable that rock stress instrumentation should be capable of measuring absolute stresses up to 5,000 psi, and be usable in boreholes up to 50 feet deep.

Permanently installed long term stress instrumentation presently in use generally measures changes in stress level rather than total stress (Sellers, 1969). Howell, Wright and Dearing reported that an instrument capable of measuring stress changes up to 5,000 psi was used in a U.S. coal mine where boreholes were drilled up to 80 feet into panels and pillars. Based on typical coal compressive strengths, instrumentation should be able to measure stress changes up to 5,000 psi in boreholes up to 50 feet deep.

The required accuracy of the instrumentation depends on its function. When the primary interest is in stress changes, the emphasis should be on precision of relative measurements rather than accuracy of absolute measurements. Based on characteristics of instruments commercially available and personal correspondence (Moebs, Wade and Curth, 1977), it should be possible to attain a precision of 50 psi. However, when absolute stress is desired, a measurement accuracy of 100 psi should be adequate.

Considerable time and expense can be consumed in installing and calibrating stress instrumentation. Where the objectives of the monitoring program justify this type of expense, 12 to 15 permanent stress cells per mine panel (Panek, 1973; Moebs, Wade and Curth, 1977) and the same number of absolute stress measurements would be appropriate. Stress change cells should be installed well in advance of mining, such that the entire stress change due to mining will be measured. This could be achieved by installing the cells in an unmined panel from an adjacent roadway or overlying level.

#### 3.4.6 Mine Level Rock Noise

The microseismic method of detecting instability and high stress zones in rock structures is based on the fact that as a rock mass is subjected to load, small-scale displacements occur within the rock mass which result in the release of seismic and sometimes acoustic energy. These small vibrations, which can be detected with sensitive geophysical equipment, are called microseisms or self-generated rock noises (Blake, Leighton and Duvall, 1974). The microseismic technique is versatile in that it provides a means of detecting stress changes and, at the same time, is a large scale field test in which large zones of rock can be monitored (Hendron, et al, 1975).

The detection of microseisms depends on the distance between the source and a geophone and also on the seismic properties of strata through which the small vibrations must travel. In mining applications, the microseismic technique has been used primarily in metal mines (Langstaff, 1976; Hedley, Soderlund and Coates, 1969), where microseisms have been detected at distances of 300 feet and used to evaluate the stability of roof strata and mine pillars. Due to the fact that seismic waves attenuate rapidly in soft sedimentary deposits it has not been considered feasible to use this technique in coal mines; however, Heyman, Szecowka, and Zuberek (1972) reported that microseismic monitoring has been used in Polish coal mines to evaluate rock burst occurrences and that

microseisms could be detected at distances over 100 meters. Similarly, Hardy (1977) described a subsidence monitoring program over a Pennsylvania coal mine which was conducted in conjunction with a rock noise investigation, in which it was suggested that the microseismic technique could be useful in sedimentary deposits such as coal. (Johnson, Drake and Piper, 1973). The most useful information is obtained from geophones located within 100 feet of microseismic source; this distance should be regarded as the maximum spacing between monitoring points for rock noise measurements in coal.

#### 3.4.7 Visual Observation at Mine Level

Consistent with present state of the art of underground design, visual observations are especially valuable in conjunction with monitoring programs when such observations are made on a systematic basis and are thoroughly documented. The impetus for gathering as much information as possible about the mine level environment comes from the need both for safety in the underground operations and also to optimize the production effort.

Visual observations should include a chronological log of underground activities as well as a detailed geologic examination of the roof, wall and floor strata with particular attention to signs of distress or spalling. With such observations, events disclosed by records of monitoring instrumentation could be directly related to documented visual observations of mining operations. Together with monitoring records, they would provide a thorough data base from which analytical models could be developed or against which such models could be tested for similarity to actual situations.

#### 3.4.8 Time Relationships for Mine Level Measurements

In general it is expected that the largest underground movements will occur immediately behind the mining operation although, in the case of stress measurements, large changes have been detected in panels at points ahead of the mining face (Morgan and Still, 1973). The time relationships for underground measurements are further complicated by the access requirements for installation of some instruments. In such cases a conflict between the monitoring program and the production effort may be expected. Thus, monitoring systems are desirable which can be installed quickly and allow for quick readings to be made. Whenever possible, instruments for measuring stress changes should be installed ahead of the mining operation in order to obtain meaningful data. This is especially important since the installation of these instruments can be time consuming and requires a relatively large working area for drilling machines to be set up.

The changes that underground instrumentation would monitor are expected to occur more rapidly than on the ground surface and almost concurrent with the mining operations. For this reason, and also due to the expense involved in installing and monitoring underground instrumentation, measurements should not be made on a time-available basis by mining personnel.

Rather, for measurements of value to be made, a sufficient number of individuals should be assigned specifically to the monitoring program.

In determining an appropriate frequency of measurement for underground systems, it should be recognized that the schedule of mining activities underground could have a significant influence upon the strata behavior. In general, correspondents to this survey felt that underground measurements should be made on a daily or, if possible, a shift basis. These measurements should then continue until the instruments become inaccessible or are destroyed, as would be the case for some mining methods. At other locations where more permanent installations are made, such as roof sag and convergence stations in entries and stress measurements in pillars and floor strata, the measurements should continue consistent with the observed changes. As the rate of change decreases, it would be possible to decrease the frequency of measurement. It was felt by the correspondents that underground monitoring should continue for at least two to three months beyond the point when changes no longer occur. It is concluded that this criteria for monitoring duration would be suitable for programs designed to investigate the behavior of the coal and rock strata in the vicinity of the mine face. Monitoring of systems established in long-term or permanent openings should continue for as long as the opening is used or until a permanent support system that would virtually preclude an unsafe condition is installed.

#### 4.0 APPLICATIONS OF SUBSIDENCE MONITORING

Legal, economic, social and engineering concerns are the principal reasons for monitoring subsidence. Persons concerned with subsidence will include mine operators, farmers, homeowners, real estate developers, regulatory agencies and others. Each will have different reasons and uses for quantitative information about ground movements. For any of the concerned parties, subsidence monitoring can be expensive, and the need for the monitoring must be clearly established to justify the implementation of a monitoring program.

Major needs for subsidence monitoring are discussed in this section. In conjunction with these needs, appropriate measurements are suggested. At the end of this section, the relationship among users, needs, and measurements are summarized in matrix form.

##### 4.1 APPLICATION OF SUBSIDENCE MONITORING TO SOME LEGAL NEEDS

###### 4.1.1 Some Views on Laws Dealing with Subsidence

All land, whether surface or subsurface, is entitled to support in its natural state from underneath (subjacent support) and horizontal support at its boundaries (lateral support). This right applies to surface owners and owners of underground minerals. This right is guaranteed by common law, the body of law developed by the courts. However, when the mineral rights beneath a property are sold, the deed may include a waiver in which the surface owner relinquishes his right to support. Most mine operators try to obtain waivers when they purchase the mineral rights. For example, in 1966 Consolidated Coal had "complete waiver of surface damage or the right to subside the surface land...in 98% or more of its title holdings" (Vandale, 1967).

The land owner who has the right to subjacent support can still suffer subsidence damage. It is difficult to get an injunction against a mine operator (Amer. Law of Mining, 1976). However, the land owner can sue for damages as long as he can show that the subsidence occurred within a reasonable time after the undermining of his property. The mine operator must show that the subsidence or damage to the surface property had some other cause.

Some legislation has been passed in recent years to supplement the common law. Not all states have legislation affecting subsidence, and the regulations vary widely in the extent to which they control mining practice. Except for the "Bituminous Mine Subsidence and Land Conservation Act of 1966" (Pennsylvania); the remaining legislation appears to be only of use to those who still retain the right to support. The laws may contain some or all of the following provisions:

- Required Annual Mine Maps: The surface owner may use these maps to show when his property was undermined.

- Limits to Lateral Extent of Mining: These limits may be used to protect adjacent mining claims by providing a minimum thickness of barrier pillar between adjacent mines. In several states, including Wyoming, Kentucky and Pennsylvania, extra restrictions come into effect as the mine approaches non-commercial structures. Missouri has prohibited subsidence of roads and railroads.
- Reclamation Plans: Some state and federal agencies require a reclamation plan before a mining permit is issued. These statutes generally encourage subsidence prevention, but allow subsidence if provisions are made to restore the land to an equal or higher quality and to prevent future movement after completion of mining.
- Bonds: The mine operator may be required to post a bond to protect the surface owner entitled to support or to guarantee the reclamation plan will be completed.
- Instrumentation: Very few laws recommend or have the power to require the mine operator to provide subsidence instrumentation. The only law found which mentions specific instrumentation is Title 30, Part 211 (Federal Register, 1976) affecting the Federal coal estate.

The 1966 Pennsylvania Law is perhaps the most exacting subsidence legislation in the United States. It prohibits damage due to mining subsidence for dwellings, non-commercial public buildings and cemeteries constructed before 1966 even if the right to support was previously waived. The Law requires a minimum of 50% of the coal to be left within an area approximately defined by extending planes at a 15° angle from the vertical from the base of the building to the coal seam.

Some comments on laws which appear to deal with subsidence conditions are given in Table 4.1.

#### 4.1.2 Data To Meet Some of the Legal Needs

The surface owner must have the right to support in order to seek damage claims unless the mine operator has been negligent. If subsidence damage occurs, the surface owner must prove that subsidence occurred within a reasonable time of the mining (American Law of Mining, 1976). The period of limitations is 10 years in Pennsylvania and 5 years in Wyoming (see Table 4.1). In cases of delayed subsidence, after the period of limitations has expired, it appears that the mine operator is usually, but not consistently liable when the structure or land was undermined (American Law of Mining, 1976).

Visual documentation such as photographs, assessor's reports, and diaries may be adequate documentation of damage. These can be supplemented by mine maps obtained from the State to demonstrate when undermining occurred. For a structure, it may be necessary to supplement the visual observations with measurements of movements before and after undermining to prove that

TABLE 4.1

## SOME LEGISLATION AFFECTING SUBSIDENCE DUE TO MINING

| STATE/<br>FEDERAL<br>AGENCY            | NAME OF LAW                                                                                                                                                                                                 | MINE MAPS                          |                        | LIMITS TO LATERAL EXTENT<br>OF MINE                                       | RECLAMATION<br>PLAN which<br>includes<br>subsidence | BONDS                              |                       | INSTRUMENTATION |             | COMMENTS                                                                                             |
|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|------------------------|---------------------------------------------------------------------------|-----------------------------------------------------|------------------------------------|-----------------------|-----------------|-------------|------------------------------------------------------------------------------------------------------|
|                                        |                                                                                                                                                                                                             | REQUIRED<br>OR CAN BE<br>REQUESTED | AVAILABLE<br>TO PUBLIC |                                                                           |                                                     | REQUIRED<br>OR CAN BE<br>REQUESTED | PUBLIC CAN<br>REQUEST | REQUIRED        | RECOMMENDED |                                                                                                      |
| Alabama                                | Coal Mining Laws<br>(1960)                                                                                                                                                                                  | X                                  | X - coal               | X                                                                         |                                                     |                                    |                       |                 |             | Adjacent land owners can inspect mine                                                                |
|                                        | Mine Safety Rules<br>(1962)                                                                                                                                                                                 |                                    |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |
| Arizona                                | Mining Code (1966)                                                                                                                                                                                          | X                                  |                        |                                                                           |                                                     |                                    |                       |                 |             | Reclamation plan required for surface<br>mining - see Senate Bill No. 756                            |
| Arkansas                               | Safety Code No. 8                                                                                                                                                                                           |                                    |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |
| California                             | Title 8, Ch. 4, Sub.<br>17, Mine Safety<br>Orders (1974)                                                                                                                                                    | X                                  |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |
| Colorado                               | Mining Laws (1971)                                                                                                                                                                                          | X                                  |                        |                                                                           | X                                                   | X                                  |                       |                 | X           | A list of methods used to monitor effect<br>of surface disturbances required in<br>reclamation plan. |
| Idaho                                  | Safety Code 5<br>Minimum Safety Stan-<br>dards and Practices,<br>July 1976                                                                                                                                  | X                                  |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |
|                                        | Idaho Code Ann. 47<br>609 (1948)                                                                                                                                                                            |                                    |                        |                                                                           |                                                     | X                                  |                       |                 |             |                                                                                                      |
| Illinois                               | The Coal Mining<br>Act (1975)                                                                                                                                                                               | X                                  | X                      | X-Near Abandoned Mines                                                    |                                                     |                                    |                       |                 |             |                                                                                                      |
| Indiana                                | Coal Mining Laws<br>(1971)                                                                                                                                                                                  | X                                  | X                      | X-Near Abandoned Mines                                                    |                                                     |                                    |                       |                 |             |                                                                                                      |
| Iowa                                   | "The Iowa General Assembly has repealed all safety and environmental regulation of underground mines", Letter Nov. 29, 1976, M.B. Ross, Director.<br>Mines & Min. Division, Department of soil conservation |                                    |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |
| Kentucky                               | KRS 350.151 -<br>Draft of Proposed<br>Law on Reclamation<br>of Surface Effects<br>of Underground<br>Mines (1976)                                                                                            | X - to<br>get per-<br>mit          |                        | X-If operation hazard to<br>structure, area may be<br>deleted from permit | X                                                   | X                                  |                       |                 |             | Must submit names of all surface<br>and subsurface owners within<br>500' (horizontal) of mine        |
| KEY: X = yes; (X) = yes, in some cases |                                                                                                                                                                                                             |                                    |                        |                                                                           |                                                     |                                    |                       |                 |             |                                                                                                      |

TABLE 4.1 (continued)  
SOME LEGISLATION AFFECTING SUBSIDENCE DUE TO MINING

| STATE/<br>FEDERAL<br>AGENCY            | NAME OF LAW                                                                                                             | MINE MAPS                          |                        | LIMITS TO LATERAL EXTENT<br>OF MINE                                                              | RECLAMATION<br>PLAN which<br>includes<br>subsidence | BONDS                                     |                       | INSTRUMENTATION |             | COMMENTS                                                                                                              |
|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------|------------------------------------|------------------------|--------------------------------------------------------------------------------------------------|-----------------------------------------------------|-------------------------------------------|-----------------------|-----------------|-------------|-----------------------------------------------------------------------------------------------------------------------|
|                                        |                                                                                                                         | REQUIRED<br>OR CAN BE<br>REQUESTED | AVAILABLE<br>TO PUBLIC |                                                                                                  |                                                     | REQUIRED<br>OR CAN BE<br>REQUESTED        | PUBLIC CAN<br>REQUEST | REQUIRED        | RECOMMENDED |                                                                                                                       |
| Michigan                               | Michigan Environ-<br>mental Protection<br>Act, July 27, 1970                                                            |                                    |                        |                                                                                                  |                                                     |                                           |                       |                 |             | Consumers can take to court any<br>group that causes "pollution,<br>impairment or destruction" of<br>the environment. |
| Missouri                               | Mine Inspection<br>Laws (1967)                                                                                          |                                    |                        | X-No subsidence allowed<br>under roads or rail-<br>roads                                         |                                                     | X-in cities,<br>towns-coal<br>mining only |                       |                 |             |                                                                                                                       |
| Montana                                | Montana Coal Mining<br>Code (1974)                                                                                      | X                                  | X                      |                                                                                                  |                                                     |                                           |                       |                 |             | Rules will probably emphasize<br>permanent subsidence stability                                                       |
|                                        | Letter, M.J. Woods<br>Reclamation Division,<br>Department of State<br>Land 11/3/76                                      |                                    |                        | X                                                                                                | X                                                   |                                           |                       |                 |             |                                                                                                                       |
| Nevada                                 | Health and Safety<br>Standards for Under-<br>ground Metal and Non-<br>Metal Mines (1975)                                |                                    |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |
| New Mexico                             | Mine and Safety Code<br>for All Mines (1975)                                                                            | X - coal<br>only                   |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |
| N. Carolina                            | Use MESA regulations,<br>Letter, 11/19/76, J.R.<br>Brandon                                                              |                                    |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |
| Ohio                                   | Mining laws (1976)                                                                                                      | X                                  |                        | X - oil and gas wells only                                                                       |                                                     | X-highways<br>only                        |                       |                 |             |                                                                                                                       |
| Oklahoma                               | Mining Laws (1973)                                                                                                      | X                                  |                        | X- coal                                                                                          | X                                                   | X                                         |                       |                 |             |                                                                                                                       |
| Pennsylvania                           | 1966 Bituminous<br>Mine Subsidence<br>and Land Conserva-<br>tion Act                                                    | X                                  | X                      | X-Spelled out for non-<br>commercial buildings,<br>cemeteries and dwellings<br>built before 1966 |                                                     | X                                         |                       |                 |             | Liability continues for 10 years                                                                                      |
| S. Dakota                              | No environmental laws regulating underground mining, Department of Environmental Protection, Letter 1/1/76 A.D. Lockner |                                    |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |
| Tennessee                              | Laws and Regulations<br>Governing Mines and<br>Mining (Title 58)<br>1976                                                | X                                  |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |
| KEY: X = yes; (X) = yes, in some cases |                                                                                                                         |                                    |                        |                                                                                                  |                                                     |                                           |                       |                 |             |                                                                                                                       |



TABLE 4.1 (continued)

## SOME LEGISLATION AFFECTING SUBSIDENCE DUE TO MINING

| STATE/<br>FEDERAL<br>AGENCY            | NAME OF LAW                                                                                                                               | MINE MAPS                          |                          | LIMITS TO LATERAL EXTENT<br>OF MINE         | RECLAMATION<br>PLAN which<br>includes<br>subsidence | BONDS                              |                       | INSTRUMENTATION |             | COMMENTS                                             |
|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|--------------------------|---------------------------------------------|-----------------------------------------------------|------------------------------------|-----------------------|-----------------|-------------|------------------------------------------------------|
|                                        |                                                                                                                                           | REQUIRED<br>OR CAN BE<br>REQUESTED | AVAILABLE<br>TO PUBLIC   |                                             |                                                     | REQUIRED<br>OR CAN BE<br>REQUESTED | PUBLIC CAN<br>REQUEST | REQUIRED        | RECOMMENDED |                                                      |
| Utah                                   | General Safety<br>Orders - Utah Coal<br>Mines                                                                                             | X                                  |                          | X                                           |                                                     |                                    |                       |                 |             |                                                      |
|                                        | Metal and Non-Metal<br>Mine Health and Safety<br>Standards ( 1/1/76)                                                                      | X                                  |                          |                                             |                                                     |                                    |                       |                 |             |                                                      |
| Virginia                               | Mining Laws<br>(1975)                                                                                                                     | X-coal                             |                          | X                                           |                                                     |                                    |                       |                 |             | Adjacent owner can survey mine                       |
| Washington                             | Coal Mining Laws<br>(1947)<br>Safety Standards-<br>Metal and Non-Metallic<br>Mines, Quarries, Pits<br>and Crushing Opera-<br>tions (1972) | X                                  |                          | X                                           |                                                     |                                    |                       |                 |             |                                                      |
| W. Virginia                            | Underground Coal Mine<br>Safety Laws (1976)                                                                                               | X                                  | X -<br>Abandoned<br>Mine |                                             |                                                     |                                    |                       |                 |             |                                                      |
| Wyoming                                | Non-Coal Mining Laws<br>(1972)                                                                                                            | X                                  |                          |                                             |                                                     |                                    | X                     |                 |             |                                                      |
|                                        | Coal Mining Laws<br>(1973)                                                                                                                | X                                  |                          | X                                           |                                                     |                                    |                       |                 |             |                                                      |
|                                        | Environmental Quality<br>Act (1975)                                                                                                       | X                                  | X                        | X - 300' of any non-<br>commercial building | X                                                   | X                                  |                       |                 |             | Must notify all surface owners<br>before undermining |
| KEY: X = yes; (X) = yes, in some cases |                                                                                                                                           |                                    |                          |                                             |                                                     |                                    |                       |                 |             |                                                      |

TABLE 4.1 (continued)

## SOME LEGISLATION AFFECTING SUBSIDENCE DUE TO MINING

| STATE/<br>FEDERAL<br>AGENCY                                                                  | NAME OF LAW                                                                                             | MINE MAPS                          |                        | LIMITS TO LATERAL EXTENT<br>OF MINE | RECLAMATION<br>PLAN which<br>includes<br>subsidence | BONDS                              |                       | INSTRUMENTATION                                           |             | COMMENTS                       |
|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|------------------------------------|------------------------|-------------------------------------|-----------------------------------------------------|------------------------------------|-----------------------|-----------------------------------------------------------|-------------|--------------------------------|
|                                                                                              |                                                                                                         | REQUIRED<br>OR CAN BE<br>REQUESTED | AVAILABLE<br>TO PUBLIC |                                     |                                                     | REQUIRED<br>OR CAN BE<br>REQUESTED | PUBLIC CAN<br>REQUEST | REQUIRED                                                  | RECOMMENDED |                                |
| MESA - Depart-<br>ment of Inter-<br>ior                                                      | Metal and Non-Metal<br>Mine Health &<br>Safety                                                          |                                    |                        |                                     |                                                     |                                    |                       |                                                           |             |                                |
| National<br>Environmental<br>Policy Act                                                      |                                                                                                         |                                    |                        |                                     | X                                                   |                                    |                       |                                                           |             |                                |
| Forest Service<br>Department of<br>Agriculture                                               | Title 36 National<br>Forests Surface Use<br>under U.S. Mining<br>Laws §252                              | X                                  | (X)                    |                                     | X                                                   | X                                  |                       |                                                           |             | Controlled Subsidence Required |
| Bureau of Land<br>Management and<br>Geological<br>Survey, Depart-<br>ment of the<br>Interior | Title 43 - Public<br>Lands: Interior Ch.<br>11, Bureau of Land<br>Management, Part<br>3040 subpart 3041 |                                    |                        | X                                   |                                                     | X                                  |                       |                                                           |             |                                |
|                                                                                              | Title 30 - ch.2<br>Geological Survey,<br>Part 211                                                       | X                                  | (X)                    | X                                   | X                                                   | X                                  |                       | X-Elevation stations<br>and tiltmeters may<br>be required |             | Controlled Subsidence Required |
| KEY: X = yes; (X) = yes, in some cases                                                       |                                                                                                         |                                    |                        |                                     |                                                     |                                    |                       |                                                           |             |                                |

subsidence deformations were the cause of damage. Similarly, land owners, such as farmers, real estate developers, and townships, might supplement visual documentation with a program of vertical settlement measurements over a wide area. The monitoring should begin well in advance of the mining to establish base movements due to other causes such as seasonal moisture changes.

The mine operator has no legal requirement to monitor subsidence on lands where he is not obligated to support the surface. However, for protected lands, the mine operator may have to show that any subsidence resulted from a cause other than the undermining. To avoid damage claims where the land must be supported, the mine operator can utilize mining methods and procedures which minimize or prevent subsidence. As a further precaution to ensure that any damage claims are valid, the mine operator may want to monitor surface movements above the mine. A defensive instrumentation program might include both an extensive and widely spaced array of vertical settlement points to monitor general subsidence results and an intensive supplementary array to monitor settlement and deformations of critical structures. Any such program should be accompanied by documented photographs of the critical structures. Monitoring must begin before undermining to establish base movements due to heat, frost, seasonal moisture changes and other causes.

Regulatory agencies may want to institute a monitoring program to ensure that subsidence is prevented on lands that have the right to support. An extensive program of monitoring vertical settlements over the mine should be adequate to document compliance with the law. In urban areas, individual structures may have the right to support. An intensive program of monitoring settlement, strain and tilt of selected structures entitled to support should reveal the performance of the mine operator in providing such support.

## 4.2 APPLICATION OF SUBSIDENCE MONITORING TO ECONOMIC NEEDS

### 4.2.1 The Cost of Subsidence to Surface Consumers

Subsidence damage can cause economic hardship to homeowners, businesses and the community as a whole.

In rural areas, the effects of subsidence may not be obvious to the casual observer. But in western Pennsylvania it was estimated that grazing land worth \$140 an acre could decline in value to \$70 an acre as a result of subsidence (Cochran, 1971). The effects of subsidence may make portions of farmland unsuitable for farming. The depressions caused by subsidence may flood in winter and remain swampy all year (Young, 1916). Changes in gradient may make irrigation canals ineffective. Ground cracking may damage irrigation ditches and drain sources of surface water into the mines to re-emerge later as acid mine drainage (Williams, 1976; Dunrud, 1976). Similarly, subsidence may crack impermeable strata isolating subsurface aquifers, allowing them to be drained or contaminated

(Wardell, 1970). In one case, methane leaked from the mine to the surface through subsidence-induced cracks and killed the scrub oak and woody plants (Dunrud, 1976).

Linear features such as roads, railroads, canals and pipelines are vulnerable to subsidence damage. Cracked and potholed roads may require extensive maintenance. As a result, Missouri has made it illegal to subside roads and railways. Railroads and canals are particularly sensitive to changes in gradient.

The most prominent economic impact of subsidence is the cost of damage to structures. In Rock Springs, Wyoming, subsidence over abandoned coal mines damaged 17 homes; repairs for 5 severely damaged houses averaged \$8,000 (Candeub, 1971). The Mine Subsidence Insurance Fund of the Commonwealth of Pennsylvania informs home owners that subsidence damage often runs to \$5,000 to \$10,000.

Candeub, et al. (1971) note that "indirect costs of subsidence include:

- reduction of marketability of property
- loss of property value
- impediments to mortgage financing
- potential changes in insurability and insurance rates
- erosion of the tax base"

#### 4.2.2 Collecting Subsidence Damages and the Insurance Problem

If the surface owner retains the right to support, he can sue for subsidence damages. Compensation can cover injuries to buildings, equipment and persons resulting from failure to provide subjacent support. A mine operator who negligently or maliciously caused subsidence damage can be assessed damages, sometimes even punitive damages, whether or not the land has the right to support.

Damages are generally assessed as the lesser of the cost of restoring the surface and repairing the buildings, or the loss in value of the land and its improvements. However, compensation for damage may include loss of value due to future expected subsidence, loss of rental value and devaluation of mortgaged securities. Protective measures undertaken by the surface owner to prevent subsidence damage are also compensatable (American Mining Law, 1976).

Except for Pennsylvania, subsidence insurance is apparently not available to property owners in mining districts (see Table 4.2). In Florida and Alabama, insurance companies must, by law, include subsidence protection in their homeowner policies. In these states, protection is provided for subsidence due to sinkholes caused by the formation of solution cavities.

TABLE 4.2  
SUBSIDENCE INSURANCE

| INSURANCE<br>COMPANY                              | WRITES POLICY<br>FOR MINING<br>SUBSIDENCE | COMMENTS/<br>DAMAGE CLAIM POLICY                                                                                                                                                                                                                                                                                                                                                                  |
|---------------------------------------------------|-------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Liberty Mutual                                    | No                                        |                                                                                                                                                                                                                                                                                                                                                                                                   |
| Firemen's Fund                                    | Yes/No                                    | Writes insurance for sinkhole<br>subsidence where regulated by<br>law in Florida<br><br>May write individual policy<br>for landslide, mudflow and<br>subsidence if good risk -<br>commercial only<br><br>Note: Once subsidence or land-<br>slide occurs, FF responsible by<br>law for all subsequent damage<br>till subsidence complete<br><br>Do not write subsidence insurance<br>for dwellings |
| Continental                                       | No                                        |                                                                                                                                                                                                                                                                                                                                                                                                   |
| Kemper                                            | No                                        | Write insurance policies for<br>sinkhole subsidence where regu-<br>lated by law in Florida and<br>Alabama                                                                                                                                                                                                                                                                                         |
| Mine Subsidence<br>Insurance Fund<br>Pennsylvania | Yes                                       | On site inspection by qualified<br>personnel - assess whether damage<br>caused by subsidence. Covers<br>structural damage only. \$250-<br>\$500 deductible. Cost \$15-\$79/<br>year. Use old surveys, pictures,<br>mining studies to evaluate claim.                                                                                                                                              |
| The Travelers                                     | No                                        |                                                                                                                                                                                                                                                                                                                                                                                                   |
| State Farm                                        | No                                        |                                                                                                                                                                                                                                                                                                                                                                                                   |

Whether this provision would cover subsidence due to undermining is not known. Insurance companies are hesitant to insure against subsidence because they may be held liable for damage that occurs anytime after the first subsidence is observed (Griebel, 1976). Because of this liability, it is unlikely that mining subsidence insurance will ever be generally available unless legislative action requires it.

In Pennsylvania the Mine Subsidence Insurance Fund offers low-cost subsidence insurance. For protection from \$5,000 to \$50,000 rates are \$15 to \$79 per year. The fund provides coverage for subsidence due to active and abandoned mining operations, and employs experienced adjustors who establish the extent and cause of damage. The adjustors may use survey data, photographs and mining records to verify a claim (Battista, 1976).

#### 4.2.3 Monitoring to Control Cost to Surface Consumers

In Section 4.1, the data useful for those surface owners with the right to support are discussed.

Surface users and communities without insurance or the legal right to support may mitigate economic impacts of subsidence, and possibly recover for certain negligent subsidence damage, by monitoring the extent and magnitude of the subsidence problem. Such communities could benefit from a monitoring program to improve safety and encourage construction. A useful program might measure vertical settlements with time to define the locations of active subsidence movement and give warning of the potential for impending movements over both active mines and abandoned mines.

Subsidence over abandoned mines may force the community to assess the need for a mine flushing program and to define the most critical areas of the community requiring such support. Mine flushing is a process whereby soil materials or grout is hydraulically transported into the mined-out area to provide support to the overlying strata. Flushing is costly. "Eleven recent backfilling projects in abandoned mines have cost over \$7 million" (Cochran, 1971). An extensive program of vertical settlement monitoring would be valuable to the decision-making process involved in mine flushing and could be helpful to assess the effectiveness of a flushing program.

#### 4.2.4 Monitoring to Reduce Economic Costs to Mine Operators

If the mine operator allows protected land to subside, he can incur costly legal fees and must pay damages to restore the property or compensate for its loss in value (American Mining Law, 1976; Herbert and Rutledge, 1927). Measurements useful to control subsidence and resulting costs are discussed in Section 4.3.4.

Even where the mine operator is not obligated to support the surface, his production costs may increase as a result of subsidence damage to his own support system or barrier pillars and access shafts. Such damage can

disrupt production and allow water or methane from adjacent mines to enter the mine (Dunrud, 1976). Surface water percolating through strata cracked by subsidence can create a costly acid mine drainage problem (Williams, 1976). The effects cited above may combine to reduce future production capability in underlying and overlying seams (Dunrud, 1976). Measurements to prevent subsidence damage at mine level are discussed in Section 4.3.3.

#### 4.3 APPLICATION OF SUBSIDENCE MONITORING TO ENGINEERING NEEDS

Subsidence monitoring can provide vital data for engineering projects which need to predict, analyze, or control the response to undermining of surface structures and the ground. Subsidence monitoring during active mining operations can be used to ensure the safety and continuity of mining operations, to evaluate the effectiveness of subsidence control procedures, and to provide insight into the effects of mining method and geology on subsidence. In abandoned mines, performance monitoring focuses on the effectiveness of remedial subsidence control measures.

##### 4.3.1 Monitoring the Influence of Geology on Subsidence

The extent and nature of subsidence due to underground mining depends on the geology of the site. A list of geologic factors which may affect subsidence are:

- a. Geologic structure, discontinuities and strength of country rock
- b. Depth and dimensions of ore body
- c. Strength and competency of ore body
- d. Tectonic stresses
- e. Earthquake activity
- f. Surface topography
- g. Hydrology of site

A brief summary of the effect of these geological factors is presented below. A more comprehensive analysis of the effect of geology on subsidence is beyond the scope of this report. The subsequent section discusses the data requirements related to geologic factors.

##### 4.3.1.1 Effects of Various Geological Factors -

- a. Geological Structure, Discontinuities and Strength of Country Rock - Discontinuities such as folds, faults, intrusive dikes and sills can dictate the choice of mining method and resulting subsidence conditions (Boyum, 1961). Discontinuities, particularly faults, can produce severe subsidence damage (Wardell, 1970).

Where faults dip toward the mine workings, movement often occurs on the fault (Crane, 1931). Undermining adjacent to a fault produces a step-like subsidence pattern at the surface rather than the smooth subsidence contour typical of unfaulted ground (Lee, 1966).

While faults may cause dramatic, locally confined subsidence damage, the overall joint pattern is the principal factor in defining the areal extent of subsidence. Crane pointed out that the dip of the joints, faults and bedding controls the angle of draw (Crane, 1929 and 1931).

Rock geometry and structural weakness of the country rock both influence subsidence. In the San Manuel mine, the thicker and more competent conglomerate over the north ore body delayed subsidence over a block caving operation for 500 days whereas over the south ore body, cracking was observed in the thinner, less competent conglomerate after 100 days (Johnson and Soule, 1963).

The behavior of undermined country rock is also influenced by the strength properties of the intact rock mass. Factors which must be considered are bedding, grain size, geometric arrangement of grains, and homogeneity. For example, roof rock consisting of sandstones and conglomerates has provided more support and produced less subsidence than shales (Martin, 1975).

Sudden changes in rock types present a potential subsidence problem. For example, the presence of dikes in iron ore formations is a weakness that may cause caving and subsidence (Crane, 1929).

- b. Depth and Dimensions of the Ore Body - The depth and dimension of the ore body determine the shape of the mined-out void. In England, subsidence estimates for coal mines are based almost entirely on the mine geometry and generally do not take into account other geological factors. Woodruff observes, however, that "the types of subsidence above the irregularly shaped cavities which are excavated during the mining of metalliferous deposits are less predictable in nature than those above bedded deposits" (Woodruff, 1966).
- c. Strength and Competency of the Ore Body - The strength of the ore body determines to some extent the mining method chosen, which in turn affects the degree and extent of subsidence. For example, weak ores are more suitable than strong ones for caving methods, and caving methods can cause substantial subsidence. Where ore pillars are left to support the mine roof, they must be able to carry the overburden and to resist weathering to prevent future subsidence. Weak pillars may fail after the mine is abandoned and cause delayed subsidence. Ore may also be left in place to protect weak, sensitive roof and floor rocks such as shale or fire clay to prevent instability due to heaving of the mine floor or due to rock falls.



- d. Tectonic Stresses - In addition to the load from the overburden, residual tectonic stresses may act on the mine roof, floor and pillars. The most common resulting phenomenon is rock burst, i.e. sudden pillar failure. As noted above, pillar failure may result in substantial subsidence at the surface.
- e. Earthquake Activity - Earthquakes may fail pillar supports and as a result produce subsidence. In Belleville, Illinois, an earthquake was blamed for initiating progressive pillar failure in an abandoned mine (Mansur and Skouby, 1970). The resulting subsidence damaged an office building under construction.
- f. Surface Topography - Steep slopes seem to displace the subsidence trough above a mine and increase the damage levels due to subsidence. As a result, Pennsylvania requires more stringent subsidence control measures to protect structures on slopes exceeding five degrees (Cortis, 1969). The effect of surface topography is still subject to debate. For example, Dahl and Choi (1975) found that subsidence was symmetrical with the mined void in a very rugged terrain. The effect of surface topography on subsidence probably depends on the geologic history of the area including extent of faulting and folding, and the residual strength and structure of the rock mass. The mining method, i.e. supported or caved, may also determine how the original surface topography affects the overall subsidence characteristics.
- g. Hydrology of the Site - Groundwater may be a stimulus to subsidence. For example, unequal hydraulic pressure across a barrier pillar may fail it or water may soften floor clays and reduce pillar stability. Mine water may come from drainage of adjacent aquifers or from precipitation entering through cracks from the surface. However, the correlation between ground water levels in flooded mines and subsidence is not well understood (Martin, 1975).

4.3.1.2 Data Requirements to Assess the Effect of Geology on Subsidence - The effect of geology on subsidence may be difficult to separate from the effects of mining method and subsidence control methods. A good assessment of the geology of the mining area and its probable effect on subsidence could probably be made from a thorough site investigation which would include appropriate sampling, in-situ testing and laboratory testing. As mining proceeds, these data could be supplemented by additional rock coring and testing at mine level.

However, long-term monitoring is essential to obtain detailed information on how various rock types and formations deform over a mined void. Repeated surface surveys of settlement and strain could be correlated with the geologic profile, strength and competency of the ore and country rock, and the patterns of joints and bedding determined from the site investigation. Since geologic discontinuities are the rule rather than the exception, time-dependent displacements across faults and joints (both surface and underground) are important. Measurement of subsurface deformations would be valuable to assess the extent to which the country rock

fractures under mining-induced stresses. In addition, long-term measurements of pillar and support stresses, as well as mine convergence, roof sag and roof strata separation will provide information about the elastic-plastic behavior of rock in and around the mine. These results could be correlated with monitored surface deformations over time. Supplemental long-term measurements which may have some use in determining the effect of geology on subsidence are long-term monitoring of seismic disturbances and ground water pressures.

#### 4.3.2 Monitoring the Influence of Mining Methods on Subsidence

The mining method, particularly the amount of support provided to the mine opening, can influence the magnitude and areal extent of subsidence. However, the impact of mining method on subsidence is related to the geology of the site since the selection of a mining method is strongly influenced by the geology. This section and Table 4.3 describe some of the potential for subsidence associated with specific mining methods, and assess related measurement needs. A later section of the report discusses specialized mining techniques which can be used to mitigate or even avoid subsidence.

4.3.2.1 Caving Methods - Caving methods can cause substantial subsidence, up to several hundred feet over a large block caving operation (Johnson and Soule, 1963). Caving methods include block caving, sublevel caving, top slicing, longwall mining and room and pillar mining with full extraction. In most caving methods the ore is undercut and shot where needed; then the weight of the capping helps to break up the ore and bring it down. The ore is then loaded onto a conveyor, or drawn through chutes to a haulageway. This procedure has traditionally been used in longwall mining, but with the advent of continuous miners, the ore may be cut and loaded in one continuous operation without undercutting and blasting.

Longwall mining is a common caving method used to extract relatively flat seams of coal, particularly in England. In the United States, longwall mining of coal has been carried out in Utah, Pennsylvania, West Virginia and Virginia (Given, 1973). In longwall mining, the mine roof near the face is generally supported by timbers or hydraulic supports. The mine roof is allowed to cave behind the supports and the caving causes a broad shallow subsidence trough at the surface. Typical coal seam thicknesses mined by longwall methods range from about 3 to 8 feet (Given, 1973); after mining, surface subsidence may be about six-tenths of the seam thickness (see Section 3.1.1) or less if fill is placed in the mined-out stope.

Room and pillar mining with pillar extraction is used in coal mines in the United States for depths less than 1500 feet. Usually rooms are developed leaving regularly spaced pillars. As soon as a section is completed, the pillars are mined. Props provide support for the mine roof as the pillars are extracted; after the coal is loaded, the support is removed and the roof allowed to cave.

TABLE 4.3

## SUBSIDENCE POTENTIAL OF THE BASIC MINING METHODS

| MINING METHOD          | NATURE OF ORE BODY AND STOPE DIMENSIONS                                           | NATURE OF COUNTRY ROCK                         | DESCRIPTION OF METHOD                                                                                                                                                                                                                                             | SUPPORT                                                                 | SUBSIDENCE POTENTIAL                                                                                                                                                           |
|------------------------|-----------------------------------------------------------------------------------|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Open stoping           | Small ore body                                                                    | Walls and roof strong and self supporting      | Mined from wall to wall with no pillars left                                                                                                                                                                                                                      | None                                                                    | Low                                                                                                                                                                            |
| Sublevel stoping       | Strong, steeply dipping ore body; stopes may be 70 to 100 ft wide and 400 ft high | Strong; free of joints, faults, bedding planes | Cut and draw starting slot. Drive sublevel drifts and crosscuts. Drill from all drifts. Start blasting from lowest sublevel. Ore falls into large open stope created by blasts at lower sublevels or by starting slot. Remove ore through draw cones below stope. | Pillars left between stopes; may be recovered; stopes may be filled.    | Subsidence not inevitable. Depends on rock strength, whether pillars recovered and whether stope filled.                                                                       |
| Room and Pillar mining | Generally flat bedded deposits; ore strength determines pillar size               | Strong enough to support large openings.       | Drive rooms leaving blocks of ore as pillars. Pillars may be extracted after panel completed.                                                                                                                                                                     | Pillars generally recovered; mine may be filled with mine waste or sand | Usually several feet of subsidence at surface. May get surface caves with less than 150 ft of cover; if pillars adequate in size and closely spaced, subsidence may not occur. |

TABLE 4.3

## SUBSIDENCE POTENTIAL OF THE BASIC MINING METHODS (continued)

| MINING METHOD        | NATURE OF ORE BODY AND STOPE DIMENSIONS                          | NATURE OF COUNTRY ROCK                                                                      | DESCRIPTION OF METHOD                                                                                                                                                                                | SUPPORT                                                                  | SUBSIDENCE POTENTIAL                                                                                                                         |
|----------------------|------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| Longwall Mining      | As Above                                                         | Weaker than for room and pillar                                                             | Long face blocked out between two panel entries. Roof support moved with the face and mined out panel allowed to cave behind roof supports.                                                          | Pillars are left in entries only. Void may be filled to limit subsidence | Subsidence up to 0.6 to 0.9 of seam thickness typically; can be reduced to 0.15 to 0.20 of seam thickness with solid stowing.                |
| Shrinkage stoping    | Strong, steeply dipping ore body. Stope up to 200 to 300 ft high | Moderately strong walls with minor faulting                                                 | Undercut bottom of ore; then blast ore in horizontal slices from bottom up. Leave most of ore to support walls and serve as floor while rest of ore mined. Then broken ore removed at end of mining. | Broken ore during mining; may be filled with waste after ore removed.    | Subsidence likely after ore drawn off.                                                                                                       |
| Cut and fill stoping | Strong, steeply dipping ore                                      | Moderately strong walls but somewhat weaker than for shrinkage stoping.                     | As above, but floor made of waste rock and ore drawn off immediately.                                                                                                                                | Waste rock                                                               | Subsidence less of a problem than for shrinkage stoping and the mined out stope is stronger because of the early placement of permanent fill |
| Stull stopes         | Narrow veins with steep dip                                      | Can be heavy squeezing ground if stope filled; open stull stopes require good hanging wall. | Timber placed between hanging wall and footwall to provide support. Filling usually added to provide permanent support.                                                                              | Timber and fill.                                                         | Subsidence depends on stope filling and size of mined out stope                                                                              |

TABLE 4.3

## SUBSIDENCE POTENTIAL OF THE BASIC MINING METHODS (continued)

| MINING METHOD      | NATURE OF ORE BODY AND STOPE DIMENSIONS                                                                                        | NATURE OF COUNTRY ROCK                                                                       | DESCRIPTION OF METHOD                                                                                                                                     | SUPPORT                                      | SUBSIDENCE POTENTIAL                                        |
|--------------------|--------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------------|
| Square set stoping | Weak high grade ore                                                                                                            | Weak running ground                                                                          | Small blocks of ore blasted, excavated, timbered; square sets added successively to form cellular structure. Filled with waste rock or mill tailings.     | Timber and fill                              | Small ground movements possible due to compression of fill. |
| Block caving       | Soft to moderately hard massive ore deposits. Should break into small pieces.<br><br>Height of stope usually less than 500 ft. | Weak capping; break into pieces coarser than ore. Usually capping thicker than 300 ft.       | Ore may be mined in blocks or as a mass. Ore undercut; then ore caves starting at bottom of block. Weight crushes ore. Capping follows ore down.          | Pillars may be used between caving blocks.   | Inevitable, up to 300 ft. Caves usually reach the surface.  |
| Sublevel caving    | Weak irregular steeply dipping ore                                                                                             | Hard capping that breaks into large blocks. Caves more slowly than required for top slicing. | Drive series of sublevels. Beginning at top of ore, undercut ore; ore caves under weight of capping. When capping caved, continue at next lower sublevel. | Pillars used between sublevels               | Inevitable                                                  |
| Top slicing        | Weak ore that will stand temporarily                                                                                           | Weak capping that will cave readily as each slice removed                                    | Ore is removed in a series of horizontal slices beginning at the top of the ore. The capping is allowed to cave as each slice is removed.                 | Temporary timber during mining of each slice | Inevitable                                                  |

Subsidence usually occurs rapidly with longwall mining. Most of the movement occurs simultaneously with mining and the rest within two to three years. For room and pillar mining with pillar extraction, the time to maximum surface subsidence is also no more than a few years.

4.3.2.2 Artificially Supported Stopes - Artificial supports in mining terminology include timber or fill or even broken ore. They may be used to support the mine void; if the support is permanent, it is expected to reduce the surface subsidence. Timber or fill may be used individually, together, or in conjunction with natural ore pillar supports. Common mining methods using artificial supports include shrinkage stoping, cut and fill stoping, stulted stopes and square set stoping. Room and pillar and longwall methods may also use fill as an artificial support for the mine.

Subsidence above filled stopes depends on the density and timing of the placement of the fill. Some closure of the stope is inevitable before the fill is placed and will continue until the fill is compacted by stope closure to a density that can resist further movement.

4.3.2.3 Stopes with Natural Supports - In small ore bodies in strong rock the ore may be mined from end to end with no pillars or artificial supports. Typically, however, some pillars of ore are used to support the mine opening. Methods which use ore pillars to support the main workings include sublevel stoping, stopes with random pillars and room and pillar mining.

For room and pillar mining coal mines, a regular array of pillars is used to support the mine roof. Room and pillar mining causes a broad shallow subsidence trough in which the vertical settlement depends on the dimensions and spacings of the pillars. Subsidence will increase if the pillars are robbed, or if spalling, weathering or other long term causes lead to pillar failure. Such failures can occur over a period ranging from a few years to a few hundred years, depending on the adequacy of the pillars. Room and pillar mining can be combined with backfilling to supplement the pillars and to provide better long term stability to the mined opening.

4.3.2.4 Measurements to Assess the Effect of Mining Methods on Subsidence - Caving and supported mining systems produce different amounts of vertical subsidence. Accompanying the larger vertical deformations in a caving system may be significant horizontal strains, ground cracking and tilt. Therefore, a detailed observation of ground surface deformations is important in determining the effect of the mining method on subsidence.

Mining methods differ in the amount of support provided to the stope, the shape of the stope and the rate of advance of the face. All these factors stress the country rock and induce deformations above the mine which may eventually propagate to the surface. To assess the effect of mining method on the development and progression of subsidence,

measurements should be made of subsurface horizontal and vertical deformations as well as the extent of subsurface fracturing.

Mine level measurements, discussed in Section 4.3.3 are recommended for monitoring the effect of mining method of subsidence.

#### 4.3.3 Monitoring the Relationship between Mine Stability and Subsidence

Subsidence (or lack of it) can create stability problems at mine level for both caving and supported mining methods. The stability problems, in turn, can disrupt production, create safety hazards and produce more subsidence at the surface.

4.3.3.1 Caving Methods - Caving methods depend on subsidence to redistribute stresses. In longwall mining, the process of caving transfers the weight of the overburden to the mine floor behind the face. Generally, an arch forms through the caved roof rock so that most of the weight of the capping is borne by the caved rock behind the face and by the ore ahead of the face. If subsidence does not occur, the "weight of the roof is thrown on the face and may buckle props and cause the roof to fracture at the face" (Woodruff, 1966). Similarly, in sublevel caving and block caving, the capping must cave and follow the ore down to prevent serious problems, such as air blasts due to sudden collapse of the capping.

For all these caving methods, measurements of surface and subsurface vertical deformations and spatial extent of subsurface fracturing may be used to monitor the progress of the caving. In longwall mining, measurements of support loading, roof sag and convergence at the face can be used to evaluate the effectiveness of the weight transfer process.

Subsidence over caving systems can cause other problems. Aside from damage to the surface, subsidence may create water problems at mine level. Cracking and sagging of the surface strata may cause surface runoff to collect above the mine and cracking of the subsurface rocks may let water enter the mine (Dunrud, 1976; Williams, 1976). Surface water percolating throughout the mine can create or increase acid mine drainage (AMD) and increase the cost and complexity of production by the need for AMD treatment facilities (Williams, 1976). Mine water can also build up differential pressure on barrier pillars leading to sudden failures.

Monitoring of surface settlements accompanied by observation of cracks, caves and pond formation can be used to detect the potential for mine water problems. Steps can then be taken to fill or drain water-collecting depressions above the mine.

4.3.3.2 Supported Methods - Subsidence can create stability problems in supported systems at mine level by distortion and cracking of overlying strata and excessive loading of mine pillars. As subsidence occurs, the strata around the mine opening bend into the mined-out

seam and may crack. As a result, the stresses around the mine opening are redistributed (Dunrud, 1976). Bending of the roof strata may fail the roof in tension and cause rock falls which, in turn, cause additional subsidence. This same process may also cause eccentric or increased loads on pillars or mine props causing sudden pillar or support failure. In addition, subsidence-induced cracking of barrier pillars between adjacent mines can lead to a sudden inrush of water or methane gas (Dunrud, 1976), and threaten production and safety.

For supported systems, the key to mine stability, safety and continuity of operations appears to be pillar and prop performance and the continuity of roof strata. Even caving operations have props near the face and pillars in shafts and roadways which can be subjected to subsidence-induced stresses. Visual observation of pillar spalling and support distress may be the best method to detect early support problems. But in heavy ground the mine crew may become accustomed to the sight of pillar distress and report such occurrences with decreasing frequency. As a result, measurement of support stress and pillar rock noise is recommended as a supplement to visual observation to detect excessive stress levels. Measurement of mine roof sag may have application in partial extraction systems to signal the need for rock bolting or other techniques to strengthen the roof arch and support the overlying strata.

#### 4.3.4 Monitoring Subsidence Control Techniques

One of the primary uses of subsidence monitoring is to evaluate the effectiveness of subsidence control techniques for both active and abandoned mines.

Since mining fuels and minerals is basic to the economy, the problem of subsidence must be approached realistically. The sterilization of mineral resources under urban areas is frequently not acceptable. As a result a number of subsidence control measures have been developed. They can be divided into three basic types:

1. Arrangement of mine workings to limit subsidence.
2. Use of artificial supports to limit subsidence.
3. Design of structures to accommodate subsidence movements.

Most of the remainder of this section deals with coal mines; however, the discussion is also appropriate to nearly horizontal metallic deposits.

##### 4.3.4.1 Arrangements of Mine Workings to Limit Subsidence Effects -

- a. Safety Pillars - Large pillars of coal may be left under structures to prevent any movement or limit subsidence damage at the surface. In general, this method wastes a large amount of coal, but may be



economical at depths less than 1000 feet (Brauner, 1973a). While strains may be negligible in the vicinity of the structure, surface deformations may be significant above the edge of the pillar (see Figure 4.1a).

- b. Partial Extraction Mining - Regular pillars of coal, generally 40 to 70 percent of the mineral in the seam, are left under a protected structure or land area to minimize or prevent subsidence deformations. This method, called room and pillar mining, will produce a uniform subsidence trough at the surface. The amount of subsidence movement depends on the size and spacing of the pillars. If more than 50% of the mineral is left as pillars, vertical surface movement can often be prevented (see Figure 4.1b).
- c. Harmonic Extraction - Longwall or room and pillar workings can be arranged so that compressive and tensile strains cancel out at the protected surface site. For example, where two overlying seams are mined simultaneously, the horizontal distance between faces must be kept to  $(h_1 \pm h_2) \cot \beta$ , where  $\beta$  is the angle of break. This method also specifies that an area of supercritical width is worked, i.e., that the workings are wide enough to produce full subsidence and a broad flat zone at the center of the subsidence trough. The mining program should locate the protected structures at the center of the trough (see Figure 4.2).
- d. Single Seam Face Arrangements to Limit Strains - Similar to harmonic mining, there are a variety of procedures for staging faces on a single seam to protect surface structures from excessive strains. They include staggered faces, mining in two directions, and favorable orientation of the face with respect to structures. These methods are summarized on Figure 4.3.
- e. Rapid Undermining - If a supercritical area is extracted quickly under a structure, the time in which a structure is exposed to traveling strains is reduced. The structure will settle, but if located at the center of a supercritical area, it will be situated in a broad, flat, strain-free area once the face is well passed.

However, some engineers argue that the rapid undermining will stress the mine rock too rapidly and cause larger deformations than would gradual loading due to slower undermining (Aynsley and Hewitt, 1961). That is, gradual loading would allow an arch to form over the mine void and restrict further deformation.

4.3.4.2 Use of Artificial Supports to Limit Subsidence Effects - A variety of techniques are available to limit subsidence by providing artificial supports usually to hold up the mine roof. These techniques generally fill the mine void with discrete or continuous supports made of grout, concrete, sand, gravel, flyash or mine waste.

- a. Continuous Support of Stowing Active Mines - Mined out stopes can be backfilled as mining progresses with waste rock, sand, fly ash

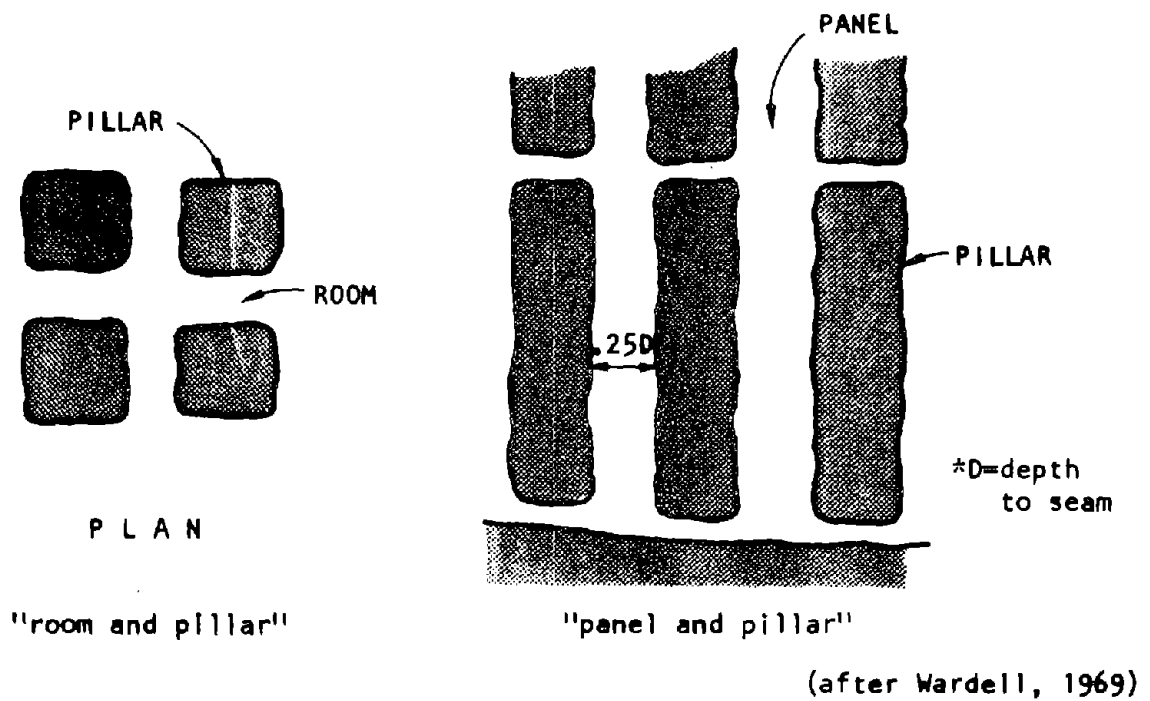
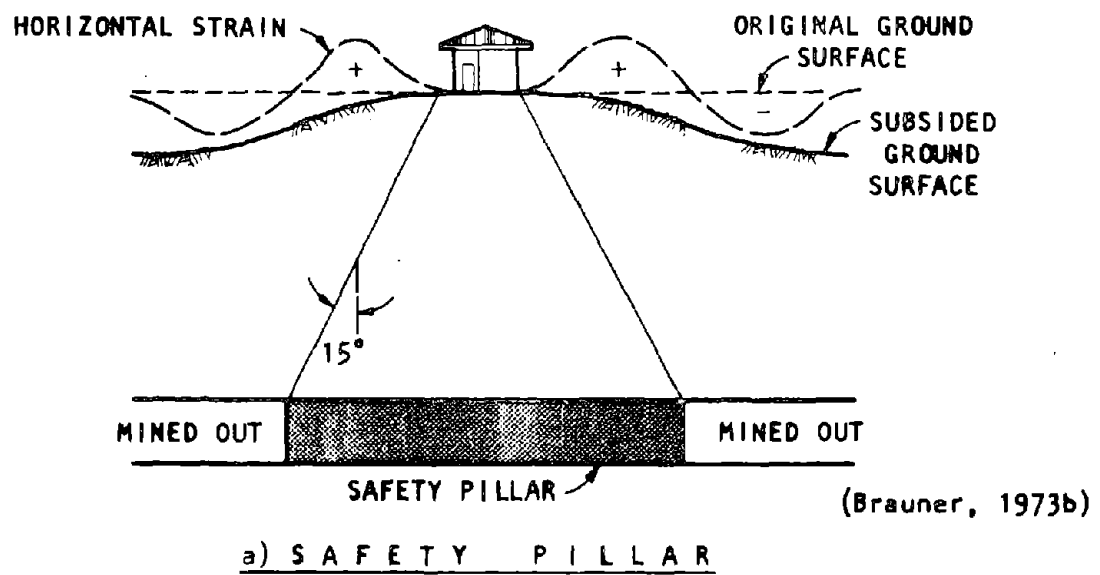


Figure 4.1 - SELECTED SUBSIDENCE CONTROL MINING METHODS USING ORE PILLARS

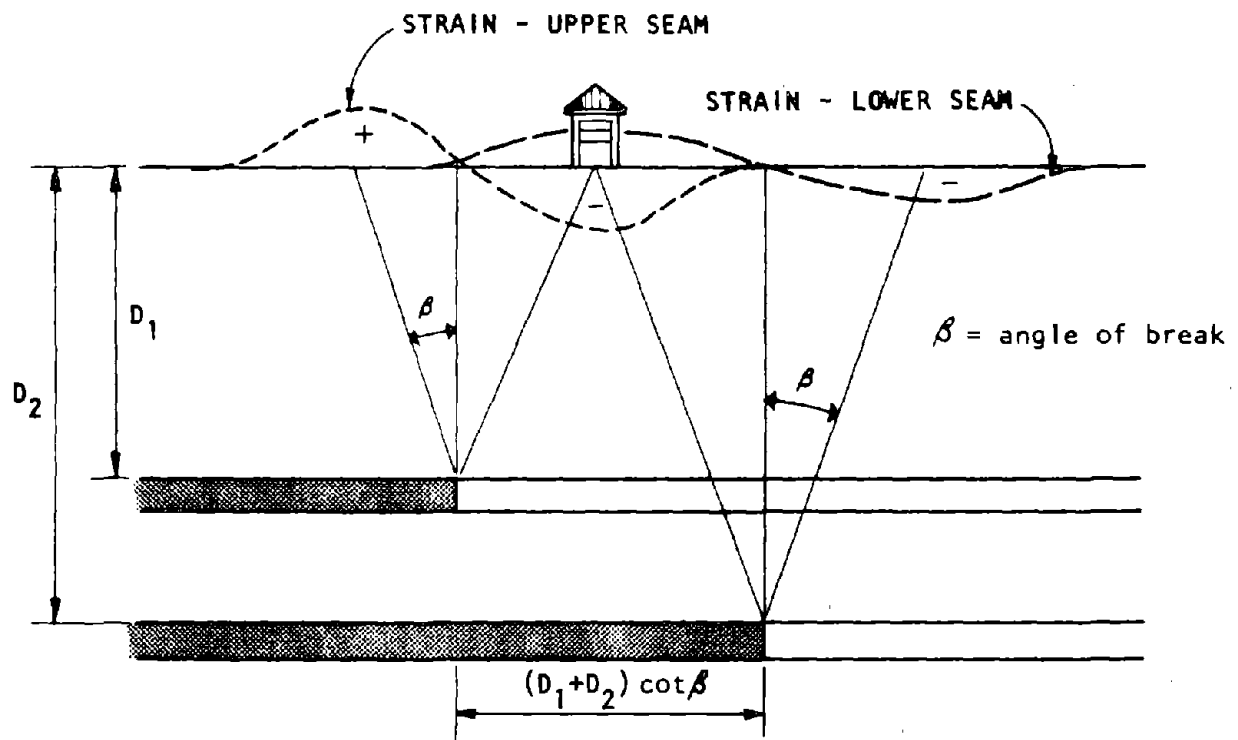
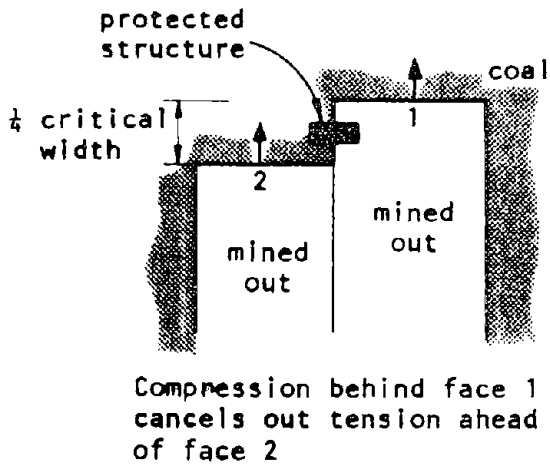


Figure 4.2 - H A R M O N I C E X T R A C T I O N  
(after Brauner, 1973b)

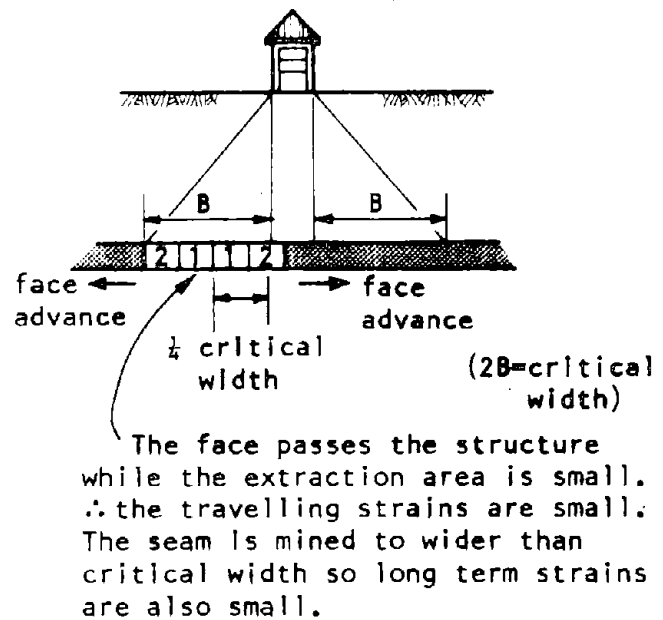
P L A N :



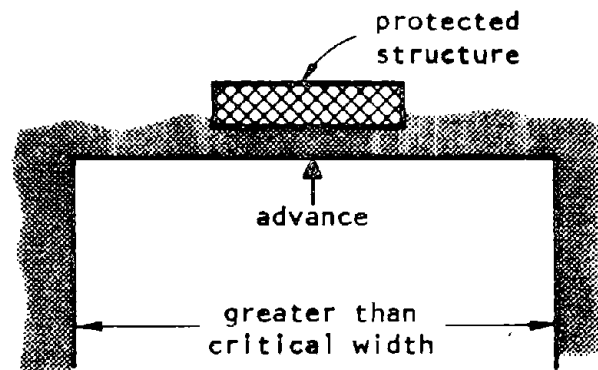
(a) STAGGERED FACES

MINING SEQUENCE:

Panels 1 then panels 2



(b) MINING IN TWO DIRECTIONS



Only shorter side subject to travelling strain.  
Ends up in flat broad center of trough.

FAVORABLE ORIENTATION OF FACE TO BUILDINGS

(c) STRAIN REDUCING FACE ARRANGEMENTS

(after Brauner, 1973)

Figure 4.3 - SINGLE SEAM MINING FACE ARRANGEMENTS TO CONTROL SUBSIDENCE DAMAGE

or other materials to limit surface subsidence. In coal mines, stowing can be used in conjunction with longwall mining or room and pillar mining.

In England, complete extraction causes vertical subsidence equal to 60% to 95% of the seam thickness. Pneumatic, slusher or hand stowing generally reduced subsidence ratios to 0.3 to 0.7. Hydraulic stowing can lessen the subsidence ratio even further to 0.1 to 0.3. A combination of partial extraction and hydraulic stowing can essentially prevent subsidence, i.e., the subsidence ratio can be reduced to near zero (Brauner, 1973). However, some movement of the roof often occurs before rock packs or fill are in place. In a longwall caving operation, 10 to 20 percent subsidence can occur in advance of the face. Also, subsidence may occur as the fill consolidates. Consequently, the most effective use of fill requires rapid placement at high density.

- b. Continuous Support by Filling Abandoned Mines - The collapse of voids tens to hundreds of years after mining can cause large subsidence deformations at the surface. The mine voids can be filled to stop caving, provide lateral support for pillars and prevent further deterioration of mine roof, walls and pillars. The filling methods include:
  - hydraulic flushing with waste rock gravel and sand
  - dowell process hydraulic filling with sand
  - pneumatic filling
  - fly ash injection
  - grouting
  - open excavation and backfilling
- c. Discrete Supports - A regular array of discrete artificial supports can be used to support the mine roof and walls to limit or prevent closure of the mine openings. Such supports can also be used to support protected structures directly on the mine floor. Several examples of discrete supports follow:
  - Strip packing has been used in active mines to try to limit subsidence. However, for total extraction operations, strip packing has not been very effective in limiting surface settlement.
  - Piers may be constructed to support the mine roof in active or abandoned mines where the mine openings are accessible. The piers must be constructed over an area larger than that of the protected structure to provide adequate protection. Mine gob and timber, masonry or concrete are commonly used materials. In abandoned

shallow mines with 50 feet or less cover, structures can be supported on concrete drilled piers which extend from the base of the building to or below the mine floor.

- Grout columns may be installed in abandoned mines from the surface on closely spaced centers to support the mine roof beneath a protected structure and prevent further subsidence without filling the entire mine. The method has been widely used in Pennsylvania for about 20 years. Grout columns are most economical for shallow mines and can be installed effectively only in dry or dewatered mines or mines with low water flow. The grout columns must extend over an area larger than that of the building to provide adequate protection. Similar to grout columns, drilled pier shafts can be filled with concrete from mine roof to floor and then backfilled with grout to ground level. In Pennsylvania, for example, a school was supported by pouring concrete piers from drill holes to support the mine roof (Gray, 1970).

4.3.4.3 Design of Structures to Accommodate Subsidence Effects - The prevention of subsidence damage is not exclusively the problem of the mine operator. In areas where the mine operator has no obligation to support the surface, the structural engineer may be called upon to design structures resistant to subsidence damage.

Some of the significant features of design used in Great Britain in subsidence-prone areas are listed below (Institution of Civil Engineers, 1962):

- Avoid building within 50 feet of a geologic fault
- Avoid building of statically indeterminate structures such as fixed arches or rigid frames
- Use very stiff or very flexible structures
- Orient structures with respect to mine workings to reduce strain

4.3.4.4 Measurements to Assess the Effectiveness of Subsidence Control Procedures - The purpose of most of the special techniques to limit subsidence effects falls into one of the following categories:

- to prevent surface movement
- to limit all surface deformations to non-damaging levels
- to limit only surface horizontal strains to non-damaging levels

To evaluate the success of a subsidence control program, the mine operator, surface owner or regulatory agency must monitor surface deformations. The selected surface deformations monitored will depend on the purpose

of the subsidence control program. The mine operator may also include selected subsurface or mine level deformations which correlate with surface movement. The mine level measurements can be used to indicate when the support system needs strengthening before surface movements become excessive. The selected mine level measurements depend both on the purpose of the subsidence control program and the nature of the mine level operations.

Where no surface movement is allowed, surface monitoring may be limited to the measurement of vertical subsidence of the land or structures. Vertical movements due to subsidence are generally many times larger than horizontal movements and as a result will be easier to detect if movement does occur.

Applicable subsurface and mine level measurements will depend on whether the mine is active or abandoned. In an active mine, the effectiveness of the subsidence prevention program requires that the mine pillars and supports must never be overstressed, and that roof sag must be minimal. Appropriate measurements for the mine operator would be pillar and support stress and roof sag. Measurement of roof strata separation may be useful to determine the extent of strata affected by mine level deformations. If the pillars are founded on clay whose bearing capacity may be in doubt, floor heave and convergence may also be useful measurements.

In abandoned mines, access is usually not possible. Subsurface deformations measured in boreholes drilled from the surface could give an early indication of the effectiveness of the mine filling procedure. Subsurface deformations will generally include measurement of vertical movement, but in steeply dipping strata, horizontal deformations may also be useful. Intensive monitoring in several boreholes should be adequate to evaluate the effectiveness of the fill.

Some subsidence control programs try to minimize the traveling and permanent strains around the surface improvements while permitting full vertical movement. Horizontal structure strain is the key measurement for this type of subsidence control program. However, differential settlements should also be monitored because even if the structure is located in a broad, flat trough, local geologic discontinuities may cause small but potentially damaging differential settlements. At the mine level, the most useful information would be the exact daily location of the face. This is the parameter that the mine operator varies to control horizontal surface strains. Because traveling strains (ahead of the face) can be damaging, the mine operator must begin his monitoring well in advance of the undermining of the structure.

A more complex program of measurement is required when it is desired to minimize but not eliminate surface movement. Vertical settlement of the ground will give an overall picture of the effectiveness of the subsidence control program. These measurements should be supplemented by an intensive program of monitoring settlement and strain at key

structures until the mine operator has enough data to predict structure movements from ground movements. The mine operator may want to monitor key mine level measurements that control surface subsidence. Convergence and roof sag can be used to determine if closure of the mine opening is within acceptable limits; roof strata separation, pillar stress and support stress can indicate the mine support system is performing adequately.

The engineer may want to monitor the performance of structures designed to resist subsidence damage to determine if his design was adequate and to see if remedial measures are needed. The monitoring program for such a structure would include structure differential vertical settlements and strains. The program should begin well in advance of undermining so that the engineer can distinguish base movements due to seasonal moisture change and consolidation of the foundation soils from those caused by mining subsidence.

#### 4.3.5 Monitoring Abandoned Mines

Subsidence accompanies nearly all mining operations. The time to completion of movement may vary considerably. For example, Dahl and Choi (1975) observed that subsidence in a longwall operation stopped abruptly when the face was stopped. On the other hand, at the San Miguel mine in Arizona (Johnson and Soule, 1963), where block caving was used to mine the copper ore, surface subsidence was not observed until 500 days after undercutting at the northern ore body. Since measurement data for the United States are not readily available, it may be assumed that subsidence usually begins shortly before the face reaches the site and may continue for two to three years after mining is complete (Wardell, 1970). If caving methods are used, subsidence is essentially complete at that time. The long-term subsidence problem results from abandoned mines excavated with partial extraction systems without full stowing. Many years in the future additional subsidence may occur due to deterioration of the mine roof, floor or pillars. Abandoned mines have created subsidence problems in many mining districts, including Rock Springs, Wyoming (Morgando, 1969), Belleville, Illinois (Mansur and Skouby, 1970) and Scranton, Pennsylvania (Griffith and Conner, 1912).

4.3.5.1 Causes of Subsidence in Abandoned Mines - Partial extraction systems have been used where the country rock is too weak to stand unsupported and full caving is unacceptable. Pillars of ore are left to support the opening. Sometimes a layer of ore is left on the roof or floor to prevent softening of weak wall materials such as shale or fire clay. Even with these precautions, mine air and water tend to degrade the pillars, roof and floor and may eventually cause a collapse of portions of the mine. The degradation and failure may occur in many ways; some possible modes of failure are:

- a. Pillar failure: Pillar failure can be caused by spalling and softening of pillars from exposure to mine water and air (Mabry, 1972), by erosion from mine water, by uneven hydraulic pressure from mine



water across barrier pillars (Martin, 1975), by crushing of under-sized pillars. The process may be complex and progressive failure may occur. For example, in Belleville, Illinois, initial pillar failure in an abandoned mine was triggered by an earthquake and then pillars crushed progressively as the weight of the overlying rock and ore was transferred to the remaining pillars (Mansur and Skouby, 1970).

- b. Bearing failure beneath pillars: The underclay beneath some Pittsburgh coal seams undergoes a reduction in strength and ability to support mine pillars when exposed to air or water (Cortis, 1969).
- c. Roof failure between pillars: Wardell notes that this is the most common problem in abandoned coal mines (Wardell, 1970). As portions of the roof slab away, stresses are redistributed and further collapse may result (Martin, 1975). The fractured zone created by the roof cave seldom exceeds in height ten times the thickness of the seam (Wardell, 1970), but bending of the rocks above the cave may propagate the disturbance to the surface.
- d. Pillar punching in multiple seam mines: Griffith and Conner (1912) noted that the pillars in certain thick overlying beds in Scranton were not vertically aligned and tended to crush through the interval between the beds. The pillars of an upper bed settled into the excavations or rooms of the lower workings.
- e. Renewed movement due to adjacent mining: Mining adjacent to an abandoned mine may increase stresses around pillars leading to their eventual failure (Mabry, 1972), or may cause unpredictable movements on faults. Lee notes that "once differential movement has occurred, further working in the area causes renewed movement which is sometimes out of all proportion to the thickness and extent of extraction" (Lee, 1966).

4.3.5.2 Measurements for Abandoned Mines - Recent legislation in states such as Wyoming and Pennsylvania (see Table 4.1) makes the mine operators liable for any subsidence of land entitled to support for five to ten years after the mine has been abandoned. The mine operator may occasionally be held liable for subsidence damage after the period of limitations has expired (American Law of Mining, 1976). Therefore, the mine operator may want to monitor surface settlements for five to ten years after abandonment of the mine to protect himself against unwarranted claims.

Most surface owners are not entitled to subjacent support and have no legal protection against subsidence damage which may occur ten or a hundred years after the mine has been abandoned. To assess the probability of future subsidence and the need for subsidence control measures in abandoned mines, the surface user might consider:

- Is the site underlain by an abandoned mine?

- Is there current subsidence due to the abandoned mine?
- How much subsidence has occurred to date?
- What has been the cause of the failure at mine level, e.g., pillar collapse, roof fall, etc.?
- What is the current status of mine pillars, roof, floor?
- What amount of subsidence could potentially occur with full collapse?

All of the above questions can be answered by a site investigation which might encompass a level survey, drilled holes to at least mine level, core recovery and testing, and the use of a borehole camera. On the whole, time-dependent data from a long-term monitoring program over an abandoned mine does not have practical value for most individual surface owners. Real estate developers may wish to monitor ground movements to determine whether remedial measures are needed before construction and whether the new construction has altered the mine's stability. However, local government bodies or regulatory agencies may wish to establish a long-term program of vertical subsidence measurements to determine the rate and magnitude of the subsidence problem, particularly with regard to its effect on future regional development. A long-term monitoring program by a public agency could also be used to protect public safety by delineating rapidly subsiding areas, evacuating families from threatened homes and fencing areas undergoing pothole development.

#### 4.4 MEASUREMENT SYSTEMS

From a review of the measurements suggested in this section for a variety of applications, it was apparent that certain combinations of measurements were repeatedly used. We have recommended seven measurement systems presented in Table 4.4, which meet most of the applications discussed in this section. In Table 4.5, the applications which are appropriate for each system are listed.

TABLE 4.4  
RECOMMENDED MEASUREMENTS  
FOR MEASUREMENT SYSTEMS

| SYSTEM<br>MEASUREMENTS                      | A: Subsidence Detection | B: Structure Performance | C: Mine Stability | D: Performance of Supported Systems | E: Performance of Caving Systems | F: Performance of Filled Mines | G: Visual Documentation |
|---------------------------------------------|-------------------------|--------------------------|-------------------|-------------------------------------|----------------------------------|--------------------------------|-------------------------|
|                                             |                         |                          |                   |                                     |                                  |                                |                         |
| Ground Surface Vertical Settlement          | X                       |                          |                   | X                                   | X                                | X                              |                         |
| Ground Surface Horizontal Strain            |                         |                          |                   | X                                   | X                                |                                |                         |
| Ground Surface Tilt                         |                         |                          |                   | X                                   | X                                |                                |                         |
| Ground Surface Crack Movement               |                         |                          |                   | X                                   | X                                |                                |                         |
| Ground Surface Visual Observation           | X                       |                          |                   | X                                   | X                                | X                              | X                       |
| Structure Differential Vertical Settlement  |                         | X                        |                   |                                     |                                  |                                |                         |
| Structure Strain                            |                         | X                        |                   |                                     |                                  |                                |                         |
| Structure Crack Movement                    |                         | X                        |                   |                                     |                                  |                                |                         |
| Structure Visual Observation                |                         | X                        |                   | X                                   | X                                | X                              | X                       |
| Subsurface Vertical Deformation             |                         |                          |                   | X                                   | X                                | X                              |                         |
| Subsurface Horizontal Deformation           |                         |                          |                   | X                                   | X                                |                                |                         |
| Extent of Subsurface Fracturing             |                         |                          |                   |                                     | X                                |                                |                         |
| Mine Level Pillar Stress                    |                         |                          |                   | X                                   | X                                |                                |                         |
| Mine Level Support Stress                   |                         |                          | X                 | X                                   | X                                |                                |                         |
| Mine Level Roof Sag                         |                         |                          | X                 | X                                   |                                  |                                |                         |
| Mine Level Roof Strata Separation           |                         |                          |                   | X                                   |                                  |                                |                         |
| Mine Level Convergence                      |                         |                          | X                 | X                                   | X                                | X                              |                         |
| Mine Level Visual Observation               |                         |                          | X                 | X                                   | X                                |                                | X                       |
| Mine Level Rock Noise<br>(Metal Mines Only) |                         |                          | X                 |                                     |                                  |                                |                         |

Table 4.5

SUMMARY OF MEASUREMENTS RECOMMENDED FOR SUBSIDENCE MONITORING APPLICATIONS

| U<br>S<br>E<br>R | A<br>P<br>P<br>L<br>I<br>C<br>A<br>T<br>I<br>O<br>N                   | M<br>E<br>A<br>S<br>U<br>R<br>E<br>M<br>E<br>N<br>T<br>S |                                  |                     |                               |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | S<br>Y<br>S<br>T<br>E<br>M |
|------------------|-----------------------------------------------------------------------|----------------------------------------------------------|----------------------------------|---------------------|-------------------------------|-----------------------------------|--------------------------------------------|------------------|--------------------------|------------------------------|---------------------------------|-----------------------------------|---------------------------------|--------------------------|---------------------------|---------------------|-----------------------------------|------------------------|-------------------------------|-----------------------|----------------------------|
|                  |                                                                       | Ground Surface Vertical Settlement                       | Ground Surface Horizontal Strain | Ground Surface Tilt | Ground Surface Crack Movement | Ground Surface Visual Observation | Structure Differential Vertical Settlement | Structure Strain | Structure Crack Movement | Structure Visual Observation | Subsurface Vertical Deformation | Subsurface Horizontal Deformation | Extent of Subsurface Fracturing | Mine Level Pillar Stress | Mine Level Support Stress | Mine Level Roof Sag | Mine Level Roof Strata Separation | Mine Level Convergence | Mine Level Visual Observation | Mine Level Rock Noise |                            |
| S                | Legal: Protect Structure with Right to Support                        |                                                          |                                  |                     |                               |                                   |                                            |                  | X                        |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | G                          |
| R,S              | Legal: As above-if additional data desired                            |                                                          |                                  |                     |                               |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | B                          |
| S                | Legal: Protect Land with right to support                             |                                                          |                                  |                     | X                             |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | G                          |
| R,S              | Legal: As above-if additional data desired                            | X                                                        |                                  |                     | X                             |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | A                          |
| M                | Legal: Prevent unwarranted damage claims                              | X                                                        |                                  |                     | X                             |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | A and B                    |
| L,S              | Economic: Mitigate economic impact to uninsured, unprotected property | X                                                        |                                  |                     | X                             |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | A                          |
| S                | Economic: Document claim for insurance purposes                       |                                                          |                                  |                     | X                             |                                   |                                            |                  | X                        |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       | G                          |
| M                | Economic: Control Subsidence to prevent damage to surface facilities  |                                                          |                                  |                     |                               |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       |                            |
| M                | - for supported mines:                                                | X                                                        | X                                | X                   | X                             | X                                 | X                                          | X                | X                        | X                            |                                 |                                   |                                 | X                        | X                         | X                   | X                                 | X                      | X                             |                       | B and D                    |
| M                | - as above, once ground and structure response well understood:       |                                                          |                                  |                     | X                             |                                   |                                            |                  | X                        |                              |                                 |                                   |                                 |                          |                           |                     |                                   | X                      |                               |                       | A                          |
| M                | - for caving mines:                                                   | X                                                        | X                                | X                   | X                             | X                                 |                                            |                  |                          | X                            |                                 |                                   |                                 | X                        | X                         |                     |                                   | X                      | X                             |                       | B and E                    |
| M                | - as above, once ground and structure response well understood:       |                                                          |                                  |                     |                               |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        | X                             |                       | B                          |

L = Local Government  
M = Mine Operator  
S = Surface Owner  
R = Regulatory Agency

Table 4.5 (continued)

SUMMARY OF MEASUREMENTS RECOMMENDED FOR SUBSIDENCE MONITORING APPLICATIONS

| C O M M E N T | A P P L I C A T I O N                                                                                                                     | M E A S U R E M E N T S Y S T E M  |                                  |                     |                               |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       |
|---------------|-------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|----------------------------------|---------------------|-------------------------------|-----------------------------------|--------------------------------------------|------------------|--------------------------|------------------------------|---------------------------------|-----------------------------------|---------------------------------|--------------------------|---------------------------|---------------------|-----------------------------------|------------------------|-------------------------------|-----------------------|
|               |                                                                                                                                           | Ground Surface Vertical Settlement | Ground Surface Horizontal Strain | Ground Surface Tilt | Ground Surface Crack Movement | Ground Surface Visual Observation | Structure Differential Vertical Settlement | Structure Strain | Structure Crack Movement | Structure Visual Observation | Subsurface Vertical Deformation | Subsurface Horizontal Deformation | Extent of Subsurface Fracturing | Mine Level Pillar Stress | Mine Level Support Stress | Mine Level Roof Sag | Mine Level Roof Strata Separation | Mine Level Convergence | Mine Level Visual Observation | Mine Level Rock Noise |
| M             | Economic: Control Sub-<br>sidence to prevent<br>damage to Mine                                                                            |                                    |                                  |                     |                               |                                   |                                            |                  |                          |                              |                                 |                                   |                                 | X                        | X                         |                     | X                                 | X                      | X                             |                       |
| M,R           | Engineering: Assess<br>Effect of Geology<br>on Subsidence                                                                                 | X                                  | X                                | X                   | X                             | X                                 |                                            |                  |                          | X                            | X                               |                                   | X                               | X                        | X                         | X                   | X                                 | X                      | X                             |                       |
| M,R           | Engineering: Assess<br>Effect of Mining<br>Method on the Magni-<br>tude and Development<br>of Subsidence                                  | X                                  | X                                | X                   | X                             | X                                 |                                            |                  |                          | X                            | X                               | X                                 |                                 |                          |                           |                     |                                   |                        |                               |                       |
| M             | Engineering: Prevent<br>subsidence damage and<br>resulting safety and<br>production problems<br>at mine level                             | X                                  |                                  |                     |                               | X                                 |                                            |                  |                          |                              |                                 |                                   |                                 | X                        | X                         |                     | X                                 | X                      | X                             | A and C               |
| M             | Engineering: Assess<br>effectiveness of<br>subsidence control<br>procedure to prevent<br>vertical movement<br>in active mines as<br>above | X                                  |                                  |                     |                               | X                                 |                                            |                  |                          |                              |                                 |                                   |                                 | X                        | X                         | X                   | X                                 | X                      | X                             | D                     |
| R,L,<br>S     | as above                                                                                                                                  | X                                  |                                  |                     |                               | X                                 |                                            |                  | X                        |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               | A                     |
| R,L,<br>S     | as above for inacessi-<br>ble abandoned mines                                                                                             | X                                  |                                  |                     |                               | X                                 |                                            |                  | X                        | X                            |                                 |                                   |                                 |                          |                           |                     | X                                 |                        |                               | F                     |
| M             | Engineering: Assess<br>effectiveness of<br>subsidence control<br>procedure to limit<br>all surface movement<br>to non-damaging<br>levels  | X                                  |                                  |                     |                               | X                                 | X                                          | X                | X                        | X                            |                                 |                                   |                                 | X                        | X                         | X                   | X                                 | X                      | X                             | B and D               |

L = Local Government  
M = Mine Operator  
S = Surface Owner  
R = Regulatory Agency

Table 4.5 (continued)

SUMMARY OF MEASUREMENTS RECOMMENDED FOR SUBSIDENCE MONITORING APPLICATIONS

| U<br>S<br>E<br>R | A<br>P<br>P<br>L<br>I<br>C<br>A<br>T<br>I<br>O<br>N                                                         | M<br>E<br>A<br>S<br>U<br>R<br>E<br>M<br>E<br>N<br>T<br><br>S<br>Y<br>S<br>T<br>E<br>M |                                  |                     |                               |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               |                       |
|------------------|-------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------------------------|---------------------|-------------------------------|-----------------------------------|--------------------------------------------|------------------|--------------------------|------------------------------|---------------------------------|-----------------------------------|---------------------------------|--------------------------|---------------------------|---------------------|-----------------------------------|------------------------|-------------------------------|-----------------------|
|                  |                                                                                                             | Ground Surface Vertical Settlement                                                    | Ground Surface Horizontal Strain | Ground Surface Tilt | Ground Surface Crack Movement | Ground Surface Visual Observation | Structure Differential Vertical Settlement | Structure Strain | Structure Crack Movement | Structure Visual Observation | Subsurface Vertical Deformation | Subsurface Horizontal Deformation | Extent of Subsurface Fracturing | Mine Level Pillar Stress | Mine Level Support Stress | Mine Level Roof Sag | Mine Level Roof Strata Separation | Mine Level Convergence | Mine Level Visual Observation | Mine Level Rock Noise |
| R,L<br>S         | As above                                                                                                    | X                                                                                     |                                  |                     | X                             |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               | A and B               |
| M                | Engineering: Assess effectiveness of subsidence control procedures to limit only surface horizontal strains |                                                                                       |                                  |                     |                               |                                   |                                            | X                | X                        | X                            | X                               |                                   |                                 |                          |                           |                     |                                   | X                      |                               | B                     |
| R,L<br>S         | As above                                                                                                    |                                                                                       |                                  |                     |                               |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               | B                     |
| S                | Engineering: Assess effectiveness of subsidence - Resultant design of structures                            |                                                                                       |                                  |                     |                               |                                   | X                                          | X                | X                        | X                            |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               | B                     |
| L,R              | Engineering: Assess magnitude of subsidence problem above abandoned mine                                    | X                                                                                     |                                  |                     | X                             |                                   |                                            |                  |                          |                              |                                 |                                   |                                 |                          |                           |                     |                                   |                        |                               | A                     |

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R = Regulatory Agency

## 5.0 SPECIFICATIONS FOR INSTRUMENT SYSTEMS

Section 3.0 identified the ranges, accuracies, frequency of reading, station spacing, and layout for measurements relevant to mining subsidence problems. In Section 4.0, seven measurement systems were proposed which vary in sophistication and extensiveness of subsidence monitoring. Each measurement system was designed to be applicable to different user problems which are similar in nature (e.g. System A, Subsidence Detection, can be used not only by a regulatory agency to detect movement over an abandoned mine, but also by a real estate developer to determine if the mine operator is providing the support to which his land is entitled).

In this section, each measurement in each of the measurement systems is assigned an appropriate range, accuracy, frequency of reading, station spacing and layout based on the values given in Section 3.0. These specifications are presented in Table 5.1. It should be noted that System G, Visual Documentation, requires no instrumentation and no specifications for range, accuracy, or station spacing, but recommended extent and frequency of observations are presented.

Table 5.1a

Specifications "System A: Subsidence Detection"

| Measurement                                               | Range     | Accuracy                                            | Spacing<br>of<br>Monitoring<br>Points | Layout<br>of<br>Monitoring<br>Points                                                                                                                       | Frequency<br>of<br>Monitoring                                                                                                                                                                                                                                   |
|-----------------------------------------------------------|-----------|-----------------------------------------------------|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ground Surface<br>Settlement                              | 0 to 5 ft | 3rd order;<br>$\pm 0.02$ ft<br>over 1000 ft<br>line | 200 ft                                | Active Mine:<br>Line parallel to<br>direction of<br>face advance<br>over center of<br>workings<br><br>Abandoned Mine:<br>Square grid over<br>mine workings | Active Mine:<br>Weekly when face<br>within 0.7D of point;<br>then monthly until<br>1st year after under-<br>mining followed by<br>twice yearly until<br>movement stops<br><br>Abandoned Mine:<br>Monthly for first<br>year of monitoring;<br>Then twice yearly. |
| Visual Observation<br>of Ground Surface<br>and Structures | ---       | ---                                                 | ---                                   | Entire area<br>covered by<br>survey                                                                                                                        | As above                                                                                                                                                                                                                                                        |



Table 5.1b

Specifications 'System B: Structure Performance'

| Measurement                                   | Range                              | Accuracy                              | Spacing<br>of<br>Monitoring<br>Points | Layout<br>of<br>Monitoring<br>Points                                                                                 | Frequency<br>of<br>Monitoring                                                                                                                                                                                  |
|-----------------------------------------------|------------------------------------|---------------------------------------|---------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Structure Differential<br>Vertical Settlement | 0 to 1 ft                          | $\pm 0.005$ ft                        | 6 ft to<br>25 ft                      | Use 3 to 12<br>points per struc-<br>ture; also have<br>1 or 2 points<br>approximately<br>100 ft outside<br>structure | Weekly when face<br>within 0.7D of struc-<br>ture; then monthly<br>until end of first<br>year after under-<br>mining followed by<br>twice yearly until<br>movement stops.                                      |
| Structure Strain                              | 0 to 0.4%<br>of station<br>spacing | $\pm 0.02\%$ of<br>station<br>spacing | as above                              | as above                                                                                                             | as above                                                                                                                                                                                                       |
| Structure Crack<br>Movement                   | 0 to 0.2 ft                        | $\pm 0.002$ ft<br>between<br>stations | 1 ft to<br>2 ft<br>across<br>crack    | As needed;<br>4 points per<br>crack                                                                                  | Weekly after first<br>appearance of crack<br>until face beyond<br>0.7D of structure;<br>then monthly until<br>end of first year<br>after undermining<br>followed by twice<br>yearly until move-<br>ment stops. |
| Visual Observation<br>of Structure            | ---                                | ---                                   | ---                                   | Structures: Doors,<br>windows, floors,<br>interior and<br>exterior walls                                             | Weekly when face<br>within 0.7D of struc-<br>ture; then monthly<br>until end of first<br>year after under-<br>mining followed by<br>twice yearly until<br>movement stops.                                      |

Table 5.1c  
Specifications 'System C: Mine Stability'

| Measurement                | Range         | Accuracy                                     | Spacing of Monitoring Points | Layout of Monitoring Points                                     | Frequency of Monitoring                                                                                                                                  |
|----------------------------|---------------|----------------------------------------------|------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mine Prop Load             | 0 to 200 tons | $\pm 1$ ton                                  | ---                          | 1 to 2 points per 100 ft of face; 10 to 15 per panel            | Install as soon as location accessible; monitor daily for two weeks; then weekly until 2 to 3 months after movement stops or point no longer accessible. |
| Mine Rock Bolt Load        | 0 to 10 tons  | $\pm 0.05$ tons                              | ---                          | 10 to 20 per panel                                              | As above                                                                                                                                                 |
| Mine Roof Sag              | 0 to 0.5 ft   | 2nd order; or $\pm 0.01$ ft in 1000 ft line; | ---                          | 20 to 50 points per panel - for supported mines only            | As above                                                                                                                                                 |
| Mine Convergence           | 0 to 1.0 ft   | $\pm 0.01$ ft                                | ---                          | As above; for caving mines use 1 to 2 points per 100 ft of face | As above                                                                                                                                                 |
| Mine Rock Noise            | ---           | ---                                          | Not greater than 100 ft      | 4 to 10 points per pillar; 1 or 2 points per 100 ft along roof  | As above                                                                                                                                                 |
| Visual Observation of Mine | ---           | ---                                          | ---                          | Entire accessible portion of mine                               | As above                                                                                                                                                 |

Table 5.1d  
Specifications 'System D: Performance of Supported Systems'

| Measurement                                         | Range                                                   | Accuracy                                                                                                                                     | Spacing of Monitoring Points                                                         | Layout of Monitoring Points                                                                                                                                                                    | Frequency of Monitoring                                                                                                                                                         |
|-----------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ground Surface Settlement                           | 0 to 2 ft                                               | 2nd order; or $\pm 0.01$ ft over 1000 ft line<br>May be lessened to 3rd order or $\pm 0.02$ over 1000 ft line after 1 year past under-mining | 25 ft to 100 ft near face; 100 to 200 ft at a distance greater than 0.7D behind face | Line parallel to direction of face advance over center of workings; Lines parallel to face at spacing equal to 2 months face advance; Lines should extend 0.7D ahead of face and outside ribs  | Weekly when face within 0.7D; then monthly until first year after under-mining; then every 3 months to end of 2nd year at a minimum; continue twice yearly until movement stops |
| Ground Surface Horizontal Strain (Line)             | 0 to 0.2% of station spacing                            | $\pm 0.01\%$ of station spacing                                                                                                              | As above                                                                             | As above                                                                                                                                                                                       | As above                                                                                                                                                                        |
| Ground Surface Horizontal Strain Triangles          | As above for each leg of triangle                       | As above for each leg of triangle                                                                                                            | 6 to 25 ft per leg                                                                   | 5 to 10 strain triangles per panel                                                                                                                                                             | As above                                                                                                                                                                        |
| Ground Surface Tilt                                 | 0 to 1 degree                                           | $\pm 30$ sec                                                                                                                                 | 25 ft to 100 ft near face; 100 to 200 ft at a distance greater than 0.7D behind face | Line parallel to direction of face advance over center of workings; Lines parallel to face at spacings equal to 2 months face advance; Lines should extend 0.7D ahead of face and outside ribs | As above                                                                                                                                                                        |
| Visual Observation of Ground Surface and Structures | ---                                                     | ---                                                                                                                                          | ---                                                                                  | Entire area covered by surface survey                                                                                                                                                          | As above                                                                                                                                                                        |
| Subsurface Vertical Deformation                     | 0 to 2 ft in 300 ft and local discontinuities of 0.5 ft | $\pm 0.005$ ft                                                                                                                               | ---                                                                                  | 2 to 4 per panel<br>At least one over mine center and one over rib                                                                                                                             | Weekly when face within 0.7D; then monthly until end of first year after undermining; then every 3 months to end of 2nd year                                                    |
| Subsurface Horizontal Deformation                   | 0 to 2 degrees                                          | $\pm 30$ sec                                                                                                                                 | ---                                                                                  | As above                                                                                                                                                                                       | As above                                                                                                                                                                        |
| Mine Pillar Stress                                  | 0 to 5000 psi                                           | $\pm 50$ psi (relative)<br>$\pm 100$ psi (absolute)                                                                                          | ---                                                                                  | 2 to 3 per location; 5 to 10 locations per panel                                                                                                                                               | Install as soon as location accessible; Monitor daily for first two weeks; then weekly until 2 to 3 months after movement stops or until point no longer accessible             |

Table 5.1d (continued)

Specifications 'System D: Performance of Supported Systems'

| Measurement                    | Range         | Accuracy                                               | Spacing<br>of<br>Monitoring<br>Points | Layout<br>of<br>Monitoring<br>Points                                                              | Frequency<br>of<br>Monitoring |
|--------------------------------|---------------|--------------------------------------------------------|---------------------------------------|---------------------------------------------------------------------------------------------------|-------------------------------|
| Mine Roof Sag                  | 0 to 0.5 ft   | 2nd order;<br>or $\pm 0.01$ ft<br>over 1000 ft<br>line | ---                                   | 20 to 50 per<br>panel                                                                             | As above                      |
| Mine Convergence               | 0 to 1 ft     | $\pm 0.01$ ft                                          | ---                                   | As above                                                                                          | As above                      |
| Mine Prop Load                 | 0 to 200 tons | $\pm 1$ ton                                            | ---                                   | 1 to 2 per<br>100 ft of face<br>and 10 to 15<br>per panel                                         | As above                      |
| Mine Rock Bolt<br>Load         | 0 to 10 tons  | $\pm 0.05$ ton                                         | ---                                   | 10 to 20 per<br>panel                                                                             | As above                      |
| Mine Roof Strata<br>Separation | 0 to 0.5 ft   | $\pm 0.001$ ft                                         | ---                                   | 2 to 6 per location;<br>vary in penetration<br>from 5 to 50 ft; 5 to<br>10 locations per<br>panel | As above                      |
| Visual Observation<br>of Mine  | ---           | ---                                                    | ---                                   | Entire accessible<br>area of mine                                                                 | As above                      |

Table 5.1e

Specifications System E: Performance of Caving Systems

| Measurement                                         | Range                                                   | Accuracy                                                                                                                              | Spacing of Monitoring Points                                      | Layout of Monitoring Points                                                                                                                                            | Frequency of Monitoring                                                                                                                                                                                                         |
|-----------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ground Surface Settlement                           | 0 to 5 ft                                               | 2nd order; or $\pm 0.01$ ft over 1000 ft line. May be lessened by 3rd order or $\pm 0.02$ ft in 1000 ft after 1 year past undermining | 25 ft to 100 ft within 0.7D of face; 100 ft to 200 ft behind face | Line parallel to direction of face advance; Lines parallel to face at spacing equal to 2 months' face advance. Lines should extend 0.7D ahead of face and beyond ribs. | Weekly when face within 0.7D; then monthly to end of first year after undermining; then every three months to end of 2nd year past undermining; then twice yearly until movement stops                                          |
| Ground Surface Horizontal Strain (Lines)            | 0 to 0.6% of station spacing                            | $\pm 0.01\%$ of station spacing                                                                                                       | As above                                                          | As above                                                                                                                                                               | As above                                                                                                                                                                                                                        |
| Ground Surface Strain Triangles                     | As above for each leg or triangle                       | As above for each leg of triangle                                                                                                     | 6 to 25 ft per leg                                                | 5 to 10 strain triangles per panel                                                                                                                                     | As above                                                                                                                                                                                                                        |
| Ground Surface Crack Movement                       | 0 to 1 ft per crack                                     | $\pm 0.01$ ft per crack                                                                                                               | 10 ft gauge length over selected cracks                           | As needed; 4 points per crack                                                                                                                                          | Weekly after first appearance of crack until face 0.7D beyond crack. Then monthly until first year after undermining; then every three months until end of second year past undermining; then twice yearly until movement stops |
| Ground Surface Tilt                                 | 0 to 2 deg.                                             | $\pm 30$ sec                                                                                                                          | 25 ft to 100 ft within 0.7D of face; 100 to 200 ft behind face    | Line parallel to direction of face advance; Lines parallel to face at spacing equal to 2 months' face advance. Lines should extend 0.7D ahead of face and beyond ribs  | Weekly when face within 0.7D; then monthly to end of first year after undermining; then every three months to end of 2nd year past undermining; then twice yearly until movement stops                                          |
| Visual Observation of Ground Surface and Structures | ---                                                     | ---                                                                                                                                   | ---                                                               | Entire area covered by surface survey                                                                                                                                  | As above                                                                                                                                                                                                                        |
| Subsurface Vertical Deformation                     | 0 to 5 ft in 300 ft and local discontinuities of 0.5 ft | $\pm 0.005$ ft                                                                                                                        | ---                                                               | 2 to 4 per panel                                                                                                                                                       | Weekly when face within 0.7D; then monthly until end of first year after undermining; then every 3 months to end of 2nd year                                                                                                    |

Table 5.1e (continued)  
Specifications System E: Performance of Caving Systems

| Measurement                       | Range                                 | Accuracy                                            | Spacing of Monitoring Points               | Layout of Monitoring Points                                                                         | Frequency of Monitoring                                                                                                |
|-----------------------------------|---------------------------------------|-----------------------------------------------------|--------------------------------------------|-----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| Subsurface Horizontal Deformation | 0 to 5 deg.                           | $\pm 30$ sec                                        | ---                                        | As above                                                                                            | As above                                                                                                               |
| Extent of Sub-surface Fracturing  | Cube: 100 ft by 100 ft by 300 ft deep | locate within $\pm 15$ ft depth                     | 100 ft to 200 ft between boreholes minimum | Boreholes along mine center; 2 to 4 per panel                                                       | As above                                                                                                               |
| Mine Pillar Stress                | 0 to 5000 psi                         | $\pm 50$ psi (relative)<br>$\pm 100$ psi (absolute) | ---                                        | 2 to 4 per location<br>1 to 2 locations per panel in roadway pillars and in adjacent unmined panels | Weekly when face of panel or adjacent panel within 0.7D; then monthly until movement stops, point lost or inaccessible |
| Mine Prop Load                    | 0 to 200 tons                         | $\pm 1$ ton                                         | ---                                        | 1 to 2 per 100 feet of face                                                                         | Daily while accessible                                                                                                 |
| Mine Rock Bolt Load               | 0 to 10 tons                          | $\pm 0.05$ ton                                      | ---                                        | 10 to 20 per panel                                                                                  | As above                                                                                                               |
| Mine Convergence                  | 0 to 1.0 ft                           | $\pm 0.01$ ft                                       | ---                                        | 1 to 2 per 100 feet of face                                                                         | As above                                                                                                               |
| Visual Observation of Mine        | ---                                   | ---                                                 | ---                                        | Entire accessible area of mine                                                                      | As above                                                                                                               |

Table 5.1f

Specifications 'System F: Performance of Filled Mines'

| Measurement                                               | Range     | Accuracy                                                                                                                                                                   | Spacing<br>of<br>Monitoring<br>Points | Layout<br>of<br>Monitoring<br>Points                                                                     | Frequency<br>of<br>Monitoring                                                                                                   |
|-----------------------------------------------------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| Ground Surface<br>Vertical Settlement                     | 0 to 1 ft | 2nd order or<br>$\pm 0.01$ ft<br>over 1000 ft<br>line; May<br>decrease to<br>3rd order or<br>$\pm 0.02$ ft<br>over 1000 ft<br>line at end<br>of first year<br>past filling | 100 to<br>200 feet                    | Square grid<br>above area being<br>filled                                                                | Weekly during<br>filling operation;<br>then monthly to<br>end of first year<br>after filling; then<br>twice yearly as<br>needed |
| Visual Observation<br>of Ground Surface<br>and Structures | ---       | ---                                                                                                                                                                        | ---                                   | Surface above<br>entire area<br>being filled                                                             | As above                                                                                                                        |
| Subsurface Vertical<br>Deformation                        | 0 to 1 ft | $\pm 0.01$ ft                                                                                                                                                              | ---                                   | 2 to 4 over area<br>being filled                                                                         | As above                                                                                                                        |
| Mine Convergence<br>(Remote)                              | 0 to 1 ft | $\pm 0.01$ ft                                                                                                                                                              | ---                                   | For mines where<br>void accessible<br>before filling;<br>4 or more points<br>per panel or<br>filled area | As above                                                                                                                        |

Table 5.1 g

Specifications 'System G: Visual Documentation'

| Measurement                                               | Range | Accuracy | Spacing<br>of<br>Monitoring<br>Points | Layout<br>of<br>Monitoring<br>Points                  | Frequency<br>of<br>Monitoring                                                                                                                                                                                   |
|-----------------------------------------------------------|-------|----------|---------------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Visual Observation of<br>Ground Surface and<br>Structures | ---   | ---      | ---                                   | Surface above<br>entire area<br>being under-<br>mined | Weekly when face<br>within 0.70; then<br>monthly until first<br>year after under-<br>mining; then every<br>3 months to end of<br>2nd year at a mini-<br>mum; continue twice<br>yearly until move-<br>ment stops |
| Visual Observation<br>of Mine                             | ---   | ---      | ---                                   | Entire accessible<br>area of mine                     | Monitor daily for<br>first two weeks;<br>then weekly until<br>2 to 3 months after<br>movement stops or<br>until point no longer<br>accessible                                                                   |



## 6.0 INSTRUMENT CAPABILITIES

The instrumentation required to monitor subsidence effects is determined by both the needs of the user and the specifications for the intended use. A thorough review of capabilities for instruments with potential for monitoring applications was made to identify the instrument characteristics relevant to those needs and specifications. The results were summarized in tabular form and are presented in Appendix A. An example review sheet is presented in Figure 6.1.

Instruments using a variety of operating principles have been reviewed. The operating principles range from the simplicity of comparing the distance between two points with a graduated tape to the sophistication of correlating pressure with the vibrating frequency of a tensioned wire. Generally, the accuracy with which an instrument can measure subsidence effects increases with sophistication, but there is also an increase in costs, difficulty in operation, and sensitivity to environmental conditions such as temperature, humidity, and pressure. Therefore, the most efficient instruments will minimize sophistication while meeting accuracy requirements.

### 6.1 INSTRUMENT CAPABILITY INFORMATION

The summary of instrument capabilities presented in the tables of Appendix A was based on quantitative data, qualitative experience, and judgment reported in approximately 500 references from the literature, appearing in Appendices C and D of this report. Listed accuracies and sensitivities of instruments are based primarily on what the published investigators found or believed them to be. Where evaluations were lacking, representative manufacturers' hardware specifications were used. The effective accuracy of a measurement system is usually not simply the accuracy of the individual manufactured components, but also a function of the care and skill exercised in the field in fitting and installing the instrument, as well as the skill and care taken to monitor and analyze the instrument readings. Consequently, it should be understood that accuracies, sensitivities, and other instrument qualities better than those given in Tables A.1 to A.10 for any listed instrument type may be obtainable.

The values and comments in the tables reflect the experience of many authors and should indicate the capabilities of the instruments under typical, conscientious field operations. It should also be remembered that the listed instrument capabilities are a general assessment for the type of instrument capabilities are a general assessment for the type of instruments, i.e. a rod extensometer or a wire extensometer, and do not apply specifically to any individual manufacturer's product. The suppliers' attainable accuracies and other qualities may be higher or lower than the listed values judged average in our review for the instrument type as a whole. In order to simplify our review and reduce

Appendix A to manageable size, only a few representative manufacturers are named as suppliers for any instrument type. This is not to be construed as an endorsement.

## 6.2 DESCRIPTION OF INSTRUMENT CAPABILITIES

There are considerable variations in the type of measurements, range, accuracy, and operating principles of instruments potentially useful for measuring subsidence effects. Accordingly, a description of instrument capabilities must be general enough to take these variations into account and, at the same time, it must be specific enough to determine which instruments can be practically applied. The description must be comprehensive, but the number of variables must be limited so a practical evaluation can be accomplished.

In order to evaluate instrument capabilities it was decided to consider twelve variables:

1. availability
2. physical characteristics
3. data collection characteristics
4. measuring range
5. accuracy of measurement
6. sensitivity to environment
7. calibration and maintenance requirements
8. ease and cost of installation
9. ease and cost of operation
10. power requirements
11. ease and cost of data reduction
12. instrument hardware costs

Collectively, these variables were used to determine which subsidence characteristics an instrument can measure with adequate accuracy and range yet with a minimum of sophistication.

The twelve variables used are defined as follows:

1. Availability - the state of development of an instrument and the availability of the instrument from commercial manufacturers.

2. Physical characteristics - the portability of the instrument, permanence of installation, ruggedness and operating life of the installation and instrument.
3. Data collection characteristics - the readout capabilities (direct readout such as a measuring tape or remote readout such as bonded resistance strain gauge) and requirement to enter the subsidence area.
4. Measuring range - the minimum and maximum value of a measurement which an instrument (or method) can obtain. For distance measurements, the gauge length across which the measurement is made may also be listed.
5. Accuracy - the closeness to the actual value of the measurement being made (as opposed to sensitivity, which is the smallest detectable value, or precision, which is the repeatability of a measurement). Sensitivity or precision may be listed when information on accuracy was unavailable.
6. Sensitivity to environment - the effect of temperature, pressure, humidity, dust, vandalism or damage, shock, erratic power supplies, corrosion, etc., not only on the instrument, but also on the accuracy of the instrument.
7. Calibration and maintenance - the need for laboratory or field calibration and maintenance, and the ease of these adjustments if required.
8. Ease and cost of operation - the skill and training of personnel required, the equipment needed for installation, and the time required for installation.
9. Ease and cost of operation - the skill and training of personnel required, and the time required for taking measurements.
10. Power - the power required for instrument operation, which may range from none to powered vehicles and continuous high voltage electrical requirements.
11. Ease and cost of data reduction - the skill and training of personnel required, the need for auxiliary equipment and data such as computers and borehole data for correlation.
12. Instrument costs - the initial costs for instrument hardware such as detection devices, readout devices, amplifiers, cables, and replacement units.

### 6.3 CLASSIFICATION OF INSTRUMENTS FOR CAPABILITY REVIEW BY SURFACE/ SUBSURFACE/MINE-LEVEL LOCATION

To evaluate the capability of a measurement instrument, it is necessary to consider conditions under which the instrument will be installed and operated. Consequently, the study classified the instruments according to surface, subsurface or mine level applications to allow for a systematic approach to instrument evaluation. The classifications are defined as follows:

- surface: instruments installed and operated above, on, or up to 5 feet below the ground surface
- subsurface: instruments installed and operated more than 5 feet below the ground surface
- mine level instruments installed but not necessarily operated at mine level

Where an instrument has several uses, for example the microseismic method, distinctions will be made in the tables between surface, subsurface and mine level instrument characteristics.

### 6.4 TABLES OF INSTRUMENT CAPABILITIES

Over 200 instruments were reviewed initially, and subsequently, the rating system presented later in Section 7.0 was used to eliminate the least effective instruments. The approximately 100 instruments remaining were then closely examined, and their capabilities are itemized and presented in Appendix A. An example review sheet is shown in Table 6.1.

The instruments are divided into general groupings such as "Surveying Instruments" and "Extensometers." The groupings are a convenient method for organizing the tables, but they have no role in the evaluation of the instruments. More specific groupings were considered, such as using the measurement types presented in Section 3.0 as titles for the tables of instrument capabilities. However, since one instrument may be suitable for several measurements, this method of organizing the instruments would have caused significant redundancy in the tables.

TABLE 6.1 - EXAMPLE OF INSTRUMENT CAPABILITIES  
REVIEW SHEET

| INSTRUMENT                                                                                                                                                                                             | AVAILABILITY                                              | INSTRUMENT CHARACTERISTICS  | DATA COLLECTION CHARACTERISTICS |                   | RANGE                                                         | ACCURACY                                                               | SENSITIVITY TO ENVIRONMENT                                                                 | CALIBRATION AND MAINTENANCE                                  | EASE/COST OF INSTALLATION               | EASE/COST OF OPERATION                                                                         | POWER REQUIREMENTS                    | EASE/COST OF DATA REDUCTION                                              | COST OF INSTRUMENT                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|-----------------------------|---------------------------------|-------------------|---------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------------|---------------------------------------|--------------------------------------------------------------------------|----------------------------------------------|
|                                                                                                                                                                                                        |                                                           |                             | REMOTE OR DIRECT                | ENTER SOURCE AREA |                                                               |                                                                        |                                                                                            |                                                              |                                         |                                                                                                |                                       |                                                                          |                                              |
| Steel tape<br><br>(structure and surface strain, surface and structure crack movement)                                                                                                                 | Lufkin; Chesterman; Keuffel & Esser                       | Portable, rugged, long life | Direct                          | Yes               | 100 ft usually; available in 3 to 200 ft lengths              | ±0.01 ft                                                               | Temperature; wind; tension                                                                 | Periodically clean, oil, and calibrate against standard tape | Install reference points                | 2 tapemen plus 1 man to set stakes; use with tensioning device, taping pins, plumbbob          | None                                  | Simple                                                                   | 100 ft: \$30 to \$100                        |
| Invar tape<br><br>(structure and surface strain, surface and structure crack movement)                                                                                                                 | Keuffel & Esser                                           | Portable, prone to breaking | Direct                          | Yes               | 50 ft to 100 ft                                               | ±0.005 ft                                                              | Wind; tension                                                                              | Clean periodically                                           | As above                                | 2 tapemen; use with tension frames and weights; for high accuracy repeat readings with 3 tapes | None                                  | Simple                                                                   | 100 ft: \$300<br>150 ft: \$400               |
| Spirit level with wood rod<br><br>(structure and surface settlement, mine convergence and roof sag)                                                                                                    | Kern; Keuffel & Esser; Wild; Eagle, David White; Jenoptik | Portable, rugged, long life | Direct                          | Yes               | Maximum change in elevation between sights approx. 13 ft      | ±0.01 to ±0.03 ft for single reading; 0.05 to 0.1 ft over mile circuit | Temperature, wind; moisture; lessen sensitivity to temperature and moisture with invar rod | Check telescope alignment annually                           | Install reference points and benchmarks | 1 instrument man; 1 rod man                                                                    | None                                  | Simple; need 1 engineer; may use computer to reduce large volume of data | Level: \$100 to \$750;<br>rod: \$60 to \$300 |
| Precision level (automatic or tilting with optical micrometer) with invar rod<br><br>(structure and surface settlement, with tape or tape extensometer for ground tilt, mine convergence and roof sag) | Jenoptik, Kern; Wild, Leitz; Zeiss                        | As above                    | Direct                          | Yes               | As above; sight length greater than 7 ft and less than 150 ft | ±0.002 ft to ±0.005 ft over mile circuit                               | Wind; bright sunlight                                                                      | As above                                                     | As above                                | As above                                                                                       | None                                  | As above                                                                 | Level: \$850 to \$1500;<br>rod: \$700        |
| Rotating beam laser with rod detector<br><br>(surface settlement; mine roof sag)                                                                                                                       | AGA; DeLong; MG Laser Systems; Laser Alignment            | Portable                    | Direct                          | Yes               | 500 ft                                                        | Less than 200 ft; ±0.006 ft; 200 to 1000 ft: ±0.01 ft                  | Affected by vibration, fog, dust, smog, air turbulence, wind                               | Check beam alignment annually                                | Install reference points and benchmarks | 1 man operates rod and sets up laser                                                           | Rechargeable battery for 1 day's work | As above                                                                 |                                              |

NOTE: The complete tables of instrument capabilities are presented in Appendix A.



## 7.0 INSTRUMENT SELECTION

In Sections 1.0 through 5.0, six measurement systems capable of multiple applications are developed. Each system includes several measurements and specifications for each measurement. In this section, one or more instruments are selected for each system. The instruments will be appropriate for the potential applications of the system, perform the needed measurements, and satisfy the specifications set out for the measurements.

### 7.1 INSTRUMENT RATING

In Appendix A the capabilities of over 100 instruments are tabulated. Some of the instruments described measure a single type of deformation or stress while other are capable of monitoring several subsidence-induced movements.

In order to compare the many instruments, a rating system was developed to quantify the relative merits of each instrument. The instruments are rated on a scale of 0 to 3 in each of the categories that were used for evaluation in Section 6. A summary of the criteria used to rate the instruments is given in Table 7.1. The ratings for any instrument depend on its intended application. For example, an instrument that measures mine convergence, i.e. a tape extensometer, was rated for use in four different measurement systems, but was found to be the most capable instrument for measuring mine convergence in only three of the systems.

An assumed typical layout of observation points was established for each measurement in each application system (Table 7.2). This typical layout provided a basis for estimating instrument hardware costs, man-hours of operation, required instrument gauge length and achievable accuracy of the instrument.

The spacing of points used in the typical layout was determined from the specifications given in Section 5.0. For example, the layout selected for evaluation of ground surface settlements in System A was a 1000-ft line with monitoring points at 100-ft intervals. For structure crack monitoring, the study assumed a structure with a crack monitored in two places by instruments with a 6-in. to 18-in. gauge length.

The evaluation categories defined in Section 6.0 examined the general qualities of an instrument and the appropriateness of that instrument for the intended application. Simple criteria were used to quantify the comments in Tables A.1 through A.10. For example, for "Availability", an instrument would score "0" if it is developmental and "3" if many manufacturers make it. The scoring system for range and accuracy compares the instrument range and accuracy with the specifications cited in Section 5. For example, if the accuracy of an

RATING SYSTEM  
Table 7.1

| EVALUATION CATEGORY             | 0                                                                                                                                        | 1                                                                                                                                                | 2                                                                                                                  | 3                                                                             |
|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Availability                    | Not available; developmental                                                                                                             | User-fabricated                                                                                                                                  | Available from 1 or manufacturers.                                                                                 | Commonly available                                                            |
| Instrument Characteristics      | Operating life less than 6 mos. Permanent installation. Not recoverable.                                                                 | Operating life more than 6 mos. Portions of system recoverable. Most of system permanent for monitoring period.                                  | Operating life more than 1 year. Moderately rugged. Significant parts of instrument portable.                      | Operating life more than 1 year. Portable except for simple reference points. |
| Data Collection Characteristics | Must enter subsidence area to read. Sensor not visible.                                                                                  | Must enter subsidence area to read.                                                                                                              | Can be read outside subsidence area.                                                                               | Can send signal long distance.                                                |
| Range and Gauge length          | Less than 25% of desired range. Gauge length less than 25% of desired spacing.                                                           | 25% to 75% of desired range and gauge length.                                                                                                    | Within 75% of desired range and gauge length, or resettable to desired range.                                      | Range equal to or better than desired. Gauge length equal to desired.         |
| Accuracy                        | More than ten times worse than desired accuracy.                                                                                         | Between 2 and 10 times worse than desired accuracy.                                                                                              | Less than desired accuracy but no more than 2 times worse.                                                         | Accuracy equal to or better than desired.                                     |
| Sensitivity to Environment      | Very sensitive to temperature pressure and humidity; not water resistant; very vulnerable to accidental damage, shock, corrosion, creep. | Sensitive to temperature and pressure<br>-or-<br>Sensitive to temperature and vulnerable to electrical problems.<br>-or-<br>vulnerable to damage | Moderately sensitive to temperature and pressure; not very vulnerable to damage; can operate in moist environment. | Small temperature correction required. Resistant to moisture, damage.         |
| Calibration and Maintenance     | Sensor cannot be replaced or repaired if it fails.                                                                                       | Requires frequent laboratory calibration. Repairs expensive if required.                                                                         | Requires field calibration with dummy gauge; repairs expensive if required.                                        | Requires annual calibration. Simple maintenance.                              |
| Ease/Cost of Installation       | Deep borehole (>10 ft.) or drillhole (>20 ft.) required.                                                                                 | Shallow borehole or drillhole required. More than 1 man-day.                                                                                     | Requires simple tools; 2 to 8 man-hours.                                                                           | Less than 2 man-hours.                                                        |



RATING SYSTEM  
Table 7.1 (continued)

| EVALUATION CATEGORY                                                                                                                                                                                                               | 0                                                          | 1                                                                                                                                 | 2                                                                                                                                   | 3                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Ease/Cost of Operation                                                                                                                                                                                                            | 2-4 men highly trained; sophisticated recording equipment. | 1 man highly trained; many instrument set-ups; -or- 2-4 men moderate training; multiple set-ups -or- remote operation by computer | 1 man moderate training; few instrument set-ups; -or- 2-4 men; simple training; few instrument set-ups -or- remote electrical alarm | 1 man - simple training. |
| Power                                                                                                                                                                                                                             | Continuous power required -or- non-portable generator      | Portable battery; will operate at least 1 day                                                                                     | Portable battery; good for several weeks without recharging                                                                         | No power                 |
| Ease/Cost of Data Reduction                                                                                                                                                                                                       | Computer required                                          | Computer may be helpful. Data from other lab or field tests needed                                                                | 1 engineer with hand calculator                                                                                                     | Simple                   |
| No. of Applications of Instrument in Measurement System                                                                                                                                                                           | 1                                                          | 2                                                                                                                                 | 3                                                                                                                                   | 4 or more                |
| Cost of Instrument Hardware:<br>Extent of Subsurface Fracturing<br>Mine Rock Noise                                                                                                                                                | More than \$100,000                                        | \$50,000 to \$100,000                                                                                                             | \$10,000 to \$50,000                                                                                                                | Less than \$10,000       |
| Ground Surface Tilt<br>Subsurface Horiz. Deformation<br>Subsurface Vertical Deformation<br>Mine Pillar Stress<br>Mine Prop Load<br>Mine Convergence<br>Mine Roof Sag<br>Ground Surface Vertical Settlement<br>Mine Rock Bolt Load | More than \$20,000                                         | \$5,000 to \$20,000                                                                                                               | \$2,000 to \$5,000                                                                                                                  | Less than \$2,000        |

RATING SYSTEM  
TABLE 7.1 (continued)

| EVALUATION CATEGORY                                                                                                                                                                                   | 0                  | 1                   | 2                  | 3                 |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------------------|--------------------|-------------------|
| Cost of Instrument<br>Hardware: (cont'd)                                                                                                                                                              |                    |                     |                    |                   |
| Ground Surface<br>Horiz. Strain<br>Ground Crack Movement<br>Ground Surface Strain<br>Triangles<br>Mine Roof Strata<br>Separation<br>Structure Differential<br>Vertical Settlement<br>Structure Strain | More than \$10,000 | \$3,000 to \$10,000 | \$1,000 to \$3,000 | Less than \$1,000 |
| Structure Crack<br>Movement                                                                                                                                                                           | More than \$3,000  | \$1,000 to \$3,000  | \$500 to \$1,000   | Less than \$500   |

TABLE 7.2  
TYPICAL LAYOUT USED TO CALCULATE COSTS FOR  
MATRIX OF INSTRUMENT CAPABILITIES

| M E A S U R E M E N T                      | T Y P I C A L L A Y O U T                                                       |
|--------------------------------------------|---------------------------------------------------------------------------------|
| Ground Surface Settlement                  | 1000 ft line; 100 ft gauge length                                               |
| Ground Surface Strain                      | 500 ft line; 100 ft gauge length                                                |
| Ground Surface Horizontal Strain Triangles | 2 triangles; 10 ft gauge length on each leg of a triangle                       |
| Ground Surface Crack Movement              | 5 cracks each instrumented in 2 placed; 6 ft to 25 ft gauge length across crack |
| Ground Tilt                                | 1000 ft line; 100 ft c/c                                                        |
| Structure Differential Vertical Settlement | 90 ft long bldg.; 10 ft to 15 ft c/c                                            |
| Structure Strains                          | 90 ft long bldg.; 10 ft to 15 ft c/c                                            |
| Structure Crack Movement                   | 1 crack monitored in 2 places; 1 ft to 2 ft gauge length across crack           |
| Subsurface Vertical Deformation            | 6 or more points in borehole 300 ft deep                                        |
| Subsurface Horizontal Deformation          | 6 or more points in borehole 300 ft deep                                        |
| Extent of Subsurface Fracturing            | Area 500 ft x 500 ft by 500 ft deep                                             |
| Mine Pillar Stress                         | 1 point; 20 ft inside pillar                                                    |
| Mine Prop Load                             | 10 stations                                                                     |
| Mine Rock Bolt Load                        | 10 instrumented rock bolts                                                      |
| Mine Roof Strata Separation                | 6 anchors in drillhole to 50 ft deep                                            |
| Mine Roof Sag                              | 1000 ft line; 100 ft c/c                                                        |
| Mine Convergence                           | 11 stations                                                                     |
| Mine Rock Noise                            | 2 pillars with 5 monitoring points each                                         |

instrument was equal to or better than that specified, it gets a "3". If the accuracy is ten times worse than specified, the instrument scores "0" in the accuracy category. The accuracy of many instruments depends on the gauge length; so the accuracy used for rating must be consistent with the typical layout of monitoring points described previously.

The rating system also ranked relative costs of instrument hardware. The cost of the hardware was based on the typical layout of monitoring points. Where reference points were needed, a cost of \$100 per surface reference point and \$50 per structure reference point was assumed unless otherwise indicated. Because costs differ widely among the various measurements, a scale of costs was developed for each measurement. For example, for subsurface horizontal deflection measurements, a cost in excess of \$20,000 gets a "0". For structure crack monitoring, a cost over \$3,000 scores "0".

In addition to the rating categories used to evaluate instruments in Appendix A, one rating category was added in this Section: "Number of Applications of Instrument in Measurement System". This category was added to emphasize the versatility of some instruments; selection of such instruments can reduce the hardware costs and training required to implement use of the Measurement System.

## 7.2 WEIGHTING OF EVALUATION CATEGORIES

The categories used to evaluate instruments are not all equally important. The weighting system developed to reflect priorities in instrument selection outlined in the contract is as follows:

| <u>Weight</u> | <u>Relative Importance</u>       |
|---------------|----------------------------------|
| 3             | Critical to Instrument Selection |
| 2             | Important but not Critical       |
| 1             | Should be Considered             |

The contract emphasized low cost and ease of installation and operation, while meeting the basic measurement requirements of range and accuracy. Accordingly, these four categories received a weight of 3. A weight of "1" was assigned to "data collection characteristics", which assessed the need to enter the subsidence area and the capability of the instrument to be adapted to remote electronic data processing systems. This parameter is not vital to subsidence monitoring over coal mines although it may be a convenience for the instrument user. The remaining categories each received a weight of "2".

### 7.3 MATRIX OF INSTRUMENT CAPABILITIES (MIC)

The instruments were rated as discussed in Section 7.1 for each measurement in each system where they were considered applicable. The rating tables are presented in Appendix B and an example is shown in Table 7.3. These tables form the Matrix of Instrument Capabilities. The rating in each category was multiplied by the appropriate weight factor and the products were totalled for each instrument. The instruments with the highest totals were considered to meet the measurement specifications most efficiently and the final instrument selection was restricted to these instruments. The instruments which were finally selected are summarized in Table 7.4.

The MIC may also be useful to subsidence investigators with priorities different from those outlined in this Section. In this case, the investigator can select the matrices for the relevant measurements and apply new weighting factors to the ratings shown in the MICs. The revised totals will then identify the appropriate instruments which reflect his priorities.

TABLE 7.3  
EXAMPLE SHEET FROM  
MATRIX OF INSTRUMENT CAPABILITIES

|                                                                                                 | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>VERTICAL SETTLEMENT                                                           | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level with wood rod                                                                      | 66               | 3            | 3                             | 1                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 3                  | 0                                |
| Precision Level with Invar rod                                                                  | 68               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| Rotating Beam Laser Level<br>with rod detector                                                  | 55               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 1     | 2                              | 1                  | 0                                |
| Theodolite with wood rod<br>(as level)                                                          | 66               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| Theodolite and Stadia Rod                                                                       | 60               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| EDM Tachymeter<br>(portable reflectors)                                                         | 54               | 2            | 3                             | 1                                  | 3     | 3        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 0                                |
| S.P. Simple Hose Manometer                                                                      | 62               | 2            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                                                  | 49               | 2            | 1                             | 2                                  | 1     | 2        | 1                             | 2                              | 1                            | 3                         | 2     | 2                              | 2                  | 0                                |
| S.P. Overflow type Manometer                                                                    | 58               | 3            | 1                             | 2                                  | 1     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Overflow type Manometer                                                                    | 62               | 2            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Two Liquid Pressure Balance<br>Manometer                                                   | 54               | 1            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| F.P. Air Balloon in Liquid Filled<br>Tube Settlement Device                                     | 46               | 2            | 1                             | 2                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Borehole inclinometer with<br>Servo-accelerometer torpedo<br>(horiz. casing in trench)     | 47               | 3            | 2                             | 1                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| M.P. Borehole inclinometer with<br>fixed Electrolytic levels<br>(horiz. casing in trench)       | 39               | 1            | 1                             | 2                                  | 3     | 0        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| S.P. Borehole Ext., Wire Type Weight<br>Anchored, Weight Tensioned with<br>Rotary Potentiometer | 44               | 2            | 0                             | 2                                  | 3     | 3        | 1                             | 2                              | 0                            | 2                         | 2     | 2                              | 1                  | 0                                |
| Ground Elevation Cart                                                                           | 39               | 0            | 3                             | 1                                  | 3     | 1        | 1                             | 2                              | 2                            | 2                         | 1     | 0                              | 0                  | 0                                |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

NOTE: Refer to Appendix B for complete  
Matrix of Instrument Capabilities

TABLE 7.4  
INSTRUMENTS SELECTED FOR MEASUREMENT SYSTEMS

| MEASUREMENT<br>SYSTEM                        | SYSTEM A:<br>SUBSIDENCE<br>DETECTION | SYSTEM B:<br>STRUCTURE<br>PERFORMANCE | SYSTEM C:<br>MINE STABILITY   | SYSTEM D:<br>PERFORMANCE OF<br>SUPPORTED SYSTEMS     | SYSTEM E:<br>PERFORMANCE OF<br>CAVING SYSTEMS        | SYSTEM F:<br>PERFORMANCE OF<br>FILLED MINES           |
|----------------------------------------------|--------------------------------------|---------------------------------------|-------------------------------|------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------|
| Ground Surface Vertical Settlement           | Precision Level                      | -                                     | -                             | Precision Level                                      | Precision Level                                      | Precision Level                                       |
| Ground Surface Horizontal Strain (Lines)     | -                                    | -                                     | -                             | Steel Tape Extensometer                              | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Horizontal Strain (Triangles) | -                                    | -                                     | -                             | Steel Tape Extensometer                              | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Crack Movement                | -                                    | -                                     | -                             | -                                                    | Steel Tape Extensometer                              | -                                                     |
| Ground Surface Till                          | -                                    | -                                     | -                             | Precision Level With Steel Tape or Tape Extensometer | Precision Level With Steel Tape or Tape Extensometer | -                                                     |
| Structure Differential Vertical Settlement   | -                                    | Precision Level                       | -                             | -                                                    | -                                                    | -                                                     |
| Structure Strain                             | -                                    | Rod Extensometer with Micrometer      | -                             | -                                                    | -                                                    | -                                                     |
| Structure Crack Movement                     | -                                    | Dial Indicator Strain Gauge           | -                             | -                                                    | -                                                    | -                                                     |
| Subsurface Vertical Deformation              | -                                    | -                                     | -                             | FPBX with Electro-magnetic Torpedo                   | FPBX with Electro-magnetic Torpedo                   | FPBX with Electro-magnetic Torpedo                    |
| Subsurface Horizontal Deformation            | -                                    | -                                     | -                             | FPBI with Servo Accelerometer Torpedo                | FPBI with Servo Accelerometer Torpedo                | -                                                     |
| Extent of Subsurface Fracturing              | -                                    | -                                     | -                             | -                                                    | Microseismic, with headphones                        | -                                                     |
| Mine Level Roof Sag                          | -                                    | -                                     | Precision Level               | Precision Level                                      | -                                                    | -                                                     |
| Mine Level Convergence                       | -                                    | -                                     | Steel Tape Extensometer       | Steel Tape Extensometer                              | Steel Tape Extensometer                              | Rod Extensometer with Spring tensioned vibrating wire |
| Mine Level Roof Strata Separation            | -                                    | -                                     | -                             | MPBX, Rod Type, with Dial Gauge                      | -                                                    | -                                                     |
| Mine Level Prop Load                         | -                                    | -                                     | Hydraulic Load Cell           | Hydraulic Load Cell                                  | Hydraulic Load Cell                                  | -                                                     |
| Mine Level Rock Bolt Load                    | -                                    | -                                     | Elastic Disc Load Cell        | Elastic Disc Load Cell                               | Elastic Disc Load Cell                               | -                                                     |
| Mine Level Pillar Stress (Absolute)          | -                                    | -                                     | -                             | USBH Borehole Deformation Gauge                      | USBH Borehole Deformation Gauge                      | -                                                     |
| Mine Level Pillar Stress (Relative)          | -                                    | -                                     | -                             | Encapsulated Flat Borehole Pressure Cell             | Encapsulated Flat Borehole Pressure Cell             | -                                                     |
| Mine Level Rock Noise                        | -                                    | -                                     | Microseismic, with headphones | -                                                    | -                                                    | -                                                     |

KEY: FPBX = Full Profile Borehole Extensometer; MPBX = Multi-Point Borehole Extensometer; FPBI = Full Profile Borehole Inclinator

125

125

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## 8.0 DESCRIPTION OF INSTRUMENT SYSTEMS AND RECOMMENDED INSTRUMENTATION

This section presents brief summaries of the composition and objectives of the recommended instrument systems. The instruments selected for the systems are then defined in design, specification and operational detail.

### 8.1 DESCRIPTION OF INSTRUMENT SYSTEMS

#### 8.1.1 System A, Subsidence Detection

For a general overview of the magnitude of subsidence and its effects, the questions that need to be answered include: when does subsidence begin, when is it complete, and how severe is the problem? It has been shown in discussions on subsidence characteristics that a good indicator of the rate and magnitude of the subsidence phenomena is the measurement of ground surface vertical settlement.

##### • Instruments Comprising Measurement System A

Precision Level

#### 8.1.2 System B, Structure Performance

Damage to undermined surface structures is often the most visible and dramatic evidence of subsidence, and can be costly for both the surface owner and the mine operator. The use of the precision level was found to be an effective means for monitoring the differential vertical movements of structures. A long-base, portable rod extensometer equipped with a micrometer readout was selected for this system for investigating structural strain. For monitoring strain at critical connections or monitoring deformations across a cracked section, a short-base dial indicator strain gauge was determined to be most effective for this system.

##### • Instruments Comprising Measurement System B

Precision Level

Rod Extensometer with Micrometer

Dial Indicator Strain Gauge

#### 8.1.3 System C, Mine Stability

Mine stability was identified as an important measurement area to maintain effective subsidence control. Uncontrolled mine level movements can lead to excessive surface subsidence and damage to surface facilities as well as to the mine itself. The response of the overburden in adjusting to the disturbances caused by mining can be observed in mine level measurements of roof sag, convergence, prop loads, and roof bolt

stresses. Timely reaction to excessive rates of deformation of loading can help avoid damaging subsidence effects both at the surface and at mine level. Most of the recommended measurements have been widely employed in mines, except perhaps the rock noise monitoring. Nevertheless, the latter measurement has been found to have significant value in warning of impending instability in tunneling or mining large underground openings, and it is recommended for monitoring stability in mines.

• Instruments Comprising Measurement System C

Precision Level

Steel Tape Extensometer

Hydraulic Load Cell (for props)

Microseismic Detector, with headphones

Elastic Disc and Dial Gauge Load Cell (for rock bolts)

8.1.4 System D, Performance of Supported Systems

Supported systems are generally used where there is a need to control subsidence at ground level to some tolerable limit, both during active undermining and for the long term afterward. Because of the long-term stability requirement, the monitoring program outlined in this system goes beyond the immediate objectives of System C, which is concerned with mine stability during active mining only.

This system examines not only mine stability parameters, but also the level of stress in the pillar supports and the response of the overlying strata and ground surface to the mining operation. All of the instrumentation recommended for this system has seen practical, successful field use.

In preliminary studies of capabilities of instruments for the ground surface measurements required for this system, a tape extensometer appeared to be a strong candidate for the ground surface horizontal strain measurements. However, the final instrument rating matrix (MIC) selected the somewhat simpler invar tape used with conventional survey techniques. Nevertheless, based on reviewer's experience in precision taping between ground surface monuments on sloping ground, it is believed that the tape extensometer may produce better consistency and accuracy in monitoring ground surface horizontal strain. Since the tape extensometer is already required in this system for measuring mine convergence, it is recommended that the monuments used to monitor ground surface strain be constructed so that they may also be used with the tape extensometer. Then, an initial trial monitoring comparison can be made between the two instruments, using the same ground monuments.

It is worth mentioning that the use of single point tilt stations, employing a portable, mechanical tilt meter, seemed attractive for tilt measurements for this measurement system early in the study, though there was concern about whether single point tilt meter readings would

be detrimentally affected by local changes in geology. However, in the final evaluation, the precision level used in conjunction with a tape was selected over the single point tilt meters. It is interesting to note that the single station tilt meter loses some in rating of availability, but loses considerably in the category, "Number of Applications in System", because the level and tape are already needed for other measurements within the system. It may thus be seen that the category, "Number of Applications in System", strongly emphasizes multiple use instruments in the selection procedure.

In the selection of the instrument for the measurement of subsurface vertical deformations, the instrument with the highest total in the MIC was not chosen for use in this system. Project personnel have had experience in installation of all of the four top rated instruments in the MIC for subsidence vertical deformation. It was felt that in-house experience with each instrument should override the broadly-based, generalized scoring of the matrix when the point spread in the MIC totals was very close. The matrix rating criteria definitely did their intended job in identifying leading candidate instruments, but the selection of the best instrument from among the tightly grouped top four cannot depend only on a 4 point spread. It was felt that wire-type extensometers, the instrument with the highest score, have shown serious limitations in borehole installations, characterized by interference between multiple wires, down-hole friction effects and problems with the readout head guides which may mask anchor movements. Because of the simplicity of installation and lowest cost, plus good past accuracy achieved under various field conditions, the full profile borehole extensometer with electromagnetic torpedo was selected for this system.

● Instruments Comprising Measurement System D

Precision Level

Invar Tape

Full Profile Borehole Extensometer (FPBX)  
with Electromagnetic Torpedo

Full Profile Borehole Inclinator (FPBI)  
with Servo Accelerometer Torpedo

Multiple Point Borehole Extensometer (MPBX)  
Rod Type with Dial Gauge

Hydraulic Load Cell (for props)

USBM Borehole Deformation Gauge

Encapsulated Flat Borehole Pressure Cell

Elastic Disc and Dial Gauge Load Cell (for rock bolts)

8.1.5 System E, Performance of Caving Systems

The use of mining methods employing caving implies higher tolerance for some of the subsidence effects at the surface, such as total vertical settlement, but other subsidence effects such as horizontal and vertical ground surface strain gradients might have to be carefully controlled

to avoid damaging surface structures which can otherwise be subsided. Almost all the same measurement capabilities recommended for System D, which monitors performance of supported systems, are repeated for caving systems. However, specifications for certain measurements may permit lower accuracies and higher measurement ranges for caving systems.

- Instruments Comprising Measurement System E

- Precision Level
- Invar Tape
- Full Profile Borehole Extensometer (FPBX)
  - with Electromagnetic Torpedo
- Full Profile Borehole Inclinator (FPBI)
  - with Servo Accelerometer Torpedo
- Hydraulic Load Cell (for props)
- USBM Borehole Deformation
- Encapsulated Flat Borehole Pressure Cell
- Microseismic Noise Detector, with earphones
- Elastic Disc and Dial Gauge Load Cell (for rock bolts)

#### 8.1.6 System F, Performance of Filled Mines

Monitoring the performance of filled mines requires instruments at surface, subsurface and mine level which have high sensitivity and accuracy, but which may have relatively small range. The process of filling abandoned mines is costly and merits careful instrumentation. The only instrument required in this system not previously mentioned in this section is a rod extensometer, equipped with a spring-tensioned vibrating wire sensor, installed in the mine opening and provided with a remote readout capability.

- Instruments Comprising Measurement System F

- Precision Level
- Full Profile Borehole Extensometer (FPBX)
  - with Electromagnetic Torpedo
- Rod Extensometer, equipped with Spring-Tensioned Vibrating Wire Sensor in Telescoping Casing

#### 8.1.7 System G, Visual Documentation

Visual observation of subsidence effects is the most basic measurement which can be made, and documentation of visual observations may be introduced as legal evidence in proceedings related to subsidence. Visual documentation such as photographs, assessor's reports, and diaries are valuable documentation of damage due to subsidence. As with all measurements, visual documentation should begin well in advance of the mining to detail deformations unrelated to subsidence.

At mine level, visual observation by experienced personnel is generally a routine procedure, not only to optimize the production effort but also to promote safety. Documentation of these observations should include a chronological log of underground activities as well as a detailed geologic examination of the roof, wall, and floor strata.

There are no instruments required in this measurement system. However, the field engineer should carry with him a field notebook, a handlevel, a plumbob, and a geologists's hammer.

## 8.2 DESCRIPTIONS OF SELECTED INSTRUMENTS

The following instruments, specified for the recommended Measurement Systems defined earlier, are described in detail in this section.

- Precision Level
- Rod Extensometer with Micrometer
- Dial Indicator Strain Gauge
- Steel Tape Extensometer
- Full Profile Borehole Extensometer (FPBX) with Electromagnetic Torpedo
- Full Profile Borehole Inclinator (FPBI) with Servo-Accelerometer Torpedo
- Microseismic Monitor with Headphones
- Multiple Point Borehole Extensometer (MPBX) Rod Type with Dial Gauge
- Rod Extensometer with Spring-Tensioned Vibrating Wire Sensor
- Hydraulic Load Cell (prop loads)
- U.S.B.M. Borehole Deformation Gauge
- Flat Encapsulated Borehole Pressure Cell
- Elastic Disc and Dial Gauge Load Cell (rock bolt loads)

### 8.2.1 Precision Level

This instrument was selected to measure ground surface vertical settlement and tilt, structure differential vertical settlement and mine level roof sag.

8.2.1.1 Description of Equipment - A precision level is an optical telescope generally used to determine relative elevations between two points. A rod graduated to 0.01 ft is held vertically on the point of interest and sighted through the telescope. The height intercepted by a hairline on the telescope is noted. This height may be read to 0.0001 ft by using the optical micrometer on the level. Absolute elevations can be calculated if such sightings are referenced to a sighting on a benchmark. A benchmark is a permanent observation point located outside the zone of subsidence.

A precision level circuit requires carefully designed and installed monuments for each observation point and for each benchmark. It is good practice to employ more than one benchmark in each monitoring circuit.

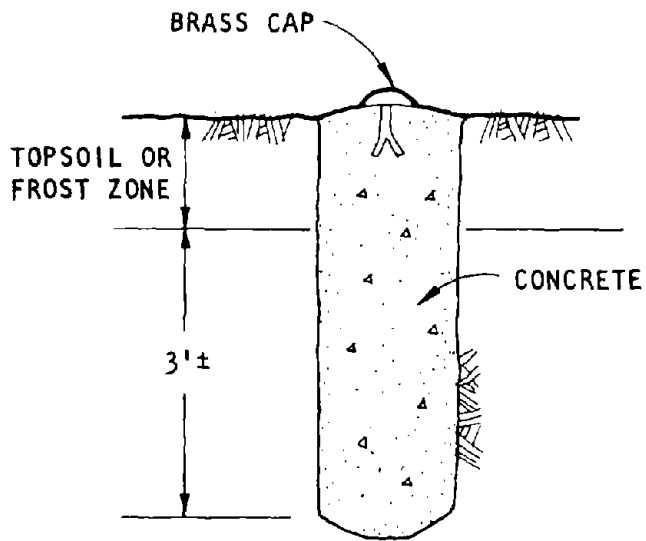
8.2.1.2 Method of Installation - A suitable benchmark is constructed by drilling a hole through the topsoil to several feet below the seasonal frost zone, backfilling the hole with concrete, and setting a domed brass cap in the top of the concrete (see Figure 8.1(a)). Where the depth of loose topsoil is considerable, or where the depth of the active frost zone is deep, the benchmark installation shown in Figure 8.1(b) should be used. In this design, a steel pipe is set in concrete over the length of the hole below the loose or frost zone, and is protected from contact with the overlying unstable soils by a larger diameter plastic pipe sleeve. A precast concrete valve cover box is set over the pipe benchmark flush with the ground surface for protection.

Simpler arrangements such as metal pipes or rods driven several feet into the ground, or paint marks on rock outcrops or structures may be used for observation points. All observation points should be protected from damage and clearly marked.

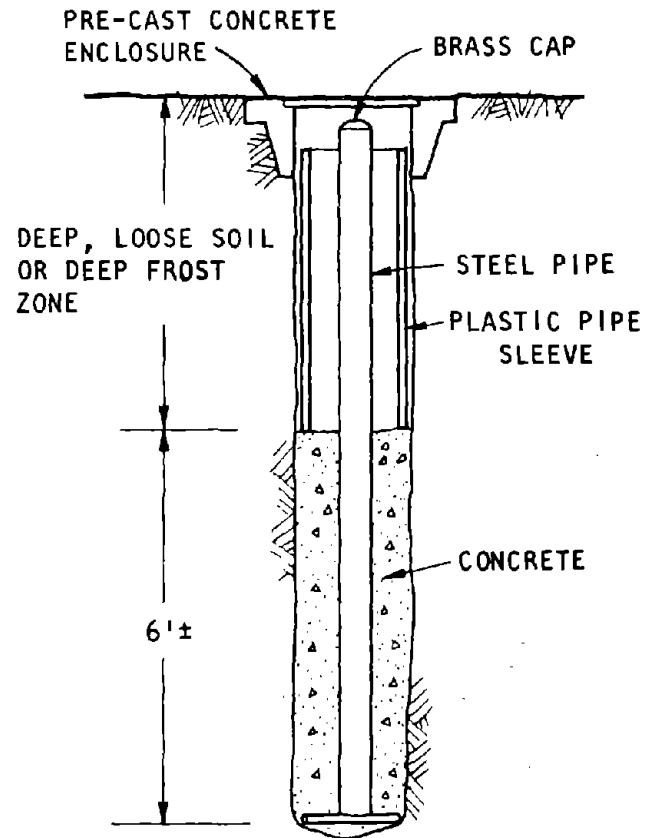
8.2.1.3 Method of Observation - The micrometer on the precision level eliminates the necessity for the instrument man to estimate by eye the distance between graduations on the leveling rod. A typical level micrometer may subdivide the distance between graduations to precisely 100 parts. For example (Moffitt, 1975), in Figure 8.1(c),

"The position of the horizontal line of sight on the rod is between 4.83 and 4.84 ft, and the micrometer drum reads zero. When the micrometer drum is turned and the plano-parallel element is rotated so that the line of sight is lowered to the 4.83-ft rod graduation, the micrometer drum reads 37. This reading means that the line of sight has been lowered  $37/100$  of 0.01 ft, or 0.0037 ft. The rod reading is therefore 4.8337 ft."

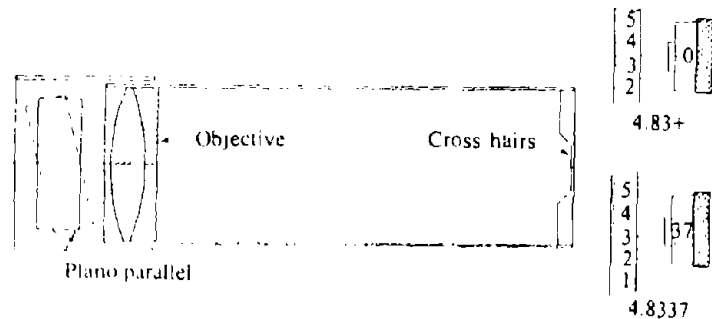
The complete procedure for running level circuits is beyond the scope of this section, and the reader is referred to the reference given in the example. Generally, successful leveling requires personnel with moderate training and regular practice at the task.



(a) SHALLOW BENCHMARK FOR LEVELING



(b) DEEP BENCHMARK FOR LEVELING



(c) OPTICAL MICROMETER PRINCIPLE USED FOR PRECISION LEVEL (Moffitt, 1975)

Figure 8.1 - PRECISION LEVEL: DETAILS OF BENCHMARKS AND OPTICAL MICROMETER

## 8.2.2 Rod Extensometer with Micrometer

This instrument was selected to measure structure strain.

8.2.2.1 Description of Equipment - The rod extensometer with micrometer is a long-base strain measurement device. A suitable model based on an available Building Research Station (BRS) design is shown in Figure 8.2. The extensometer is comprised of a 2 inch x 2 inch aluminum box beam section, fitted with a drum micrometer at one end. At each end, the beam is fitted with a stainless steel plate drilled to seat on a spherical head reference point.

Each reference point is a portable 1-inch diameter spherical head machined on a stainless steel extension rod tapped at the base. The reference point seats on an anchored stainless steel cone with a threaded stud. This cone is permanently installed and generally recessed for protection. The threaded connections between the base of the extension rod and the top of the anchor have tapered conical mating surfaces to provide positive repeatable seating, as shown in Figure 8.2b.

The reference point assembly is proposed for use in either vertical or horizontal orientations. The existing BRS design details the beam for monitoring horizontal ground movement only. For monitoring horizontal strain in vertical walls, the BRS plans must be modified to include side slots in the extensometer box section to permit entry of horizontal extension rods below the top stainless steel plates and different anchor details, as described in the next section.

8.2.2.2 Method of Installation - The permanent part of the reference point assembly, the threaded stainless steel cone, should be anchored to the structure as follows. Assuming a completed structure, the nominal gauge length of the beam is marked on the structure. For concrete structures the anchor will consist of a rebar threaded to receive a tapped cone. The rebar will have a washer screwed on to act as a grout stop. A 3-inch diameter and 6-inch deep hole is drilled into the concrete surface and is packed with a stiff sand-cement grout. The washer-rebar anchor is then pressed into the grout. For steel structures, the anchor consists of a flat steel plate with a threaded stud and the plate is welded directly to the steel surface. The next step in either case is to thread the stainless steel cone to the anchor assembly, using a "Lok-Tite" bolt compound to make the connection semi-permanent. A protective cover or enclosure is recommended over the cone to prevent mechanical damage or accumulation of dirt.

8.2.2.3 Method of Observation - Covers are removed from two anchor cones, and the cone surfaces are cleaned. The extension rods are screwed down onto the cone's threaded stud by hand until positive contact of the machined taper is felt. The beam is carefully lowered so that the appropriate socket position in the extensometer's multi-hole stainless steel plate seats on one of the extension rods. Then



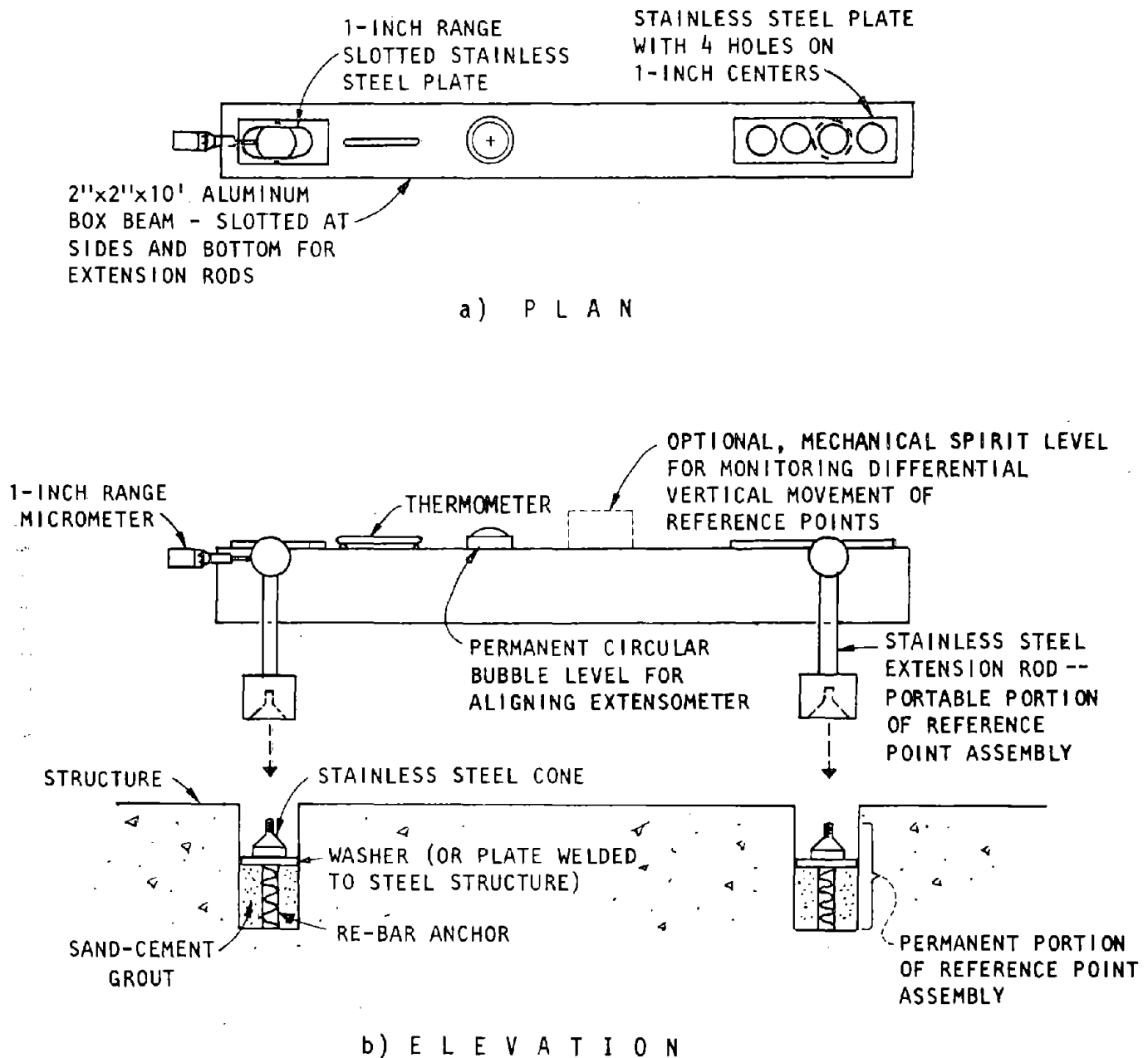


Figure 8.2 - ROD EXTENSOMETER WITH MICROMETER  
(after Burland and Moore, 1973)

the other end of the beam with the slotted stainless steel plate is carefully lowered onto the other extension rod. A circular bubble level on the extensometer is used to orient the upper surface of the extensometer. The micrometer is adjusted until it makes contact with the spherical head of the extension rod. A small, battery operated lamp may be wired between the micrometer body and the stainless steel plate. Thus, when the micrometer just touches the extension rod head, the lamp circuit is closed and the lamp lights. Each time a micrometer reading is taken, the thermometer on the top of the extensometer should be read and the temperature recorded. The change in micrometer readings from the initial reading to subsequent readings is corrected for thermal expansion or contraction of the nominal gauge length between socket and slot due to temperature difference between the readings. Structural strain is the corrected micrometer difference divided by the original gauge length.

When the limit of the micrometer stroke is reached, the next adjacent socket of the multi-hole stainless steel plate of the extensometer is used to extend the micrometer range.

A mechanical spirit level instrument may be added to the extensometer to measure the differential vertical movement of the reference points as shown in Figure 8.2b.

### 8.2.3 Tape Extensometer

This instrument was selected to measure ground surface strain and tilt and mine level convergence.

8.2.3.1 Description of Instrument - The tape extensometer is a precision-tensioned, distance measuring instrument. Basically, all tape extensometer models employ a tensioning device with which a constant, repeatable tension may be applied to the tape between measuring points, and a precision displacement sensor to measure the distance between the temporary fastening point of the tape and the reference point of the extensometer. The model shown in Figure 8.3 has a mechanical adjusting screw for tensioning the tape between anchor points, a proving ring and a dial gauge combination to sense the amount of tension being transferred to the tape by the screw, and a separate dial gauge to measure the change in distance between the reference point of the instrument and the punched hole of the tape. The standard tape is punched with a small diameter hole every one or two inches, depending on the range of the dial gauge measuring distance changes. The extensometer has one ball socket fixed to the main frame; the other moveable ball socket is fixed to the leading end of the tape. The ball sockets are designed to seat on spherical reference points machined on rods. If the rod is not permanently installed, it should be machined with a conical taper and female thread as shown in Figure 8.3. The tape extensometer may be used without modification to measure distances transverse to the axis of the reference rods, as shown in Figure 8.3, and distances coaxial with the rods, as shown in Figure 8.4.

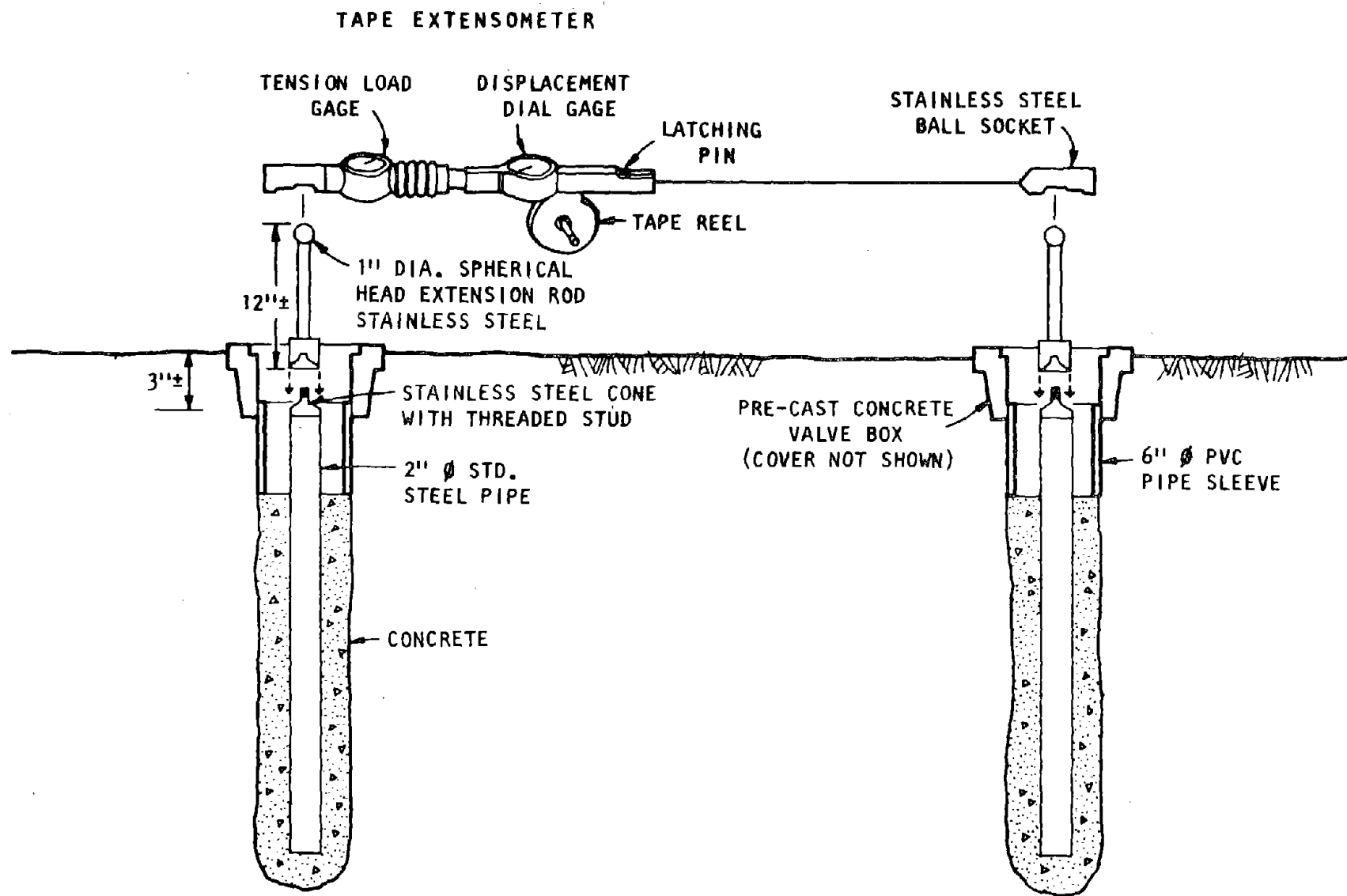
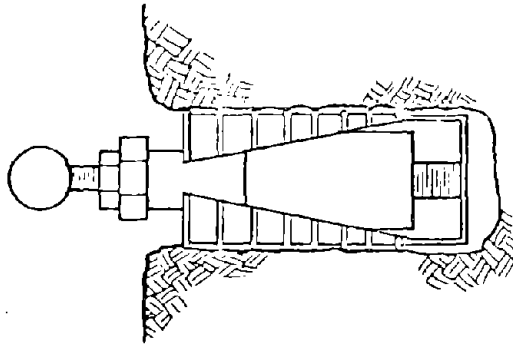
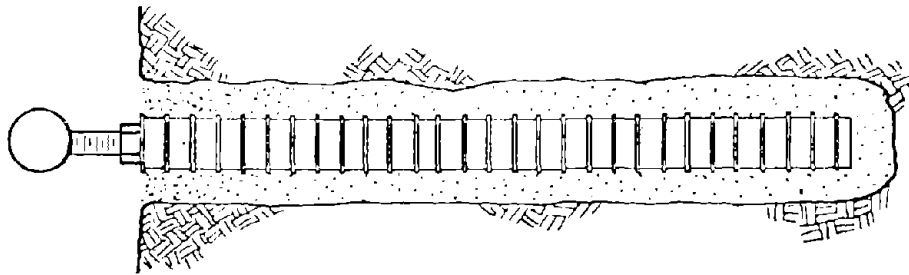


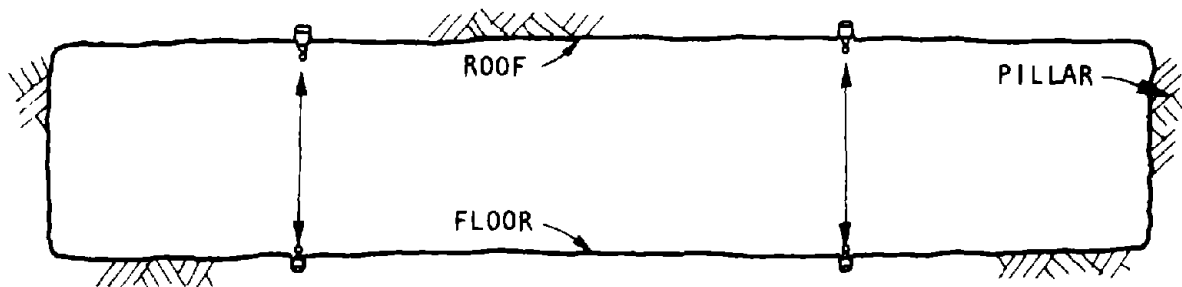
Figure 8.3 - SURFACE MEASUREMENTS WITH TAPE EXTENSOMETER



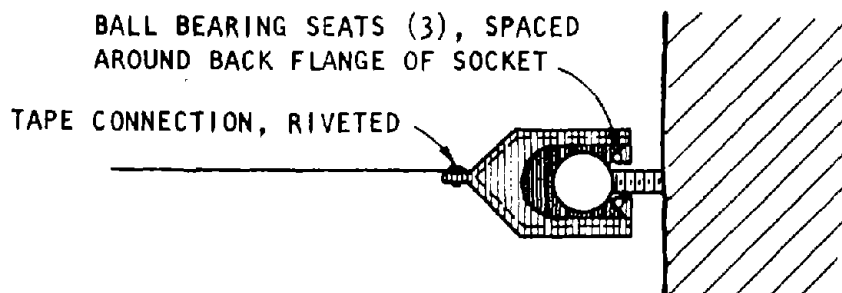
(a) REFERENCE POINT: EXPANDING ROCK ANCHOR BOLT DRILLED & TAPPED  
(after Sinco)



(b) REFERENCE POINT: 3/4" DIA. x 24" REBAR DRILLED & TAPPED  
GROUTED IN PLACE (after Sinco)



(c) MINE CONVERGENCE MEASUREMENTS



(d) TAPE EXTENSOMETER BALL SOCKET SEATING DETAIL FOR  
CONVERGENCE MEASUREMENT

8.2.3.2 Method of Installation - Several different types of reference points may be used. For ground surface deformation measurements, steel monument pipes are set in concrete in shallow auger holes as shown in Figure 8.3. The upper part of the monument pipe is sleeved through the frost zone, or top three feet of ground, with a larger diameter plastic pipe. The plastic pipe shields the monument from seasonal and shallow-seated surface disturbance. The top of the monument is recessed below ground surface and further protected with a recessed concrete casting and cover, such as used for water valves. The top of each monument pipe is fitted with a permanent, stainless steel cone. The cone has a threaded stud for attaching temporary extension rods used to make measurements between monuments. The top of the threaded stud has a polished surface so that the monuments can also be used for geodetic leveling.

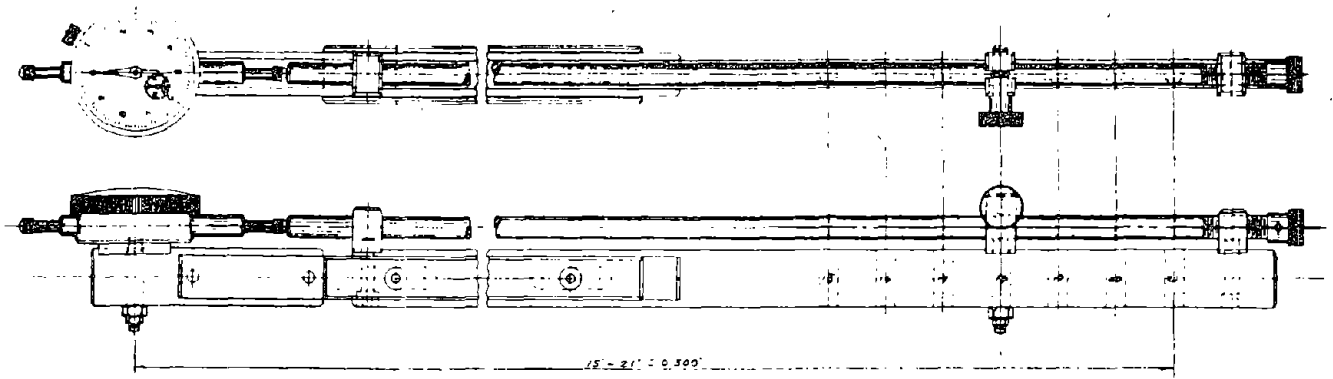
For mine convergence, the spherical-head reference monuments are permanently set in shallow drill holes in mine roof, floor and pillar walls with mechanical or grouted anchors, as shown in Figure 8.4.

8.2.3.3 Method of Observation - For ground surface measurements, extension rods are screwed down on the monument cone, so that the rod seats firmly on the monument cone. The moveable ball socket of the tape extensometer is placed on the spherical head of one extension rod, and the tape is played out of the reel as the tape extensometer is walked over to the other monument, where its fixed ball socket is placed on the extension rod. The nearest punch hole in the tape is fixed to the extensometer with a latching pin. Tension is then applied to the tape by turning a knurled ring on the extensometer until the proving ring dial gauge indicates the tape is at the specified tension. The reading on the displacement dial gauge is then subtracted from the tape reading at the fixed punch mark to obtain the distance between monuments. Unless an invar tape is used with the extensometer, temperature measurements should be made at each reading and appropriate corrections applied to the data.

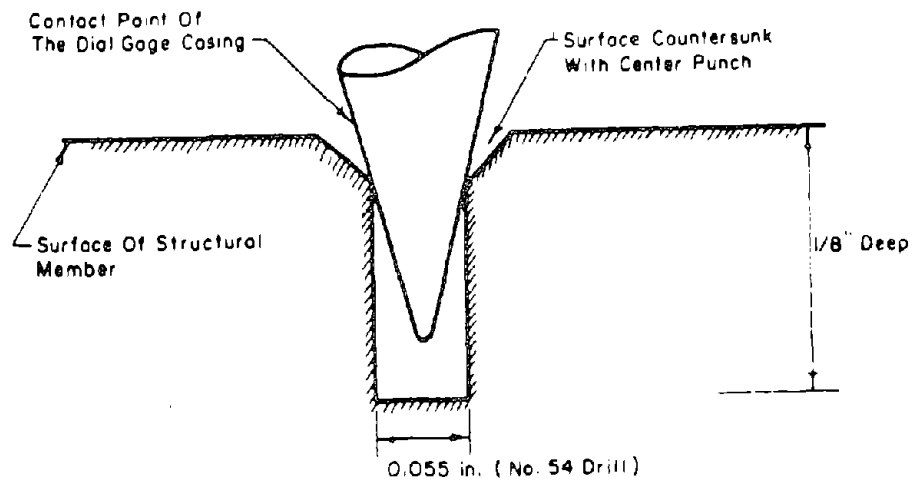
#### 8.2.4 Dial Indicator Mechanical Strain Gauge

This instrument was selected to measure structure crack movement.

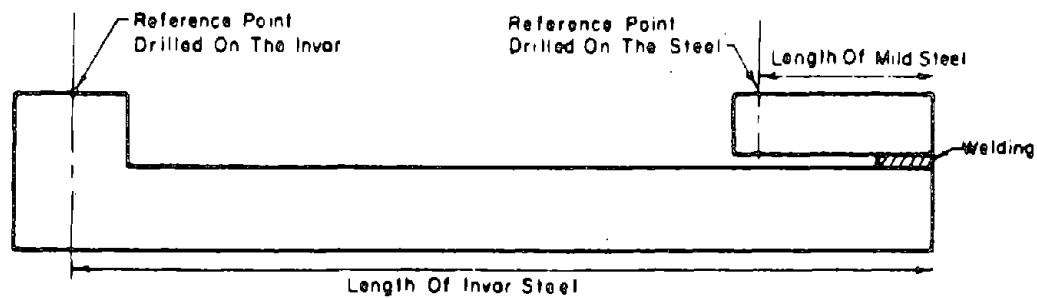
8.2.4.1 Description of Equipment - The Dial Indicator Mechanical Strain Gauge is a portable, hand-held device with which small changes in 2-inch to 80-inch gauge lengths can be precisely measured. The length changes are observed on a dial indicator after the contact points of the gauge are positioned at reference points on the monitored structure. For subsidence applications, the body of a suitable strain gauge typically consists of two telescoping tubes. On the outside end of each tube an extension arm carrying a contact point is rigidly connected; see Figure 8.5(a). A dial indicator is fixed to one tube, and its sensing stem indicates the relative position of the other telescoping tube when the gauge is positioned over the reference points. Larger ranges of measurement are possible



(a) SCHEMATIC SECTION OF DIAL INDICATOR STRAIN GAUGE  
(after Structural Behavior Engineering Laboratories, Inc.)



(b) REFERENCE POINT DETAIL (Cording, 1975)



Note: Lengths of invar and of steel are inversely proportional to their respective linear coefficient of thermal expansion; thus the separation of the reference points does not vary with temperature.

(c) TEMPERATURE COMPENSATED STANDARD BAR (Cording, 1975)

Figure 8.5 - DIAL INDICATOR MECHANICAL STRAIN GAUGE DETAILS

with this type of gauge than are generally possible with other hinged or flexible, cantilevered arm types.

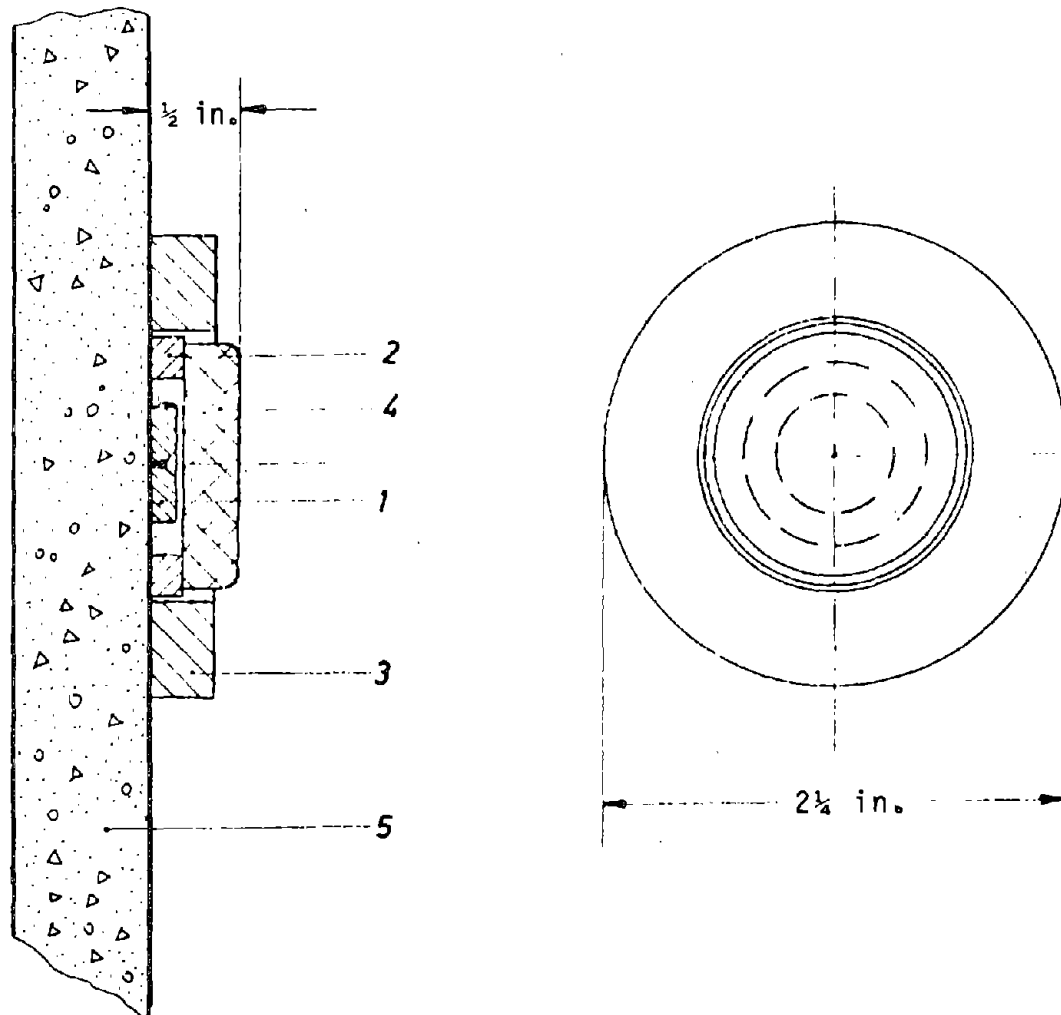
The reference points for concrete structures may be corrosion-resistant metal dowels set flush to the surface by direct embedment during construction or by grouting in holes drilled into the finished concrete. The reference points are then precision-drilled to receive conical or spherical contact points of the strain gauge. Similar reference points may be rigidly attached to surfaces of steel structures, or the structure itself may be drilled to receive directly the conical or spherical contact point of the strain gauge.

8.2.4.2 Method of Installation - Pairs of reference points are installed at selected monitoring points on the structure. The reference points must be easily accessible and convenient to the gauge operator, for the careful placing and reading of the gauge on the points. Corrosion-resistant metal dowels may be set flush to concrete surfaces by direct embedment or drilling and grouting. Shallow corrosion-resistant metal markers may be affixed by welding, brazing, or epoxy cement to the surfaces of steel structures. In the case of steel structures, the structure may be drilled and punched directly, though the reference point must then be protected from corrosion.

The holes for one of the typical mechanical gauges, the Whittemore gauge, are 1/8 in. deep and are made with a standard No. 54 drill. The holes are then counter sunk with a 90° center angle conical punch. This forms a cylindrical edge upon which the measuring arm points, which have 30° conical points, can rest; see Figure 8.5(b). The punching action also serves to strain harden the surface where the measuring arm point and the side of the reference hole touch.

The key to maintaining reference points from damage or the elements lies in providing some sort of protective cover. A workable arrangement devised by Interfels is shown in Figure 8.6. Two nickel-plated steel washers of unequal thickness are fixed onto the surface of the structure concentric to the reference point. A disc-shaped magnet fits inside the outer washer and adheres to the face of the inner washer, covering the reference point. The arrangement keeps dust and dirt out of the reference point and protects it from mechanical damage.

8.2.4.3 Method of Observation - Accuracies with the dial indicator strain gauge depend to a large extent on the care and experience of the operator with the device. The reference point holes should be inspected for damage and cleaned thoroughly before each reading. The contact points are pressed into the reference points with a force of about 1 lb. The pressure is then decreased to an amount at which the user, according to experience, obtains the best repeatability. At the time of making a measurement on a structure, the gauge should be checked for instrumental error or drift by making a measurement on a standard reference bar. See Figure 8.5(c) for a detail of a reference bar that is temperature compensated, i.e. the gauge length remains



KEY :

- 1 - REFERENCE POINT
- 2 - INNER PROTECTIVE WASHER
- 3 - OUTER PROTECTIVE WASHER
- 4 - PROTECTIVE MAGNETIC DISC
- 5 - STRUCTURE

Figure 8.6 - PROTECTIVE COVERS FOR REFERENCE POINTS  
(after Interfels)



constant irrespective of ambient temperature change. Both gauge and reference bar must be given time to reach their own equilibrium temperatures at the site ambient temperature before making the reference measurement and the measurement on the structure.

The difference between the reading on the reference bar and the reading on the structure is recorded and compared with the original difference, or datum. After correcting for structure strain over the gauge length due to temperature difference from the datum temperature, the remaining change in differences is the structural strain due to subsidence movements.

#### 8.2.5 Full Profile Borehole Extensometer with Electromagnetic Torpedo

This instrument was selected to measure subsurface vertical deformation.

8.2.5.1 Description of Instrument - This instrument is also known as an induction probe extensometer. The torpedo or probe detects the location of wire rings fixed around a flexible borehole casing which deforms along with the subsurface ground movements. As the torpedo passes through a wire ring an inductive coupling between ring and torpedo is achieved and an electrical signal is transmitted to the surface.

The induction probe is fabricated of plastic, usually about 2 inches in diameter and about 8 inches long. The electronics are waterproofed by encapsulating them in the probe and the probe is attached in a waterproofed manner to a strain-resistant electric cable. The cable may itself be distance graduated, or it may be attached to a surveying tape. The probe is lowered into the borehole casing from a portable cable reel. The end of the cable is connected to a battery-operated ammeter and to a buzzer built into the reel.

Borehole casing suitable for use with the induction probe extensometer is fabricated of corrugated plastic, which is highly elastic in the axial direction and very rigid in the radial direction (Figure 8.7). These properties make it easy for the casing to deform with vertical settlements or extensions of the ground while resisting the inward lateral pressures of the ground. Where the casing is required for passage of the induction probe only, it may have a diameter of about 1 1/2 or 2 inches. However, the same borehole may be used for both the induction probe extensometer and the full profile borehole inclinometer (FPBI) discussed in Section 8.2.6. In that case, a 3-inch inside diameter corrugated plastic casing is available for use with 2 3/4-inch outside diameter slotted plastic casing for the FPBI. Stainless steel wire rings are secured about the corrugated casing at selected increments of length. The rings serve as the monitoring points for vertical movements after the casing is installed and keyed to the borehole wall.

8.2.5.2 Description of Related Equipment - A level is required to determine the elevation of the top of the casing at each reading. When that elevation is known, the absolute elevation of each marker ring may be calculated from the distance readings of the probe.

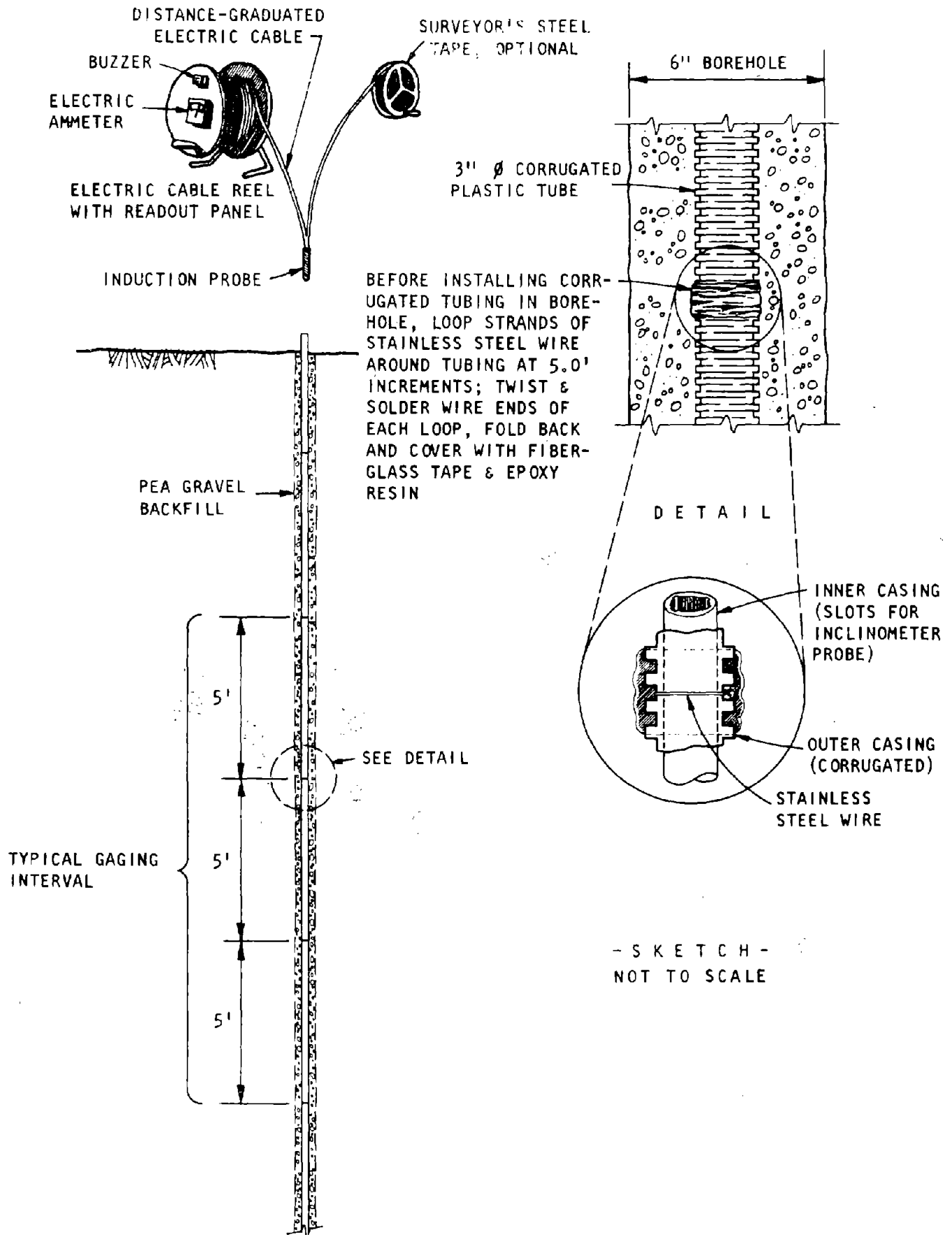


Figure 8.7 - COMBINED BOREHOLE INSTALLATION FOR INDUCTION PROBE EXTENSOMETER AND SERVO-ACCELEROMETER INCLINOMETER

8.2.5.3 Method of Installation - A borehole of 6 inch nominal diameter must be drilled for the installation of 3" O.D. casing. The use of drilling mud should be avoided if possible, or the borehole should be washed thoroughly after drilling and just before installing the extensometer/inclinometer casing.

For deep installations, it is convenient to make up twenty foot sections of casing on the ground. Inclinometer casing is ordered with flush, square shoulder, lap joints. The lap joint is secured with four pop-rivets spaced around the joint. The outer, corrugated plastic casing is joined with a special short segment of split-corrugated casing. The split section is lapped onto the casing lengths to be joined, and is secured with at least two nylon ties, such as are used in harnessing electric cables. The twenty-foot sections are hoisted onto the drill rig mast and then lowered incrementally into the borehole. A screen may be placed over the lower end to keep out debris but to allow fluid to rise within the casing, avoiding buoyancy. After the casing has been lowered to its full depth, pea gravel is hand backfilled into the annular space between the outer casing and the borehole wall.

If this installation is used in conjunction with a FPBI, or if additional resistance to lateral pressures are required in deep, squeezing ground, then an additional inner casing will be installed.

8.2.5.4 Method of Observation - To obtain readings in the finished installation, the induction probe is lowered into the inner casing to the bottom of the hole (Figure 8.7). The probe is then slowly raised by winding the cable onto its reel. As the probe reaches a marker ring, an audio/visual signal is observed on the reel's readout panel, and the distance between the probe and the top of the installation is recorded. The distance may be read from the probe's distance-graduated cable, or for higher required accuracy, from a surveyor's steel tape independently attached to the probe. The absolute elevation of each ring is calculated from the surveyed elevation of the top of the casing. The variation of the absolute elevation of a marker ring with time indicates the subsurface vertical displacement at that point.

#### 8.2.6 Full Profile Borehole Inclinometer with Servo-Accelerometer Torpedo

This instrument was selected to measure subsurface horizontal deformation.

8.2.6.1 Description of Instrument - The inclinometer, shown in Figure 8.8, consists of 1) a field-assembled casing of plastic pipe lengths joined with flush shoulder, riveted lap joints and installed in a borehole; 2) a portable electrical, torpedo-shaped probe which rides on three pairs of guide wheels (Figure 8.9) and contains internal force-balance accelerometers which sense the angle of inclination of the probe from vertical; and 3) a battery-powered, digital readout set connected by a distance-graduated electrical cable to the probe. The probe shown measures tilt along two orthogonal axes in the plane perpendicular to its axis.

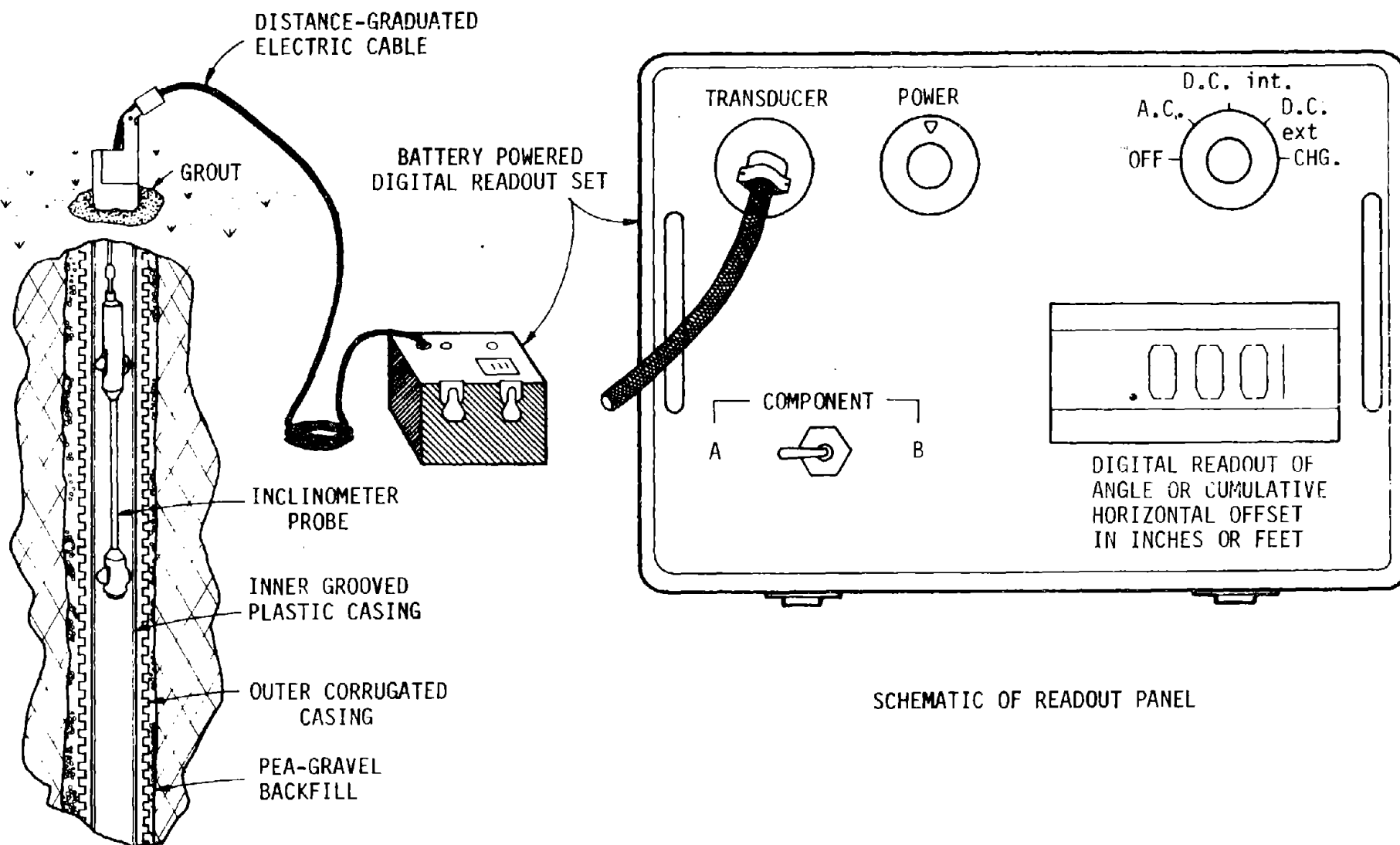


Figure 8.8 - INCLINOMETER PROBE FOR SUBSURFACE HORIZONTAL DEFORMATION MEASUREMENTS  
(after Sinco)

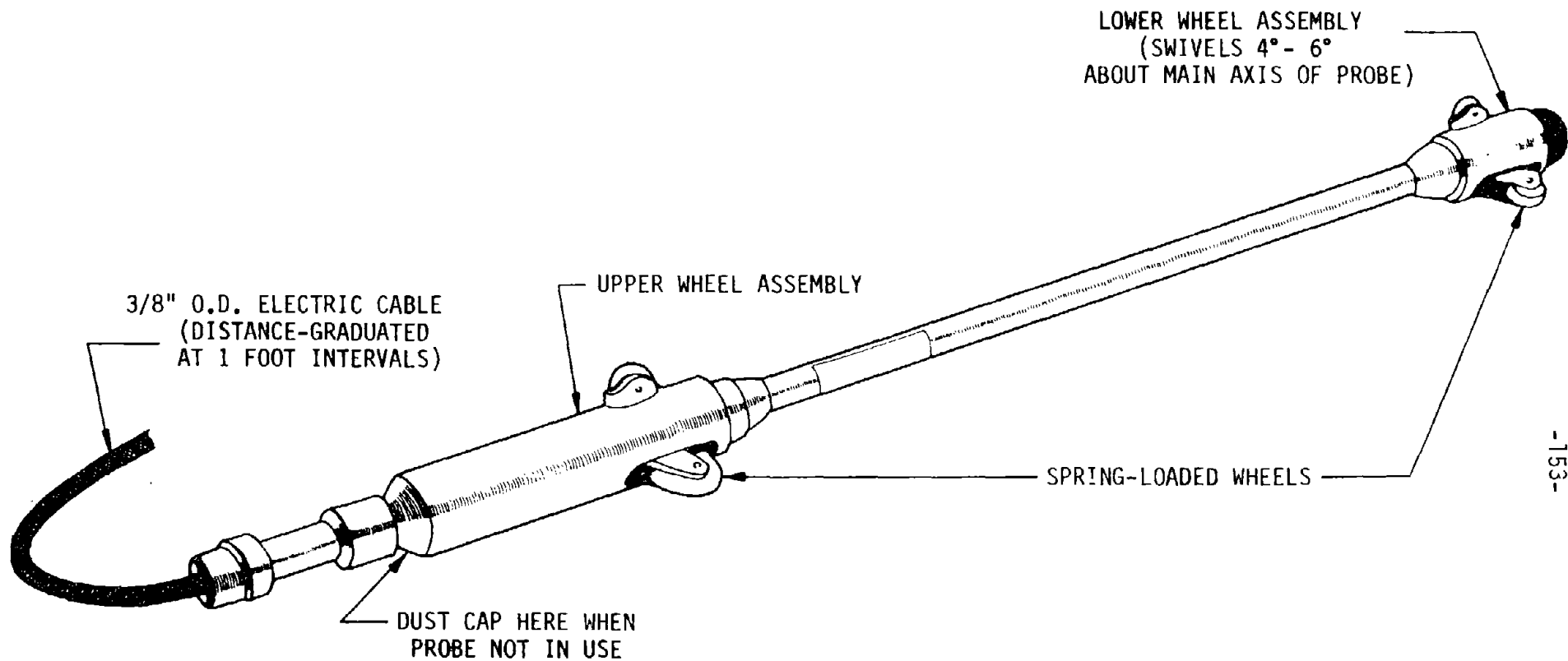


Figure 8.9 - INCLINOMETER PROBE DETAILS  
(after Sinco)

The inclinometer casing has 4 slots at 90 degree intervals around its inside perimeter, as shown in Figure 8.7. One 180-degree set of slots is typically installed parallel to the expected plane of maximum horizontal movement. The casing is installed inside an outer, corrugated plastic casing as shown in Figure 8.7.

8.2.6.2 Method of Installation - Refer to the procedure for borehole installation of a combined induction probe extensometer and inclinometer probe.

8.2.6.3 Method of Observation - To measure horizontal displacements, the portable probe, shown in Figure 8.9 is connected to an electrical cable and lowered to the bottom of the inner casing where it is allowed to reach a uniform temperature. Then it is incrementally winched up the casing, stopping at two-foot intervals for readings. The probe's internal electrical force-balance accelerometers produce electrical signals at the readout that are proportional to the angle of tilt of the torpedo. A series of calculations are needed to convert the recorded electrical measurements to horizontal displacement.

#### 8.2.7 Microseismic Monitor with Headphones

This instrument was selected to monitor mine level rock noise and extent of subsurface fracturing.

8.2.7.1 Description of Equipment - The microseismic monitor consists of a geophone probe, an amplifier, and earphones. One type of geophone contains cantilevered, piezoelectric crystals within the geophone probe which respond to movement caused by rock noises and produce a current flow. A battery-powered amplifier raises the output of the geophone to a level which can be monitored by earphones. Most of the field work up to now has been done with earphone systems, though significant development is taking place in the use of automatic recorders, equipped with filters to suppress extraneous background noise signals.

Microseisms are produced by grain fracturing and slippage in soil or rock formations. When subsidence deformations occur, zones subject to high stresses will emit detectable microseisms before large deformations occur. Thus, the microseismic method can detect both zones of active subsidence and potential subsidence zones subject to high stress.

In general, detection of microseismic activity is most favorable in hard, brittle rock formations, but a number of field users report successes in sedimentary formations including coal, shale and sandstone. Other field users have reported difficulties in monitoring microseismic activity in soft rock formations. Difficulties may lie in effective coupling of the geophone to the formations. This problem can be overcome; for example, monitoring of even soil microseisms has been carried out by embedding steel rods called waveform guides in an earth-fill, and placing the geophone on the end of the rod outside the fill.

#### 8.2.7.2 Method of Installation

(i) Installation for Monitoring from Ground Surface - Subsurface micro-seismic monitoring may be carried out in boreholes. The boreholes are drilled from ground surface at 100 ft to 600 ft spacings to the selected depth within the area expected to be subsided. The boreholes should be drilled at an angle so that the geophone will rest on the side of the borehole and improve the contact between the geophone and rock. Boreholes should not approach closer than 20 ft to the mine roof.

For an installation where geophones are removed after each reading, no further preliminary work is needed if the borehole is stable and water-tight. However, if these conditions are not met, steel casing may be installed in the borehole and sealed at the bottom with grout. The casing may then be filled with water. A protective cover should be provided over the borehole in either case. Typical installations are shown on Figure 8.10(a).

For the permanent installation shown in Figure 8.10(b), geophones may be permanently grouted in-place at selected depths in the borehole. This will provide better repeatability and better coupling of the geophone to the rock. Borehole reaches between geophones and their grout envelopes are backfilled with acoustic-insulating material. A layer of tamped clay or sand between the insulation and the grout may be required to provide a seal against grout intrusion. Cable ends from the geophones may be left coiled at the top of the hole in a protective enclosure.

(ii) Installation for Monitoring at Mine Level - Mine level monitoring is generally carried out in drillholes. Geophone installation may be either permanent or temporary. Minimum 1 1/2-inch diameter drill holes in the surfaces of the mined opening are required for geophone monitoring. Depths as short as 6 ft have been used; however rock fracturing and stress adjustment have been observed up to 15 ft or 20 ft outside 7 ft x 5 ft adits. Probably a 15 ft monitoring depth would be most suitable for subsidence-related monitoring purposes. Drill holes must be absolutely clean of cuttings so that the weight of the geophone against the clean borehole wall will provide adequate coupling to detect micro-seismic events. Horizontal holes may have to be washed and air-cleaned only once, but down-holes may have to be cleaned regularly. Drill holes should be fitted with protective covers.

8.2.7.3 Method of Observation - The basic mode of monitoring is to count the number of rock-pops, or microseisms, over a 15 minute listening period. This data is recorded and provides the basic index of subsidence activity. Rapidly increasing rates of microseisms would be indicative of rapidly increasing fracturing. If sufficient monitoring stations are available, it may be possible to contour between points of equal micro-seismic activity and hence locate a focus of microseismic activity, or at least broadly delineate the area of active subsidence. Figure 8.11 shows an example of monitoring for locating the center of microseismic activity at a block caving mine (Oudenhoven and Tipton, 1973); here the analysis technique used was computer-assisted triangulation of the

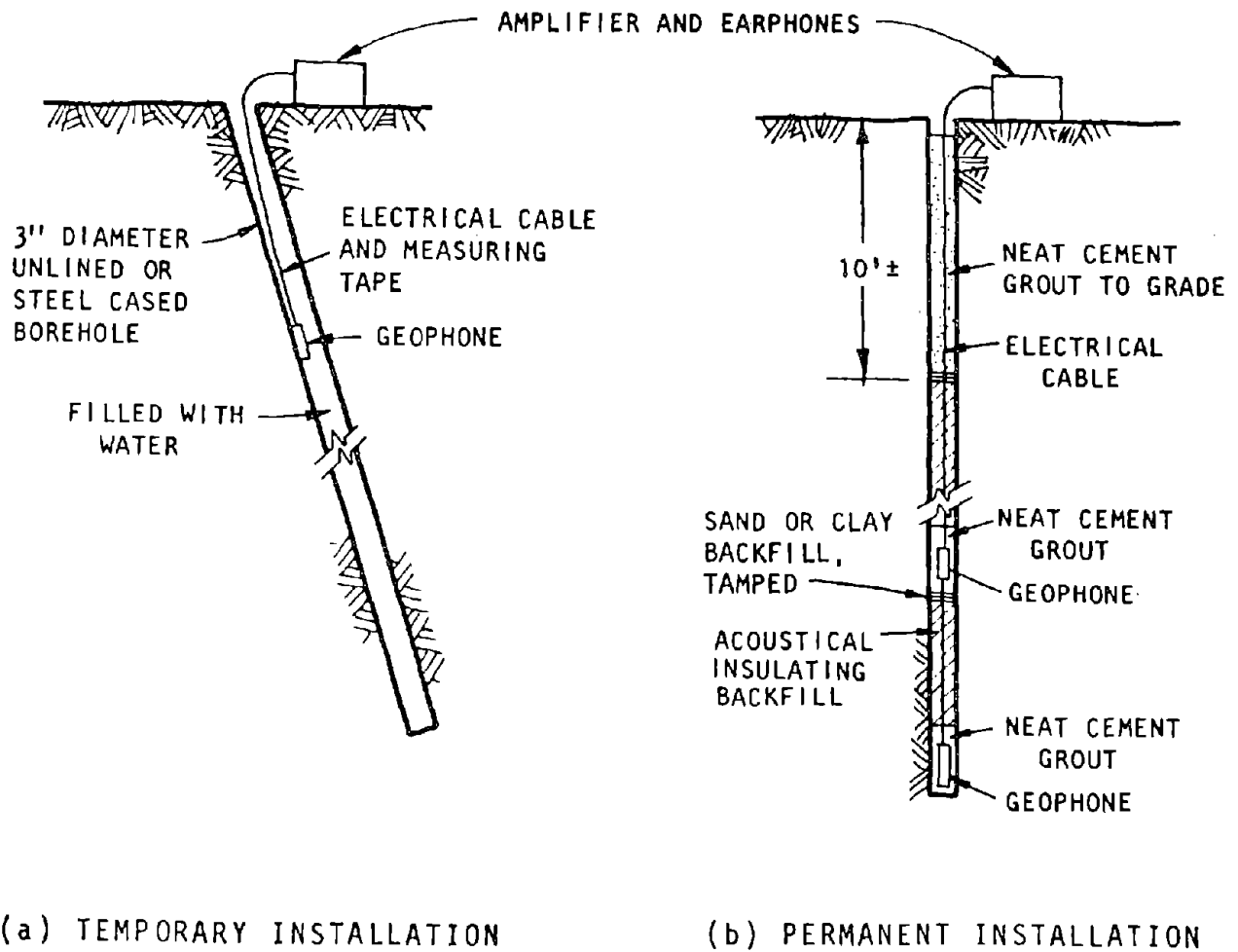
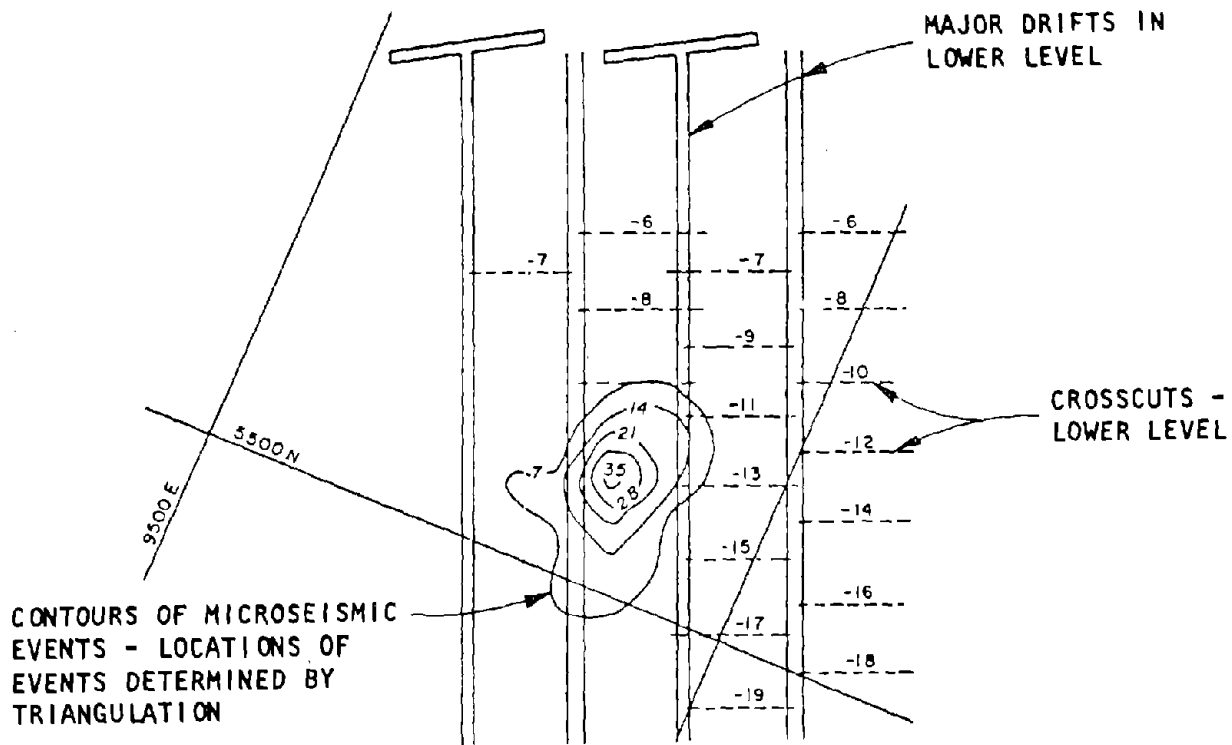


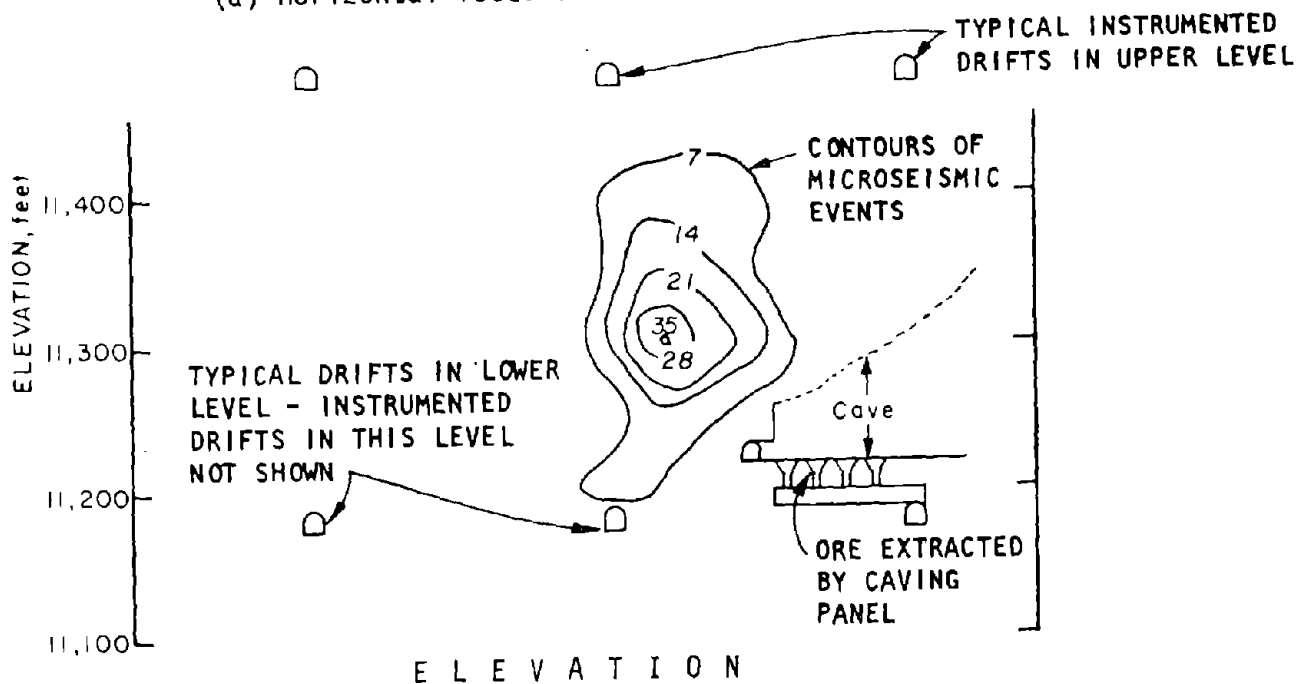
Figure 8.10 - MICROSEISMIC MONITOR WITH HEADPHONES,  
INSTALLED FROM GROUND SURFACE





P L A N

(a) Horizontal focus of microseismic events



(b) Vertical focus of microseismic events

Figure 8.11 - EXAMPLES OF MICROSEISMIC MONITORING  
FOR A BLOCK-CAVING MINE  
(after Oudenhoven and Tipton, 1973)

output signals from any seven of about a dozen geophones located about the mine level workings.

#### 8.2.8 Multiple Point Borehole Extensometer, Rod Type with Dial Gauge

This instrument was selected to measure mine level roof strata separation.

8.2.8.1 Description of Equipment - Figure 8.12 shows a rod type multiple point borehole extensometer (MPBX). The extensometer consists of 3/8-inch steel rods, each sleeved with a high-density polyethylene plastic tube from the anchor to the readout head. Each rod is anchored at a different depth. In Figure 8.12 two anchors are shown, but up to 6 to 8 anchors may be used in a 3-inch drill hole. The readout head is essentially a machined dial gauge platform with an opening over each extensometer rod. Measurement of the displacement of the top of the extensometer rod by a dial gauge gives a simple direct measurement of the anchor movement.

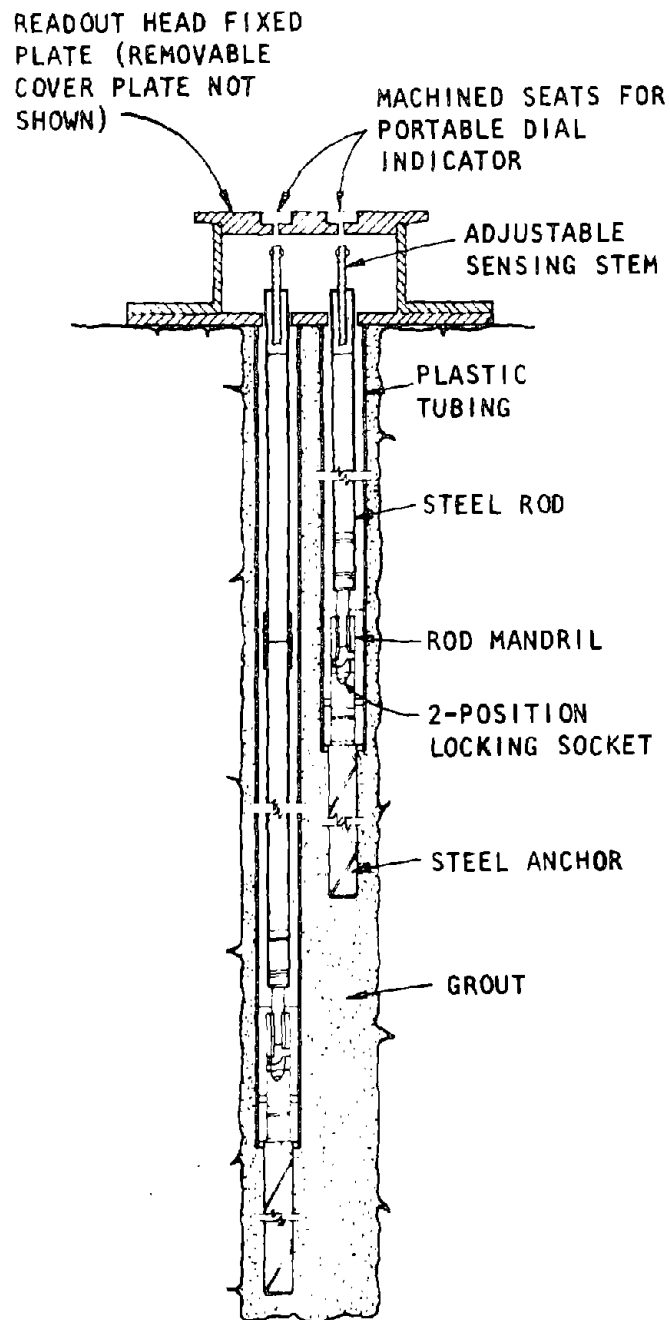
Extensometer rods may be cut, or added to, as the ground deformations between readout head and grouted anchor may require, thus providing very broad ranges of vertical deformation measurement capability.

In some deep, down-hole applications, an additional empty plastic tube is provided over the length of the borehole for use in measurement of temperature at various depths, in order to precisely correct for extensometer rod length changes due to any small temperature changes. The tube is filled with water and traversed by a pencil-slim resistance thermometer. The resistance of the thermometer is proportional to the temperature and is read from an electrical readout at the surface.

8.2.8.2 Method of Installation - The extensometer plastic tubes are cut to the appropriate length on a workbench, and the base of each tube is cemented onto a steel anchor cone. The tubing is carefully kept in straight alignment on the bench. The tubes are bundled and short pieces of large diameter tubing are taped to the main tubing bundle at numerous points to serve as guide bushings for withdrawing temporary grout injection tubes and air exhaust tubes. After inserting the tubing bundle in the borehole, it is necessary to immediately install the extension rods in the anchor cone tubes to ensure straight tubing lengths before grouting.

The following discussion assumes a vertical, "down"-hole, but the MPBX may be installed in any orientation, including vertical "up"-holes. Grouting is carried out using a neat cement grout injected into the borehole by means of a hand pump. Grouting heads are limited to stages of about 65 feet of grout, to avoid excessive grout pressures in the surrounding rock.

After grouting, the extension rods are firmly seated on the anchors at the base of the tubes by inserting the anchor mandrels of the extension



NOTE :

ONLY TWO RODS SHOWN; UP TO  
6 OR 8 POSSIBLE

Figure 8.12 - MULTIPLE POINT BOREHOLE EXTENSOMETER (MPBX), ROD TYPE,  
WITH DIAL GAUGE READOUT  
(Hillis et al, 1974)

rods into the bayonet joint of the anchor cones. There are two seating positions in the 3/8 inch diameter extension rod anchor cone. This is checked using a dial indicator at the readout head to ensure that the rods are free and true within the grouted plastic tubes, thus affording a simple, but effective calibration check of the installation to this point. Next the rods are cut to length at the top of the borehole and fitted with a machined contact head. The readout head is then bolted into position.

8.2.8.3 Method of Observation - The protective cover plate on the extensometer head is unlocked and removed, and a dial indicator is sequentially inserted through each of the ports in the fixed plate overlying the extensometer rods. The dial indicator body is seated on a machined surface of the fixed plate, and the indicator stem senses the position of the top of the extensometer rod to 0.01 mm. Minor range adjustments may be made by screwing a threaded stainless steel extension rod into or out of the uppermost joint of extensometer rod. Major range adjustments are made by shortening the extensometer rod with a hand-held pipe cutter, or by adding a short joint of extensometer rod, using an internal threaded stud for the joint.

In-situ performance of the MPBX may be checked at any time by unlocking the mandril attached to the lower end of the extensometer rod from its seating position in the bayonet-joint cone in the upper end of the grouted anchor. If no shear movements have intersected the borehole and the grouted anchor is intact, the extensometer-rod may be lifted 5 mm and locked rigidly into the second test position in the bayonet-joint cone.

#### 8.2.9 Rod or Wire Extensometer with Spring Tensioned Vibrating Wire

This instrument was selected to measure remote mine level convergence.

8.2.9.1 Description of Equipment - An electrical vibrating wire convergence extensometer is shown in Figure 8.13. The essential components are a roof anchor bolt, floor anchor bolt, connecting cable (or rod), a vibrating wire dynamometer, and a tensioning spring. An electrical cable is usually also provided from the dynamometer so that the readings may be made remotely.

The vibrating wire dynamometer is made up of a vibrating steel wire and an electromagnetic transducer assembly, housed in a waterproof axially deformable steel casing. Movement between the mine roof and mine floor changes the tension in the spring. This, in turn, changes the state of stress in the vibrating wire within the dynamometer and consequently the resonant frequency of the vibrating wire, when excited by an external source. The movement between the two anchors is calculated from this frequency. For vibrating wire instruments, the readout station may be thousands of feet away without any degradation of the frequency signal.

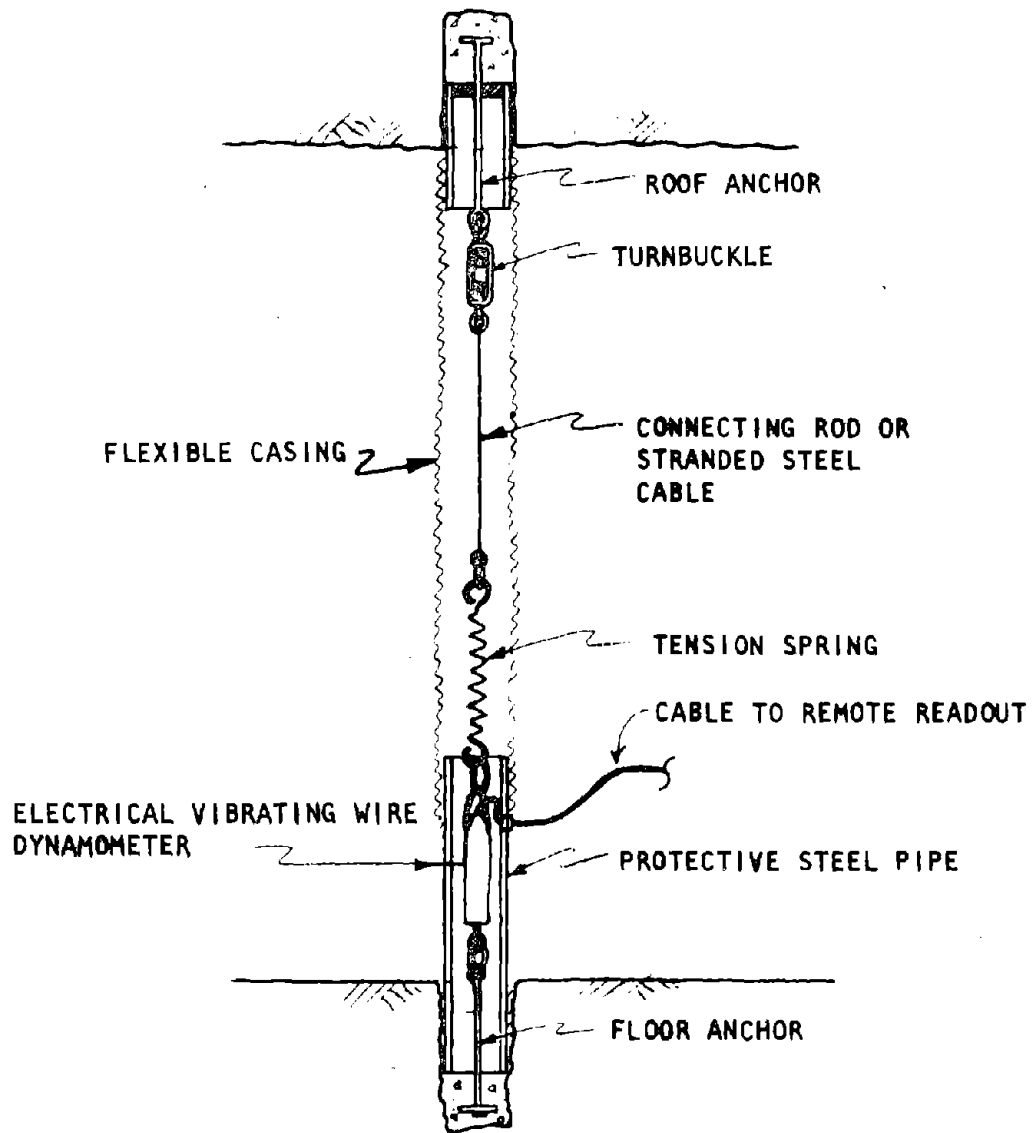


Figure 8.13 - EXTENSOMETER FOR REMOTE MEASUREMENT OF MINE CONVERGENCE IN CAVED OR FILLED MINES

8.2.9.2 Method of Installation - Shallow holes are drilled into the mine roof and floor, and the anchor bolts and protective steel pipe sleeves are grouted into the drill holes. The assembly of dynamometer, tensioning spring, and connecting links and cable are installed between anchor bolts. The length of tensioning spring is selected so that when the maximum expected convergence has occurred, a significant amount of extension is still present in the spring. The spring constant is selected such that the force transmitted by the maximum and minimum extension of the spring produces forces within the measuring range of the dynamometer. A turnbuckle is provided in the linkage to calibrate the readout response of the extensometer over a part of the range of expected movement. A flexible corrugated plastic casing, or telescoping plastic pipe is placed over the rod or cable and is secured to the upper and lower grouted pipe sleeves to protect the completed assembly. The electrical cable from the extensometer may be routed in steel conduit to the mine entrance, or it may be routed through a vertical borehole to ground surface. The borehole should be grout backfilled after routing the cable.

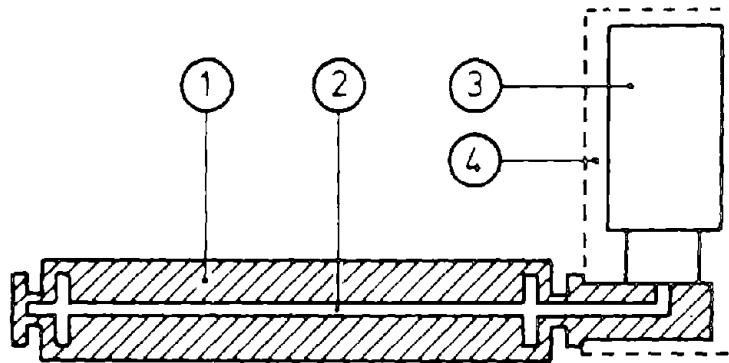
8.2.9.3 Method of Observation - The readout set, consisting of an internal power supply, excitation circuitry, and a frequency meter with digital readout, is generally connected directly to the readout end of the electrical cable at the remote terminal station. Telemetry may also be used with vibrating wire systems under certain conditions. The frequency of the dynamometer is recorded and the mine convergence is calculated from the difference between the square of the initial frequency and the square of the frequency at a later reading.

#### 8.2.10 Hydraulic Load Cells

This instrument was selected to measure mine level prop loads.

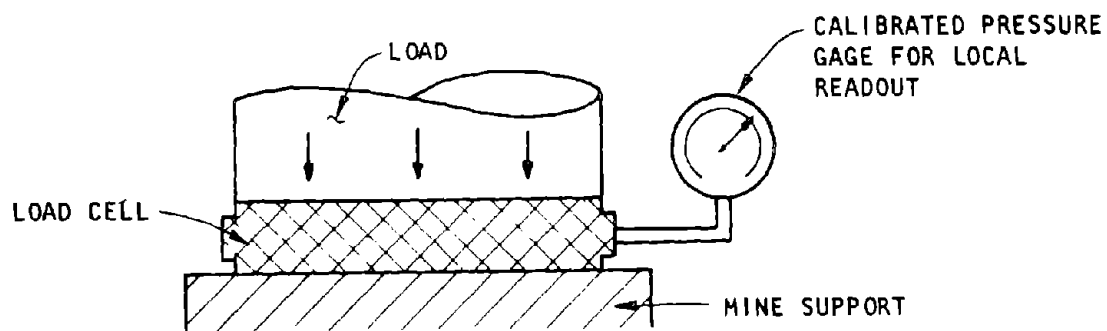
8.2.10.1 Description of Equipment - The hydraulic load cell is typically comprised of two corrosion-resistant steel plates separated by a thin film of fluid, generally oil, and an external gauge to sense the change in pressure of the load cell fluid as working loads are applied normal to the surfaces of the load cell plates. Figure 8.14(a) shows construction details for a Gloetzl hydraulic load cell. Note the special configuration used to join the opposing pressure plates around the load cell edges, to avoid stress concentration in the cell body.

Readout of the cell pressure may be either direct or remote. Figure 8.14(b) shows the simplest arrangement for measurement of support loads, using a locally read Bourdon gauge or similar with the load cell. Figure 8.14(c) shows an alternate method for precise local reading of pressure, plus less exact remote reading. This system utilizes indicator lights at the remote terminal, connecting electric wire to the load cell location, and electric limit switches on the local pressure gauge. A third readout possibility is shown in Figure 8.15(a). Here the load cell has a local, compensating type diaphragm valve (Figure 8.15(b))

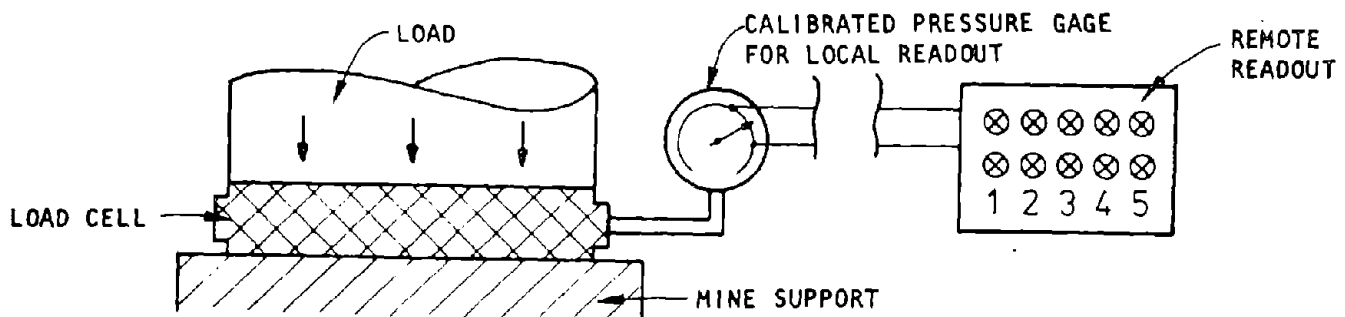


(a) CROSS-SECTION OF LOAD CELL

- 1 - CORROSION-RESISTANT STEEL PRESSURE PLATE
- 2 - OIL
- 3 - PRESSURE GAGE
- 4 - PROTECTIVE ENCLOSURE

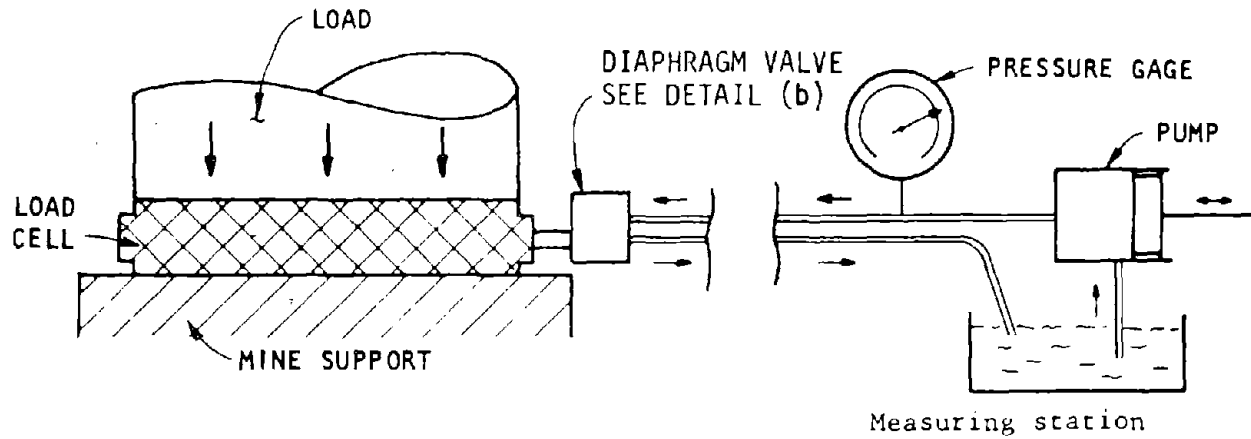


(b) LOCAL READOUT WITH CALIBRATED GAGE

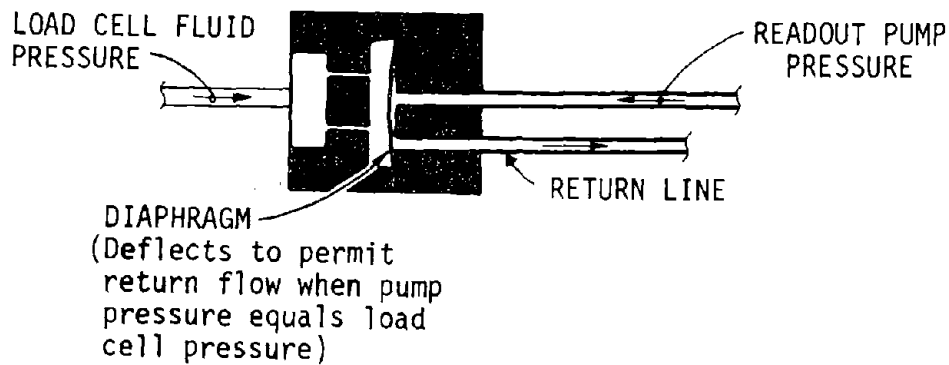


(c) LOCAL READOUT WITH CALIBRATED GAGE AND REMOTE INDICATION OF LOAD RANGES BY ELECTRIC LIMIT SWITCHES

Figure 8.14 - HYDRAULIC LOAD CELL AND LOCAL READOUTS  
(after Gloetzl)



(a) REMOTE READOUT OF PRECISE LOAD USING LOCAL DIAPHRAGM VALVE AND REMOTE PUMP WITH CALIBRATED PRESSURE GAGE



(b) DIAPHRAGM VALVE

Figure 8.15 - HYDRAULIC LOAD CELL AND REMOTE READOUTS  
(after Gloetzl)



which is connected by 1/4 inch plastic or steel tubing to a remote readout terminal. At the terminal, a hydraulic pressure pump, air pump, or regulated pressure gas cylinder supplies fluid under pressure to the diaphragm valve. When the pressure on the diaphragm valve exactly compensates for the hydraulic load cell pressure on the opposite side of the diaphragm, the valve deflects open, permitting a small, metered return flow back to the terminal. The compensating pressure is read on a calibrated pressure gauge on the pump.

8.2.10.2 Method of Installation - Hydraulic load cells may be installed at the foot of supports in mined openings, or between the prop and overlying strata. If the contact area of the load or the load cell pressure plate is significantly less than the load cell diameter, thick, full-diameter bearing plates may have to be inserted between load and load cell to better distribute the load.

8.2.10.3 Method of Observation - For locally read cells, the indicated pressure on the face of a bourdon-tube or similar pressure gauge is observed directly and recorded. Any initial preload, applied when the supports were wedged or jacked into place, should be subtracted from the load cell readings to obtain the pressure increase on the supports.

#### 8.2.11 U.S. Bureau of Mines Borehole Deformation Gauge

This instrument was selected to measure absolute mine pillar stress.

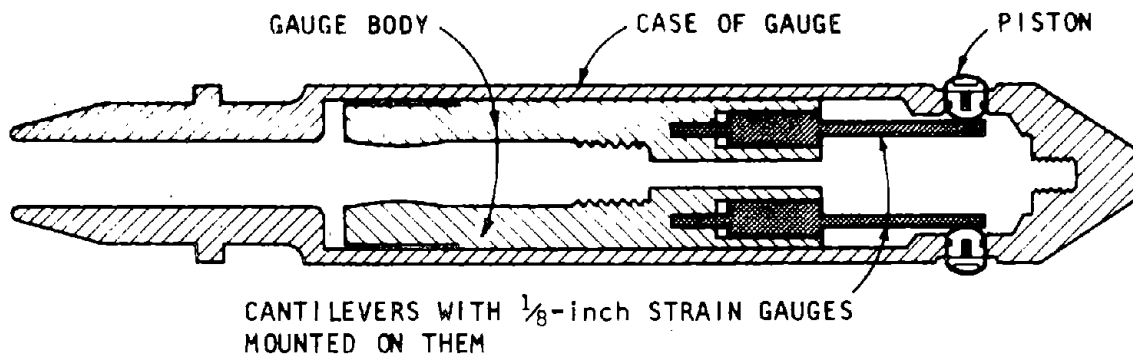
8.2.11.1 Description of Equipment - The U.S.B.M. Borehole Deformation Gauge is used in conjunction with a portable readout device and a biaxial pressure cell.

The U.S.B.M. Borehole Deformation Gauge measures the radial deformations of a 1-1/2-inch diameter borehole when a concentric 6-inch diameter hole is drilled around it. The gauge, shown in Figure 8.16a, consists of six pistons which respond to radial borehole movements. The pistons are attached to cantilevers on which electrical resistance strain gauges are mounted. The electrical resistance of the strain gauges, altered by piston displacement, is monitored on a portable digital balancing bridge (not shown).

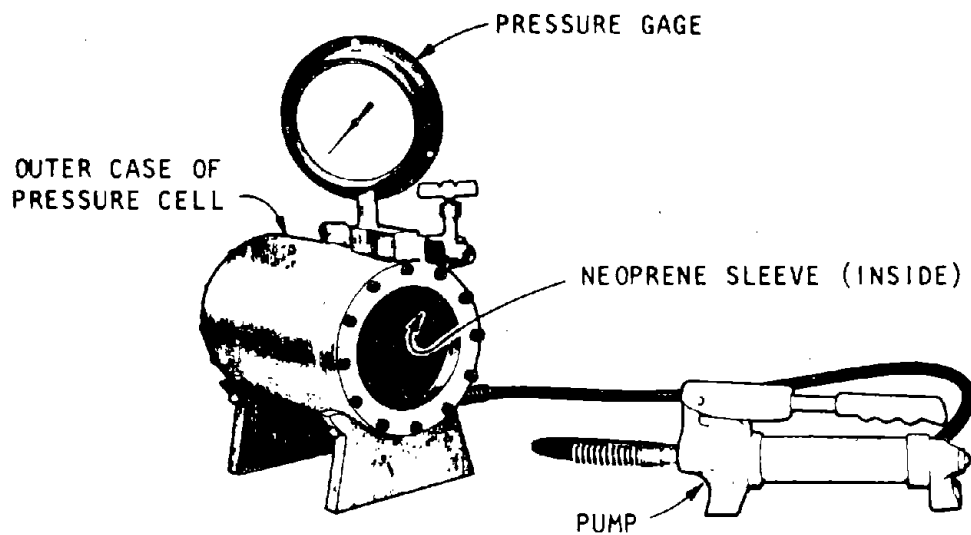
The biaxial cell, shown in Figure 8.16b, is used to determine the modulus of elasticity of retrieved core samples. That value is used to convert the borehole deflections, measured by the deformation gauge, into stresses. The biaxial cell consists of a cylindrical steel housing over an oil-filled neoprene sleeve. A hand pump is used to pressurize the sleeve.

8.2.11.2 Method of Installation - The stress determination process requires two separate procedures: overcoring and biaxial testing.

The overcoring operation is carried out in a 1-1/2-inch EX pilot hole. Approximately 7 feet of EX hole is drilled past the previous end of the borehole. The deformation gauge is inserted in the EX hole so that the pistons are 9 inches past the start of the EX-sized section (as shown in Figure 8.16c). A 6-inch diameter hole is then overcored concentrically

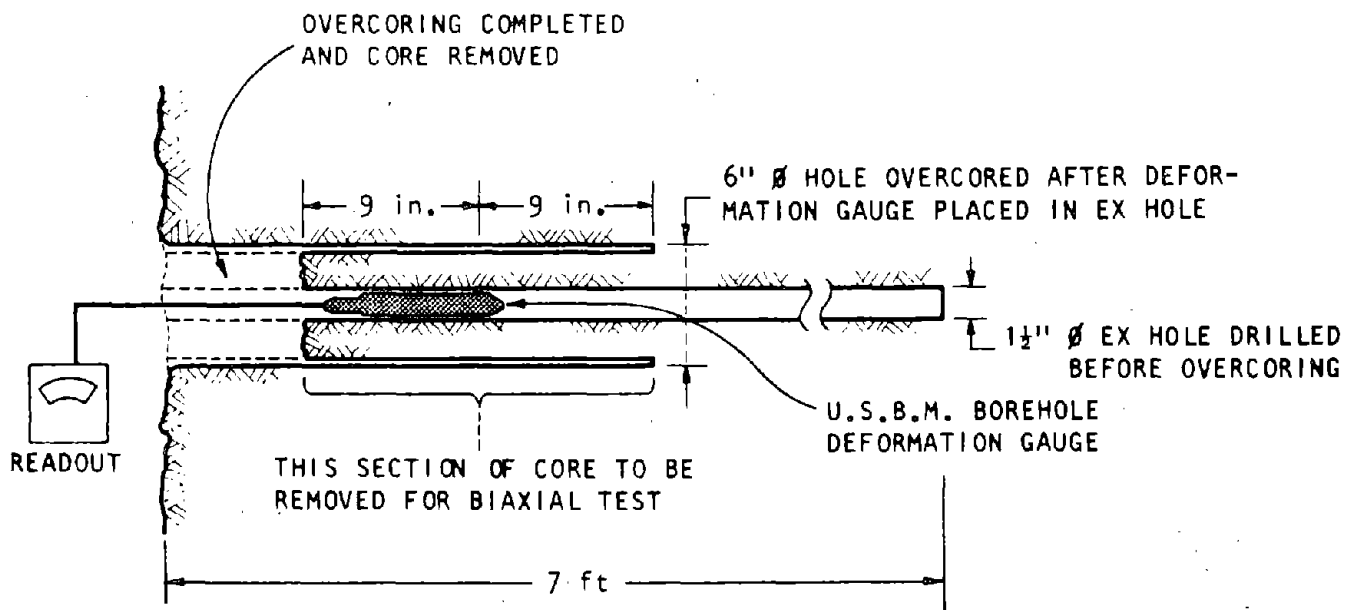


a) SCHEMATIC SECTION OF U.S.B.M. BOREHOLE DEFORMATION GAUGE  
SHOWING TWO OF SIX PISTONS (after Aggson, 1972)

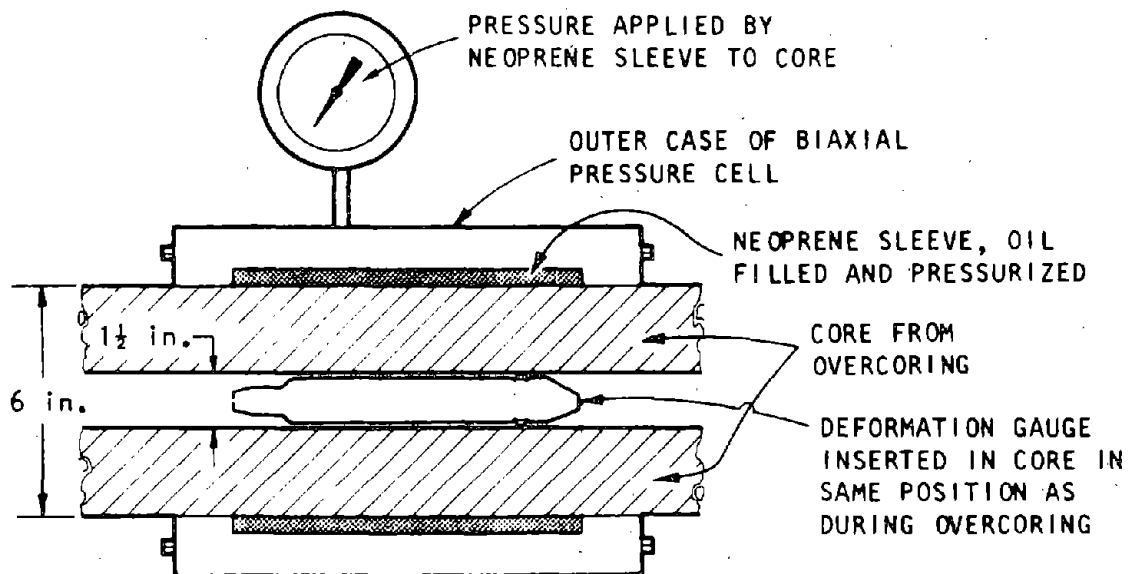


b) BIAXIAL PRESSURE CELL (Irad)

Figure 8.16 - U.S.B.M. BOREHOLE DEFORMATION GAUGE AND BIAXIAL PRESSURE CELL FOR IN-SITU ROCK STRESS



c) 6 in. Ø OVERCORED HOLE AROUND DEFORMATION GAUGE  
INSERTED IN 1½ in. Ø HOLE  
(after Cummins & Given, 1973)



d) CROSS-SECTION SHOWING CORE DURING BIAXIAL PRESSURE TEST

Figure 8.16 (Cont'd.) - U.S.B.M. BOREHOLE DEFORMATION GAUGE AND BIAXIAL PRESSURE CELL FOR IN-SITU ROCK STRESS

around the EX hole to 9 inches past the pistons. Displacements of the borehole deformation gauge's pistons are monitored during this procedure. After the 6-inch core barrel and rods are removed, the deformation gauge is retrieved. Then the 18-inch long annular-shaped core is broken free and removed. Refer to Hooker and Bickel (1974) for further details on the overcoring procedure.

The core is then tested in the biaxial pressure cell. The borehole deformation gauge is reinserted into the EX hole in the retrieved core and the core inserted in the biaxial cell, as shown in Figure 8.16d. The pressure in the neoprene sleeve is increased incrementally while the displacements of the borehole deformation gauge's pistons are monitored.

This procedure is repeated along the length of the EX pilot hole. The EX hole may be advanced further once overcoring is completed along its length. The borehole deformation gauge could theoretically be left in an EX borehole to measure stress changes due to mining, but for reason of expense and long-term stability, it is not used for this purpose.

8.2.11.3 Method of Operation - During the overcoring test, the displacements of the borehole deformation gauge's pistons are monitored for each 1/2 inch of overcoring advance. The six pistons are spaced evenly around the gauge perimeter. The strain gauges corresponding to each pair of pistons directly opposite each other are tied together and connected to a balancing bridge. The readout value for each pair of pistons is converted to diametral deformation by means of a gauge constant (Hooker and Bickel, 1974); and the results are plotted as shown in Figure 8.17.

During the biaxial pressure test, the displacements of the pistons are monitored for each pressure increment. The readings are converted into diametral deformation, as discussed above. Then a pressure versus strain plot is developed and a modulus of elasticity computed for the rock (Aggson, 1972).

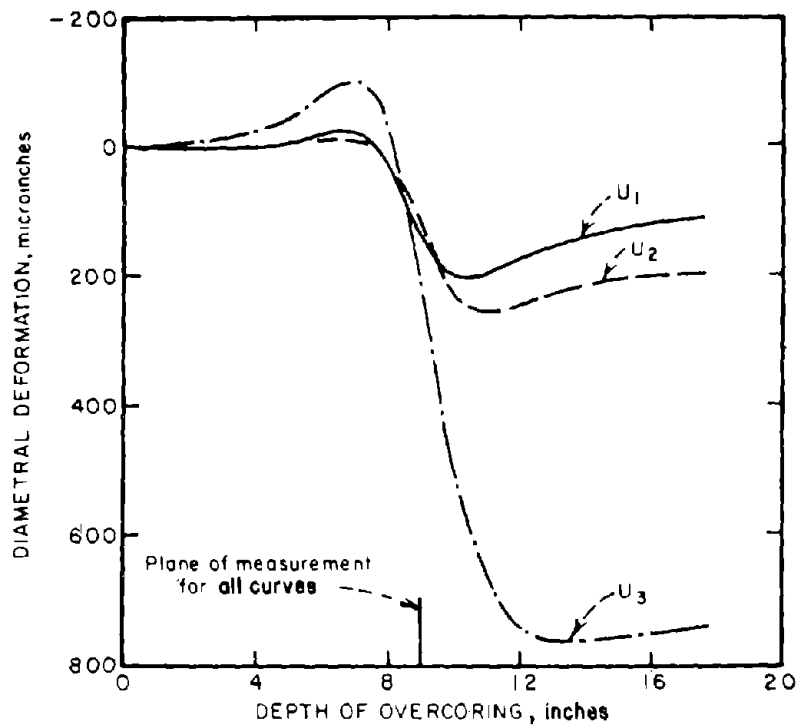
This modulus value, combined with diametral deformations during overcoring, is used to compute in-situ stresses in the rock mass (Hooker et al, 1974).

To determine the maximum principal stress or the complete stress distribution in the rock, diametral stresses must be computed for three orthogonal axes or for a vertical hole and two horizontal holes separated by 60 to 70 degrees. However, if the maximum stress direction is known, one hole is sufficient to calculate the maximum stress. For example, one horizontal hole is adequate in a free standing mine pillar where the maximum stress is vertical.

#### 8.2.12 Encapsulated Flat Borehole Pressure Cell

This instrument was selected to monitor mine level pillar stress change.

8.2.12.1 Description of Equipment - The Borehole Pressure Cell (BPC), Figure 8.18, is comprised of a hydraulic cell formed by two flat steel sheets each typically 10 inches long by 2 inches wide, and joined at the edges. The



STRESS-RELIEF DEFORMATION CURVES TAKEN FROM FIELD DATA:  
DEPTH OF MEASUREMENT 9 INCHES. (Hooker et al., 1974)

N O T E :

U<sub>1</sub>, U<sub>2</sub>, U<sub>3</sub> ARE DIAMETRAL DEFORMATION  
CURVES FOR EACH OF THREE CANTILEVER  
PAIRS IN THE BOREHOLE DEFORMATION  
GAUGE.

Figure 8.17 - TYPICAL OVERCORING DEFORMATION DATA

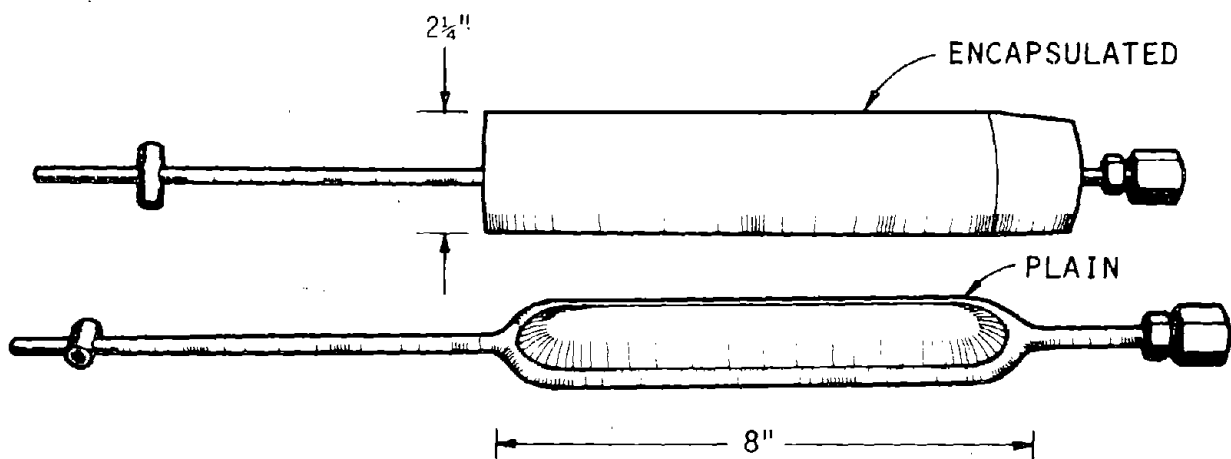


Figure 8.18 - ENCAPSULATED AND PLAIN VERSION OF FLAT BOREHOLE PRESSURE CELL (after Smith, 1972)

cell cavity as well as the attached hydraulic tubing is filled with hydraulic fluid prior to installation. After the cell is installed, a special valve assembly with a mounted pressure gauge is attached to the tubing at the drill hole collar. The valve assembly allows a hydraulic pressurizing pump to be attached and removed from the BPC tubing without disturbing the pressure in the BPC and the pressure gauge. Changes in the cell pressure are observed on the pressure gauge.

The cell may be pre-encapsulated in a cylinder of cement grout for rapid installation and pressurizing in a 2-1/4-inch smooth-walled drill hole. This method is recommended for general field use, though it requires a smooth, close-tolerance diameter drill hole. The encapsulated BPC should be calibrated for the specific rock type in which it will be used (Smith, 1972). A calibration curve of confining pressure versus BPC pressure can be obtained if a 6-inch diameter rock core with a concentric 2-1/4-inch drill hole containing the encapsulated BPC is tested in a triaxial pressure chamber.

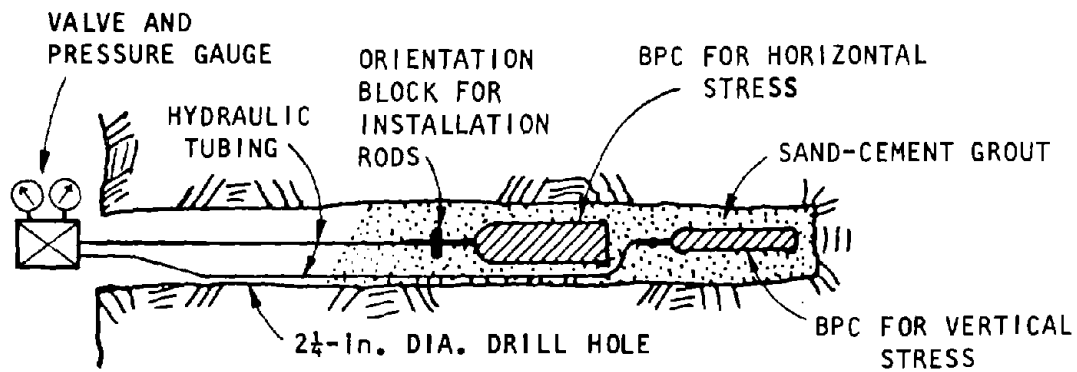
8.2.12.2 Method of Installation - For BPC units to be installed without cement grout encapsulation beforehand, a rough-drilled hole of 2-1/4 inch nominal diameter is satisfactory. To install the BPC, the hole is first completely filled with a moderately stiff sand-cement grout, carefully eliminating all voids. Next, the BPC is forced into the grout with the flat plate oriented transverse to the direction of stress to be measured. The flat borehole pressure cell is oriented by means of a rigid rod which attaches to an orientation block immediately behind the cell and which extends out beyond the collar of the hole (Figure 8.19a). A high early strength grout may be required if the cell is to be rapidly loaded soon after installation.

To install pre-encapsulated cells (Figure 8.19b), it is necessary to prepare a relatively precise-diameter drill hole, sized closely to the diameter of the pre-encapsulation cylinder. A drill hole of  $2.240 \pm 0.060$  inches was specified by one investigator, and a special set of calipers reading to  $\pm 0.005$  inch was used to measure the required hole diameter (Smith, 1972).

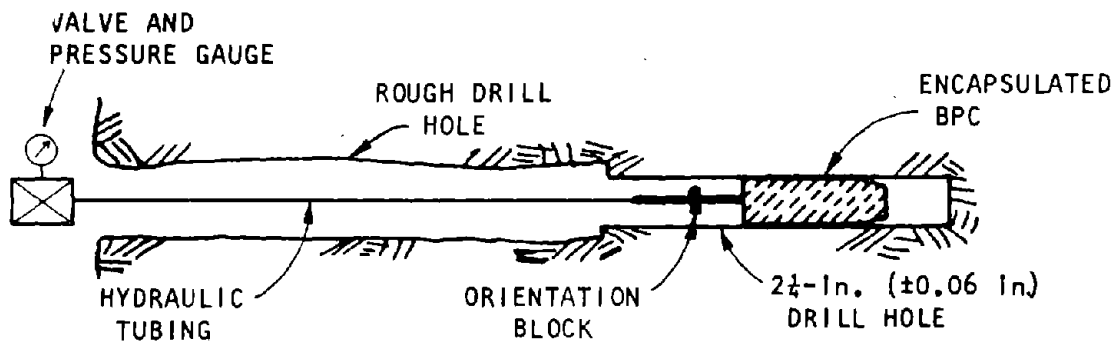
After the cell is installed, the hydraulic tubing from either type of installation is connected to the external valve assembly which is wedged to the borehole collar or fixed to any other convenient support outside the hole.

The installed BPC may be used to assess the modulus of elasticity of the support rock. The cell is pressurized and the injected fluid volume is measured to obtain the volumetric strain. The modulus is then computed from these data. A small precharge pressure may then be left in the BPC to make it immediately responsive to stress changes in the surrounding rock.

8.2.12.3 Methods of Observation - Pressures in the pre-loaded BPC will stabilize at some datum value after some short period following installation. Thereafter, pressure is simply read from the pressure gauge outside the drill hole, and compared with the datum pressure. The change in pressure is converted to a change in stress level by use of the laboratory calibration curve.



(a) INSTALLATION OF NON-ENCAPSULATED BOREHOLE PRESSURE CELLS



(b) INSTALLATION OF ENCAPSULATED BOREHOLE PRESSURE CELL

Figure 8.19 - HYDRAULIC BOREHOLE PRESSURE CELLS (BPC)  
(after Smith, 1972)



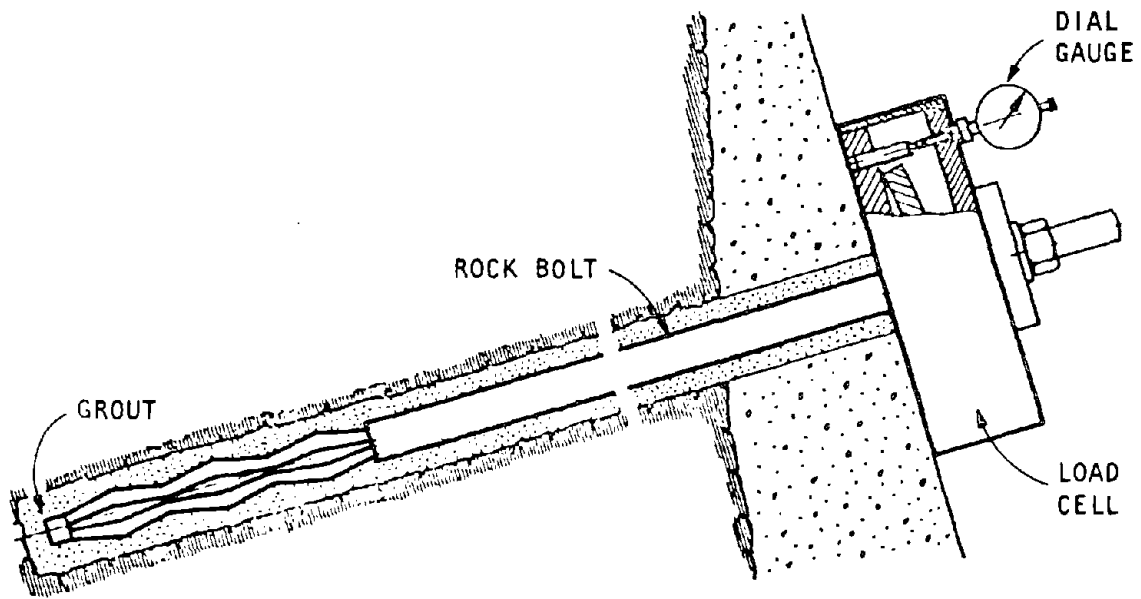
### 8.2.13 Elastic Disc and Dial Gauge Load Cell

This instrument was selected to measure rock bolt loads.

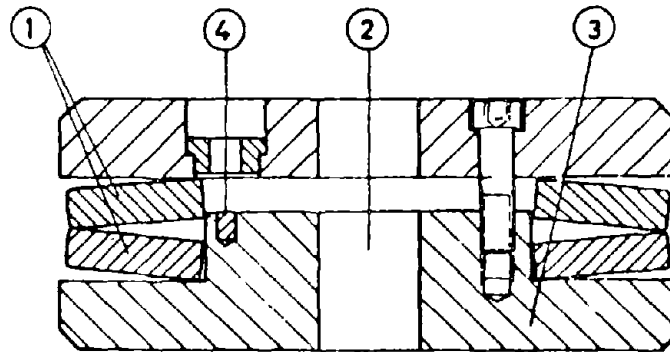
8.2.13.1 Description of Equipment - The elastic disc and dial gauge load cell consists of an elastic cup spring fastened between two plates in a watertight construction. A dial gauge indicator measures the distance between the two plates (Figure 8.20). This rock bolt load cell can measure both increases and decreases in tension and thus it is possible to detect tension decreases from stress relaxation in the bolt as well as tension increases due to normal rock loading. Due to the hysteresis of the cup spring, the direction of the loading, i.e., increase or decrease in tension, must be known to achieve maximum accuracy. Variations in rock-bolt tension due to such factors as temperature changes are not observed in the data unless these variations exceed the hysteresis.

8.2.13.2 Method of Installation - After a rock bolt has been set into the mine roof, the load cell (without dial gauge), bearing plate bevel washers and nut assembly are placed over the bolt and the entire bolt and load cell assembly is loaded by the bolt tensioning action of the rock bolt torque wrench.

8.2.13.2 Method of Observation - To take readings, the dial gauge is screwed onto the cell and then read. The dial gauge may be left in place after a reading or it can be removed to reduce the likelihood of damage.



(a) SCHEMATIC SKETCH OF A DISC LOAD CELL INSTALLATION WITH DIAL GAUGE READOUT



- 1 cup springs
- 2 central hole for rock bolt
- 3 load distribution plate
- 4 sensor plate for read-out

(b) SCHEMATIC OF DISC LOAD CELL

Figure 8.20 - ELASTIC DISC LOAD CELL WITH DIAL GAUGE READOUT  
(Interfels)

## 9.0 COMPARATIVE INSTRUMENT SYSTEM CAPABILITIES

In this report, seven instrumentation systems are developed. These systems vary in number and complexity of instruments, cost and time to install and operate the systems, and technical expertise needed to install, maintain and operate the instrumentation. A subsidence investigator will select an appropriate instrumentation system based primarily on the application for which he needs data. Some applications and the appropriate systems were summarized in Table 4.5. But other factors can enter into the decision process, including cost limitations, availability of technical personnel and time constraints. This section examines those factors.

### 9.1 NON-TECHNICAL INSTRUMENT SYSTEM CHARACTERISTICS

Some of the non-technical factors which may affect the selection of an instrument system include:

- Number of Instruments in the System: The number of instruments influences the initial capital outlay for the measurement system and manpower required to install and operate it. The number, together with the cost, time and versatility information discussed below, is shown in Table 9.2.
- Number of Cross-System Uses for Equipment: The data user may wish to expand or change his monitoring program once it is underway. Many of the instruments listed in each system can be used in other systems. If a system contains instruments with many applications in other instrument systems, the investigator's monitoring program can easily change with minimal additional capital outlay and training costs. For each instrument, the number of systems in which it appears was determined. Then the appropriate totals were summed for the instruments in each system as a measure of the versatility built into that system; see Table 9.2.
- Estimated Time to Install Prototype: Using the typical layouts presented in Table 7.1, the number of days needed to install the instrumentation system was estimated; see Table 9.2.
- Estimated Cost for Installation of Prototype: Small typical layouts for monitoring stations (refer to Table 7.1) were used in Section 7.0 to compare the costs of various instrumentation. These layouts were made as simple as possible to reduce the complexity of calculations and increase the general utility of the results. The layouts were again used here to estimate the costs of installation for each instrument system. The resulting costs, which include labor, reference points, and incidental materials, are shown on Table 9.1.

TABLE 9.1  
ESTIMATED COST AND TIME FOR INSTALLATION OF INSTRUMENTS

| MEASUREMENT                                | QUANTITY                                                      | ESTIMATED UNIT COST FOR LABOR AND INCIDENTAL MATERIALS                                              | ESTIMATED TOTAL COST, (\$) | ESTIMATED TIME TO INSTALL, (Days) |
|--------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|----------------------------|-----------------------------------|
| Ground Surface Settlement                  | 11 monuments                                                  | \$100 each, including drilling, pipe, concrete, and labor                                           | 1100                       | 3                                 |
| Ground Surface Strain (lines)              | 6 monuments                                                   | \$200 each, including drilling, pipe machined cones, concrete, and labor                            | 1200                       | 2                                 |
| Ground Surface Horizontal Strain Triangles | 2 triangles=<br>6 monuments                                   | as above                                                                                            | 1200                       | 2                                 |
| Ground Surface Crack Movement              | 5 cracks, each instrumented in 2 places = 20 monuments        | as above                                                                                            | 4000                       | 6                                 |
| Ground Tilt                                | 11 monuments                                                  | \$100 each, including drilling, pipe, concrete, and labor                                           | 1100                       | 3                                 |
| Structure Differential Vertical Settlement | 8 monitor points                                              | \$75 each, including leveling point, cover, and labor                                               | 600                        | 2                                 |
| Structure Strains                          | 8 monitor points                                              | \$100 each, including drilling, machined post, and labor                                            | 800                        | 2                                 |
| Structure Crack Movement                   | 1 crack monitored in 2 places = 4 monuments                   | \$75 each, including precision drilling, cover, and labor                                           | 300                        | 1                                 |
| Subsurface Vertical Deformation            | 1 borehole 300 ft deep                                        | \$3600 drilling and labor; \$750 for 2 engineers and \$650 for drill crew to install special casing | 5000                       | 7                                 |
| Subsurface Horizontal Deformation          | 1 borehole 300 ft deep                                        | as above                                                                                            | 5000                       | 7                                 |
| Extent of Subsurface Fracturing            | 4 boreholes 500 ft deep at corners of square 500 ft by 500 ft | \$6000 each, materials and labor                                                                    | 24000                      | 20                                |
| Mine Roof Sag                              | 11 monitor points                                             | \$150 each, including leveling point, cover, and labor                                              | 1650                       | 3                                 |
| Mine Convergence                           | 11 monitor stations with 2 points each                        | \$150 each, including machined post, cover, drilling, and labor                                     | 3300                       | 3                                 |
| Mine Roof Strata Separation                | 1 drillhole 50 ft deep with 6 anchors                         | \$750 drilling and labor; \$750 engineer for installation                                           | 1500                       | 4                                 |
| Mine Prop Load                             | Installation of 10 prop load cells                            | \$75 each for labor and shims                                                                       | 750                        | 3                                 |
| Mine Rock Bolt Load                        | installation of 10 rock bolt load cells                       | \$55 each for labor                                                                                 | 550                        | 2                                 |
| Mine Pillar Stress                         | 1 drillhole instrumented at least 20 ft into pillar           | \$450 drilling and labor; \$550 engineer for installation                                           | 1000                       | 2                                 |
| Mine Level Rock Noise                      | 10 monitor holes                                              | \$50 each including drilling and labor                                                              | 500                        | 3                                 |

TABLE 9.2  
ESTIMATED COST AND TIME<sup>1</sup>  
TO CONSTRUCT PROTOTYPE INSTRUMENT SYSTEMS

| SYSTEM | NUMBER OF<br>INSTRUMENTS<br>IN<br>SYSTEM | NUMBER OF<br>CROSS-SYSTEM<br>USES<br>FOR EQUIPMENT | ESTIMATED<br>TIME TO<br>INSTALL<br>PROTOTYPE,<br>DAYS | ESTIMATED<br>COST FOR<br>INSTALLATION<br>OF PROTOTYPE,<br>\$ | ESTIMATED<br>COST OF<br>INSTRUMENT<br>HARDWARE,<br>\$ | ESTIMATED<br>TOTAL INITIAL<br>COSTS OF<br>PROTOTYPE,<br>\$ | VERSATILITY<br>COST,<br>\$ | FIELD<br>EXPERIENCE<br>FACTOR |
|--------|------------------------------------------|----------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------|------------------------------------------------------------|----------------------------|-------------------------------|
| A      | 1                                        | 5                                                  | 3                                                     | 1100                                                         | 2000                                                  | 3100                                                       | 400                        | 3.00                          |
| B      | 3                                        | 7                                                  | 5                                                     | 1700                                                         | 6000                                                  | 7700                                                       | 860                        | 2.33                          |
| C      | 5                                        | 16                                                 | 14                                                    | 6750                                                         | 13500                                                 | 20250                                                      | 840                        | 1.40                          |
| D      | 9                                        | 24                                                 | 47                                                    | 27350                                                        | 25000                                                 | 52350                                                      | 1040                       | 2.38                          |
| E      | 9                                        | 25                                                 | 60                                                    | 48200                                                        | 33000                                                 | 81200                                                      | 1320                       | 2.15                          |
| F      | 3                                        | 9                                                  | 13                                                    | 9100                                                         | 15000                                                 | 24100                                                      | 1670                       | 2.00                          |
| G      | 0                                        | 0                                                  | 0                                                     | 0                                                            | 0                                                     | 0                                                          | -                          | -                             |

<sup>1</sup>Time does not include time spent in purchasing or ordering equipment or delays due to ongoing mining or surface activities.

- Estimated Cost of Instrument Hardware for Prototype: Using the typical layouts presented in Table 7.1, the cost of the instrument hardware, both portable and permanent, was estimated for each instrument system; see Table 9.2.
- Estimated Total Initial Cost of Prototype System: This value, also shown in Table 9.2, is the sum of the estimated costs of installation and instrument hardware for the prototype version of each system. It does not include operating costs.
- Versatility Cost: An instrument system with many instruments can easily be modified to perform the measurements recommended for other systems. But in order to obtain this flexibility, a significant initial outlay is required for instrument hardware. This factor, the cost of the instrument hardware divided by the number of cross-system uses, was calculated as a measure of the cost of having versatility built into the instrument system; see Table 9.2.

The prototype installations are used to estimate costs and installation time but are not intended to be suggested sizes for actual installation. They provide a convenient basis for comparing the instrument systems. A typical longwall panel might have been used as an example but this or other special cases may place emphasis on certain measurements, and may thus be less suitable for general comparison of systems. The actual cost and time requirements of a working instrument system will depend on the size of the subsiding area and the specific data needs of the data user.

## 9.2 TECHNICAL INSTRUMENT SYSTEM CHARACTERISTICS

A monitoring system is valuable only when the data it produces are reliable and repeatable. All of the instruments selected for use in the systems are made by one or more manufacturers or plans are readily available. However, the availability of an instrument is not a measure of the success with which it can be used. Table 9.3 describes the extent to which the instruments in the systems have been successfully used. To get a measure of the combined field experience of each instrument system, the field experience for each instrument in the system was tabulated using the following rating, and then the individual instrument ratings were averaged for the system.

| <u>Field Experience</u>               | <u>Numerical Rating</u> |
|---------------------------------------|-------------------------|
| Widely reported successful experience | 3                       |
| Significant successful experience     | 2                       |

TABLE 9.3  
FIELD EXPERIENCE OF INSTRUMENTATION

| INSTRUMENT                                                                  | FIELD EXPERIENCE                                                                                   | RATING | MEASUREMENTS FOR WHICH INSTRUMENT USED                                                                                           |
|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|--------|----------------------------------------------------------------------------------------------------------------------------------|
| Precision Level                                                             | Widely reported as successful                                                                      | 3      | Ground Surface Vertical Settlement<br>Ground Surface Tilt, Structure<br>Differential Vertical Settlement,<br>Mine Level Roof Sag |
| Rod Extensometer with Micrometer                                            | Significant successful use                                                                         | 2      | Structure Strain                                                                                                                 |
| Dial Indicator Strain Gauge                                                 | Significant successful use                                                                         | 2      | Structure Crack Movement                                                                                                         |
| Steel Tape Extensometer                                                     | Widely reported as successful                                                                      | 3      | Ground Surface Horizontal Strain<br>(Lines and Triangles), Ground<br>Surface Tilt, Mine Level<br>Convergence                     |
| Hydraulic Load Cell                                                         | Some significant successful use                                                                    | 1      | Mine Level Prop Load                                                                                                             |
| Elastic Disc Load Cell                                                      | No evaluation of instrument encountered in literature                                              | 0      | Mine Level Rock Bolt Load                                                                                                        |
| Microseismic with Headphones                                                | Potential shown, but problems remain, particularly in coal measures                                | 0      | Mine Level Rock Noise, Extent of<br>Subsurface Fracturing                                                                        |
| Full Profile Borehole Extensometer with Electromagnetic Torpedo             | Significant successful use                                                                         | 2      | Subsurface Vertical Deformation                                                                                                  |
| Full Profile Borehole Inclinator with Servo-Accelerometer Torpedo           | Widely reported as successful                                                                      | 3      | Subsurface Horizontal Deformation                                                                                                |
| Multiple Point Borehole Extensometer, Rod Type, with Dial Gauge             | Widely reported as successful                                                                      | 3      | Mine Level Roof Strata Separation                                                                                                |
| USBM Borehole Deformation Gauge                                             | Significant successful use                                                                         | 2      | Mine Level Pillar Stress<br>(Absolute)                                                                                           |
| Flat Encapsulated Borehole Pressure Cell                                    | Significant successful use                                                                         | 2      | Mine Level Pillar Stress<br>(Relative)                                                                                           |
| Rod Extensometer with Spring-Tensioned Vibrating Wire in Telescoping Casing | Significant successful use in trenches and dams; good potential for convergence but not yet proven | 1      | Mine Level Convergence (Remote)                                                                                                  |

| <u>Field Experience (cont)</u>                                                                          | <u>Numerical Rating (cont)</u> |
|---------------------------------------------------------------------------------------------------------|--------------------------------|
| Some successful experience, or experience in application somewhat different from intended use in system | 1                              |
| No experience encountered in literature, or literature notes unresolved problems with instrument use    | 0                              |

The averaged field experience factor for each instrument system is presented in the last column of Table 9.2.

### 9.3 COMPARATIVE RATING OF INSTRUMENT SYSTEMS

A rating system was developed to synthesize the information in Table 9.2. The rating criteria are presented in Table 9.4. A weighting factor of 2 was applied to cost and field experience to emphasize their relative importance.

The results of rating the systems are shown in the Matrix of System Capabilities, Table 9.5. All studies should begin with an inspection of the subsidence area, as presented in System G. Instrumentation can then be added to supplement System G. Referring to Table 9.5, it is apparent that it is economically and technically advantageous to begin an instrumented monitoring program using only System A. Then, as the needs for data are clarified and the magnitude of the problem is better understood, more sophisticated and costly instrumentation programs can be implemented.



TABLE 9.4  
RATING FACTORS FOR COMPARISON OF  
INSTRUMENT SYSTEMS

| <u>Estimated Total Cost of<br/>Prototype Installations</u>                                                | <u>Rating Factor</u> |
|-----------------------------------------------------------------------------------------------------------|----------------------|
| less than \$5,000                                                                                         | 3                    |
| \$ 5,000 - \$10,000                                                                                       | 2                    |
| \$10,000 - \$25,000                                                                                       | 1                    |
| \$25,001 and up                                                                                           | 0                    |
| <u>Estimated Time to Construct<br/>Prototype, days</u>                                                    | <u>Rating Factor</u> |
| less than 5                                                                                               | 3                    |
| 5 to 15                                                                                                   | 2                    |
| 16 to 30                                                                                                  | 1                    |
| 31 and up                                                                                                 | 0                    |
| <u>Versatility Cost</u>                                                                                   | <u>Rating Factor</u> |
| less than \$500                                                                                           | 3                    |
| \$500 - \$1,000                                                                                           | 2                    |
| \$1,001 - \$1,500                                                                                         | 1                    |
| \$1,501 - \$2,000                                                                                         | 0                    |
| <u>Field Experience</u>                                                                                   | <u>Rating Factor</u> |
| Widely reported successful experience                                                                     | 3                    |
| Significant successful experience                                                                         | 2                    |
| Some successful experience, or experience in applications somewhat different from intended use in system. | 1                    |
| No experience encountered in literature, or literature notes unresolved problems with instrument use.     | 0                    |

TABLE 9.5  
MATRIX OF SYSTEM CAPABILITIES

| SYSTEM                                    | (1)<br>ESTIMATED<br>TOTAL COST<br>OF<br>PROTOTYPE,<br>\$ | (2)<br>ESTIMATED<br>TIME TO<br>INSTALL<br>PROTOTYPE,<br>DAYS | (3)<br>VERSATILITY<br>COST,<br>\$ | (4)<br>FIELD<br>EXPERIENCE<br>FACTOR | (5)<br>WEIGHTED<br>SUM | (6)<br>RANK |
|-------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------|-----------------------------------|--------------------------------------|------------------------|-------------|
| WEIGHT                                    | 2                                                        | 1                                                            | 1                                 | 2                                    |                        |             |
| A: SUBSIDENCE<br>DETECTION                | 3                                                        | 3                                                            | 3                                 | 3.00                                 | 18.00                  | 1           |
| B: STRUCTURE<br>PERFORMANCE               | 2                                                        | 2                                                            | 2                                 | 2.33                                 | 12.66                  | 2           |
| C: MINE STABILITY                         | 1                                                        | 2                                                            | 2                                 | 1.40                                 | 8.80                   | 3           |
| D: PERFORMANCE OF<br>SUPPORTED<br>SYSTEMS | 0                                                        | 0                                                            | 1                                 | 2.38                                 | 5.76                   | 5           |
| E: PERFORMANCE OF<br>CAVING SYSTEMS       | 0                                                        | 0                                                            | 1                                 | 2.15                                 | 5.30                   | 6           |
| F: PERFORMANCE OF<br>FILLED MINES         | 1                                                        | 2                                                            | 0                                 | 2.00                                 | 8.00                   | 4           |
| G: VISUAL<br>DOCUMENTATION                | 3                                                        | 3                                                            | -                                 | -                                    | -                      | -           |

KEY:

Columns 1, 2, 3, 4: 0 = poor 3 = excellent

Column 5: Sum of weighted values of columns 1-4

Column 6: 1 = most effective 6 = least effective

## 10.0 CONCLUSIONS AND RECOMMENDATIONS

Subsidence is an inevitable result of underground mining unless measures are taken to provide permanent support for the mine opening. Uncontrolled subsidence can result in costly legal battles and substantial economic impact to both the surface user and the mine operator. Damage from subsidence can also be expected to intensify environmental concerns and reactions from affected surface communities. Surface users are becoming increasingly aware of their environment and are taking steps to improve it. The current climate of environmental awareness will create an increasing demand to control subsidence that can result from underground mining.

Subsidence engineering, a well developed field in Great Britain and parts of Europe, is in its infancy in the United States. There is a need for data on surface and underground movements as subsidence develops in order to define the nature of subsidence processes in the United States and to develop methods for controlling subsidence and subsidence damage. Monitoring of underground mining needs to be emphasized to develop a broad based subsidence engineering capability in the United States.

Seventeen measurements were identified in this report as potentially useful in a subsidence monitoring program. Of them, only ground surface vertical settlement measurements have been made extensively in the United States. All of the surface measurements, however, have been made to some degree in other countries. Surface movements alone cannot be used to analyze the movements in strata above the mine, the progression of subsidence movements toward the surface, and the effect of the mining method and geology on subsidence development. Additional information is also needed to supplement surface measurements to evaluate the effectiveness of subsidence control measures and to control underground operations to limit subsidence damage. It is therefore recommended that subsurface and mine level measurements be given more emphasis in subsidence monitoring programs.

Some of the mine level measurements, such as roof sag measurements, recommended in this report have been widely used to analyze mine and tunnel stability. Other recommended mine level and subsurface measurements, such as subsurface horizontal deformation and mine level prop loads, must still be field-demonstrated as appropriate and applicable to mining subsidence evaluation.

Over two hundred instruments were reviewed in the first appraisal of relevant instrumentation to make the recommended measurements. This list was analyzed and shortened to approximately one hundred instruments for presentation in Section 6.0 of this report. Finally, thirteen instruments were identified as most useful for a wide variety of subsidence monitoring problems.

For the measurements for which many appropriate instruments are available, the traditional, well-proven instruments almost always ranked highest in our selection system. The primary reason for this is equipment cost. Generally savings in labor during installation, operation and data reduction by the use of sophisticated equipment were not significant enough to warrant its use. For example, electronic distance measurement devices (EDM) showed great promise for ground surface and structure deformations, but were roughly ten times more expensive than precision levelling equipment or steel tape extensometers. For the cases studied, monuments are too closely spaced to realize the potential labor and time savings that EDMs can offer. Similarly, vibrating wire equipment often has excellent accuracy and resistance to environmental effects, but requires sophisticated, expensive signal conditioning equipment for readout. The ground elevation cart eliminates much human error and tedium in settlement measurements, but requires a large capital outlay for constructing the cart and demands high-powered computer capabilities for analyzing the data. For much of the advanced subsidence instrumentation, the price has to come down before traditional instrumentation will be challenged.

Surface instrumentation has been in use and has seen many refinements over the years. On the other hand, subsurface and mine level instrumentation is only beginning to come into general use. A primary obstacle to the increased use of subsurface instrumentation is the high cost of installation. In addition, installation of instrumentation at mine level may disrupt the mining operation. High instrument mortality rates due to accidental damage or unsuccessful installation are always a threat in the harsh subsurface and mine environments. We believe that the most pressing need in subsidence instrumentation is the development of more durable and more easily installed subsurface and mine level instruments.

The report develops six instrumentation systems applicable to a wide variety of subsidence monitoring problems. The systems were developed to emphasize low cost, ease of use and practical application. Because they utilize mostly well-established instrumentation, it is felt that the instrumentation systems presented here will be relevant and practical for many years to come. Nonetheless, subsidence instrumentation will be improved and new instruments developed in future years. The procedures presented in this report for instrument evaluation and selection will provide a guide for subsidence investigators to assess new instruments and compare their merits with current subsidence instrumentation.

APPENDIX A  
INSTRUMENT CAPABILITIES



TABLE A.1 - INSTRUMENT CAPABILITIES  
•Surveying Instruments•

Sheet 1 of 4

| INSTRUMENT                                                                                                                                                                                             | AVAILABILITY                                              | INSTRUMENT CHARACTERISTICS  | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                                         | ACCURACY                                                               | SENSITIVITY TO ENVIRONMENT                                                                 | CALIBRATION AND MAINTENANCE                                  | EASE/COST OF INSTALLATION               | EASE/COST OF OPERATION                                                                         | POWER REQUIREMENTS                    | EASE/COST OF DATA REDUCTION                                              | COST OF INSTRUMENT                        |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|-----------------------------|---------------------------------|------------------------|---------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------------|---------------------------------------|--------------------------------------------------------------------------|-------------------------------------------|
|                                                                                                                                                                                                        |                                                           |                             | REMOTE OR DIRECT                | ENTER SUBSISTANCE AREA |                                                               |                                                                        |                                                                                            |                                                              |                                         |                                                                                                |                                       |                                                                          |                                           |
| Steel tape<br><br>(structure and surface strain, surface and structure crack movement)                                                                                                                 | Lufkin; Chesterman; Keuffel & Esser                       | Portable, rugged, long life | Direct                          | Yes                    | 100 ft usually; available in 3 to 200 ft lengths              | ±0.01 ft                                                               | Temperature; wind; tension                                                                 | Periodically clean, oil, and calibrate against standard tape | Install reference points                | 2 tapemen plus 1 man to set stakes; use with tensioning device, taping pins, plumbbob          | None                                  | Simple                                                                   | 100 ft: \$30 to \$300                     |
| Invar tape<br><br>(structure and surface strain, surface and structure crack movement)                                                                                                                 | Keuffel & Esser                                           | Portable, prone to breaking | Direct                          | Yes                    | 50 ft to 100 ft                                               | ±0.005 ft                                                              | Wind; tension                                                                              | Clean periodically                                           | As above                                | 2 tapemen; use with tension frames and weights; for high accuracy repeat readings with 3 tapes | None                                  | Simple                                                                   | 100 ft: \$300<br>150 ft: \$400            |
| Spirit level with wood rod<br><br>(structure and surface settlement; mine convergence and roof sag)                                                                                                    | Kern; Keuffel & Esser; Wild; Eagle; David White; Jenoptik | Portable, rugged, long life | Direct                          | Yes                    | Maximum change in elevation between sights approx. 13 ft      | ±0.01 to ±0.03 ft for single reading; 0.05 to 0.1 ft over mile circuit | Temperature; wind; moisture; lessen sensitivity to temperature and moisture with invar rod | Check telescope alignment annually                           | Install reference points and benchmarks | 1 instrument man; 1 rod man                                                                    | None                                  | Simple; need 1 engineer; may use computer to reduce large volume of data | Level: \$300 to \$750; rod: \$60 to \$300 |
| Precision level (automatic or tilting with optical micrometer) with invar rod<br><br>(structure and surface settlement; with tape or tape extensometer for ground tilt; mine convergence and roof sag) | Jenoptik; Kern; Wild; Leitz; Zeiss                        | As above                    | Direct                          | Yes                    | As above; sight length greater than 7 ft and less than 150 ft | ±0.002 ft to ±0.005 ft over mile circuit                               | Wind; bright sunlight                                                                      | As above                                                     | As above                                | As above                                                                                       | None                                  | As above                                                                 | Level: \$850 to \$1500; rod: \$700        |
| Rotating beam laser with rod detector<br><br>(surface settlement; mine roof sag)                                                                                                                       | AGA; Deitzgen; MG Laser Systems; Laser Alignment          | Portable                    | Direct                          | Yes                    | 500 ft                                                        | Less than 200 ft: ±0.006 ft; 200 to 1000 ft: ±0.01 ft                  | Affected by vibration, fog, dust, smog, air turbulence, wind                               | Check beam alignment annually                                | Install reference points and benchmarks | 1 man operates rod and sets up laser                                                           | Rechargeable battery for 1 day's work | As above                                                                 |                                           |

TABLE A.1 - INSTRUMENT CAPABILITIES  
-Surveying Instruments (Continued)-

Sheet 2 of 4

| INSTRUMENT                                                                                                                                                                                                    | AVAILABILITY                        | INSTRUMENT CHARACTERISTICS                                          | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                          | ACCURACY                                                                                                                 | SENSITIVITY TO ENVIRONMENT                                                                                             | CALIBRATION AND MAINTENANCE        | EASE/COST OF INSTALLATION                                | EASE/COST OF OPERATION                                                                                       | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                            | COST OF INSTRUMENT                                                  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|---------------------------------------------------------------------|---------------------------------|------------------------|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------|
|                                                                                                                                                                                                               |                                     |                                                                     | REMOTE OR DIRECT                | ENTER SURSIS-ENCE AREA |                                                |                                                                                                                          |                                                                                                                        |                                    |                                                          |                                                                                                              |                    |                                                                                        |                                                                     |
| Transit (angles)                                                                                                                                                                                              | Gurley; Eagle; Path; Leitz; Paragon | Portable; rugged; long life                                         | Direct                          | Usually Yes            | Angles: 360° horizontal and vertical           | 20 seconds to 5 minutes; repeat angles for accuracy to 1 second                                                          | Direct sun; in tense heat; wind                                                                                        | Check telescope alignment annually | Install reference points and instrument stations if used | 1 surveyor, 1 rodman                                                                                         | None               | Read angle                                                                             | \$500 to \$1500                                                     |
| Theodolite or precision (1 sec or better) theodolite (as level: structure and surface settlement, mine roof sag; with steel tape in vertical angle traverse: surface and structure settlement, mine roof sag) | Kern; Wild; Jenoptik; Leitz         | Portable; rugged; more sensitive than transit due to optical system | Direct                          | Depends on use         | Angles: 360° horizontal and vertical           | Angles: 1 sec to 0.1 sec; 1:200,000 for precision theodolite                                                             | Temperature; wind; vibration; direct sun                                                                               | Check telescope alignment annually | Install reference points and instrument stations if used | 1 surveyor and 1 rodman                                                                                      | No                 | Simple; 1 engineer                                                                     | Theodolite \$1300 to \$4500; precision theodolite: \$3000 to \$9000 |
| Transit or theodolite with stadia rod (surface and structure settlement, surface and structure strain)                                                                                                        | As above                            | As above                                                            | Direct                          | Yes                    | Sight length: 5 ft to 400 ft for best accuracy | Distance: 1 ft in 400 ft and 10 ft in 1000 ft; Elevation: 0.1 ft to 0.5 ft in 400 ft                                     | As above; accuracy less on steep slopes                                                                                | As above                           | As above                                                 | As above                                                                                                     | No                 | 1 engineer; convert by tables or Beaman arc; may use computer for large volume of data | As above; stadia rod \$60-100                                       |
| Precision theodolite with tape for baseline (triangulation) (surface and structure settlement, surface and structure strain)                                                                                  | As above                            | As above                                                            | Direct                          | No                     |                                                | 1 sec instrument read to 0.2 sec by angle repetition: 1:20,000 to 1:50,000; best positional accuracy ±0.001 in ±0.005 ft | Temperature; wind; vibration; direct sun; temperature sensitivity can be made minimal by using invar tape for baseline | As above                           | Install reference points and 3 instrument stations       | 1 surveyor; and 1 rodman if targets not fixed; 2 men needed for taping of baselines between instrument piers | No                 | As above; computer programs readily available                                          | As above                                                            |
| Precision theodolite with subtense bar (surface and structure settlement, surface and structure strain)                                                                                                       | As above                            | As above                                                            | Direct                          | Yes                    | Sight length: 5 ft to 500 ft for best accuracy | ±0.1 ft in 500 ft ±0.02 ft in 100 ft                                                                                     | As above; minimal sensitivity to temperature                                                                           | As above                           | Install reference points                                 | 1 surveyor and 1 rodman                                                                                      | No                 | 1 engineer; convert by tables or simple calculations                                   | As above; subtense bar \$1300                                       |
| Reduction tachymeter with stadia rod (surface strain)                                                                                                                                                         | Kern; Wild; Jenoptik                | As above                                                            | Direct                          | Yes                    | As above                                       | ±0.01 ft in 100 ft                                                                                                       | Temperature; wind; vibration; direct sun                                                                               | As above                           | As above                                                 | As above                                                                                                     | No                 | Simple; multiply reading by constant                                                   | \$3300 to \$4200                                                    |



TABLE A.1 - INSTRUMENT CAPABILITIES  
 Surveying Instruments (Continued)

Sheet 3 of 4

| INSTRUMENT                                                                                                                                                                         | AVAILABILITY                                                                     | INSTRUMENT CHARACTERISTICS                                             | DATA COLLECTION CHARACTERISTICS |                       | RANGE                           | ACCURACY                                                                                                                           | SENSITIVITY TO ENVIRONMENT                                                                        | CALIBRATION AND MAINTENANCE                           | EASE/COST OF INSTALLATION                                     | EASE/COST OF OPERATION                                                                                                          | POWER REQUIREMENTS                                                              | EASE/COST OF DATA REDUCTION                                                                                                             | COST OF INSTRUMENT HARDWARE                                                                      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------------|---------------------------------|-----------------------|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
|                                                                                                                                                                                    |                                                                                  |                                                                        | REMOTE OR DIRECT                | ENTER, SUBSTANCE AREA |                                 |                                                                                                                                    |                                                                                                   |                                                       |                                                               |                                                                                                                                 |                                                                                 |                                                                                                                                         |                                                                                                  |
| Optical electronic distance measurement device (EDM)<br><br>(use with theodolite if not built-in)<br><br>(structure and surface strain)                                            | First developed 1948; AGA; Kern                                                  | Portable; retro-reflectors may be portable or fixed to reference point | Direct                          | Yes - rodman only     | 20,000 ft                       | $\pm 0.02$ to $0.2$ ft plus<br>1:25,000 to 1:650,000<br><br>Hekometer 3000: $\pm 0.0007$ ft plus<br>1:1,000,000 (as good as invar) | Temperature and pressure along line of sight; smog can disrupt readings; may be used day or night | Calibrate against 50 meter invar tape every two years | As above                                                      | 1 surveyor plus 1 laborer if retro-reflectors portable or adjustable; lower cost per mile of traverse than conventional methods | Rechargeable battery for 1 day's work                                           | Distance usually automatic; a few provide only phase shift and surveyor must convert to distance                                        | Typical EDM: \$34,000; Hekometer 3000: \$34,000; reflectors: \$0.50 to \$410                     |
| Infrared EDM<br><br>(use with theodolite if not built-in)<br><br>(structure and surface strain; wine convergence; structure settlement)                                            | Wild; AGA; Kern; Keuffel & Esser; Zeiss; HP; I-ecision; Cubic Corp; Tellurometer | As above                                                               | Direct                          | Yes - rodman only     | 1000 to 16,000 ft; minimum 1 ft | Typically $0.02$ ft plus<br>1:100,000 to 1:300,000;<br><br>Tellurometer NA 100: $0.002$ ft over 300 ft                             | Temperature and pressure; less sensitive than other EDM's; can use day or night and in bright sun | As above                                              | As above                                                      | As above                                                                                                                        | Rechargeable battery for 1 day's work                                           | Distance usually automatic; most have automatic correction for temperature and pressure                                                 | Reflectors: \$0.50 to \$260 each; EDM: \$3000 to \$7000 without theodolite; Tellurometer NA 100: |
| Infrared EDM (3-D trilateration)<br><br>(structure settlement and strain; ground surface strain and settlement)                                                                    | As above                                                                         | As above                                                               | Direct                          | No                    | As above                        | As above                                                                                                                           | As above                                                                                          | As above                                              | Install reference points and instrument stations              | 1 surveyor                                                                                                                      | As above                                                                        | As above; reduce distances to EDM to coordinates                                                                                        | As above                                                                                         |
| Laser EDM<br><br>(structure and surface strain)                                                                                                                                    | Developed late 1960's; AGA                                                       | As above                                                               | Direct                          | Yes - rodman only     | 5000 to 20,000 ft               | $\pm 0.01$ to $0.08$ ft and<br>1:1,000,000 to $0.015$ over 19 miles                                                                | Temperature and pressure; smog; dust; fog; air turbulence; sensitive to vibration                 | As above                                              | As above                                                      | 1 surveyor and 1 rodman                                                                                                         | Lower power consumption than other EDM's; rechargeable battery for 1 day's work | Distance automatic                                                                                                                      |                                                                                                  |
| EDM tachymeter<br>(distance, angles horizontal distance and elevation automatically computed)<br><br>(structure and surface settlement; strain and tilt; convergence and roof sag) | AGA geodimeter models 700 and 710; Wild model DI-35                              | Portable                                                               | Direct with portable reflectors | Yes - rodman only     | 1000 to 15,000 ft               | $\pm 0.02$ ft plus<br>1:1,000,000 to $\pm 0.02$ ft plus<br>5:1,000,000                                                             | Temperature; pressure; vibration; dust                                                            | As above                                              | Install reference points; install instrument stations if used | 1 surveyor and 1 rodman, if targets not fixed                                                                                   | Rechargeable battery for 1 day's operation                                      | Automatic data reduction; surveyor may have to enter horizontal or vertical angle to get horizontal distance and elevation (DI-35 only) | \$18,000; \$10,000 (DI-35 without theodolite); reflectors \$0.50 to \$260 each                   |

TABLE A.1 - INSTRUMENT CAPABILITIES  
-Surveying Instruments (Continued)-

Sheet 4 of 4

| INSTRUMENT                                                                       | AVAILABILITY                                              | INSTRUMENT CHARACTERISTICS | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                                                                        | ACCURACY                                                                      | SENSITIVITY TO ENVIRONMENT                                                                                              | CALIBRATION AND MAINTENANCE                | EASE/COST OF INSTALLATION                                                                                                   | EASE/COST OF OPERATION                | POWER REQUIREMENTS         | EASE/COST OF DATA REDUCTION                                                                 | COST OF INSTRUMENT |
|----------------------------------------------------------------------------------|-----------------------------------------------------------|----------------------------|---------------------------------|-----------------------|------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------------------|----------------------------|---------------------------------------------------------------------------------------------|--------------------|
|                                                                                  |                                                           |                            | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                                                              |                                                                               |                                                                                                                         |                                            |                                                                                                                             |                                       |                            |                                                                                             |                    |
| Close-range structure photogrammetry (structure strain, structure settlement)    | Wild P3 phototheodolite<br>Galileo-Santon phototheodolite | Portable                   | Remote                          | No                    | Depends on accuracy desired; portion of structure in each photograph should be less than 20 to 100 ft wide for best accuracy | ±0.002 ft achievable; 1:10,000 to 1:50,000 of width object in photograph      | Wind; weather; temperature; humidity and direct sunlight affect photo quality                                           | Requires control survey                    | Install permanent stations for camera set-up; two monuments required for photographing; install control points on structure | 1 surveyor                            | None                       | Stereoscope and photogrammetric plotter at minimum; usually computer used to analyze strain |                    |
| Close-range mine photogrammetry (mine convergence)                               | As above                                                  | Portable                   | Direct                          | Yes                   |                                                                                                                              |                                                                               | Lighting, humidity, vibration may affect photo quality                                                                  | As above                                   | As above; difficult to maintain reference points and instrument stations at mine level                                      | 1 surveyor                            | Mine illumination required | As above                                                                                    |                    |
| Aerial surface photogrammetry (B & W, color, IR) (surface strain and settlement) | Mine services of consultants                              | Portable                   | Remote                          | No                    | Photo scale: 1:10,000 to 1:30,000 most useful for subsidence detection                                                       | Can plot 5 ft contours with accuracy of ±4 ft horizontal and ±1.6 ft vertical | Best in late winter and early spring; vegetation may obscure details in summer; weather conditions affect photo quality | Calibrate with second-order surface survey | Install several reflectors or markers as control points at every mile                                                       | Use aerial photogrammetry consultants |                            | As above                                                                                    | Over \$10,000      |

TABLE A.2 - INSTRUMENT CAPABILITIES

-Settlement Devices-

Sheet 1 of 2

| INSTRUMENT                                                                                           | AVAILABILITY                                                          | INSTRUMENT CHARACTERISTICS                          | DATA COLLECTION CHARACTERISTICS |                            | RANGE                                                                       | ACCURACY       | SENSITIVITY TO ENVIRONMENT                                                                                                                                | CALIBRATION AND MAINTENANCE                                                                                                                                | EASE/COST OF INSTALLATION                                                                                                                                           | EASE/COST OF OPERATION                                                                                                                                              | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                          | COST OF INSTRUMENT HARDWARE                                                                                                                           |
|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-----------------------------------------------------|---------------------------------|----------------------------|-----------------------------------------------------------------------------|----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                      |                                                                       |                                                     | REMOTE OR DIRECT                | ENTER, SUBSIDENCE AREA     |                                                                             |                |                                                                                                                                                           |                                                                                                                                                            |                                                                                                                                                                     |                                                                                                                                                                     |                    |                                                                      |                                                                                                                                                       |
| Single point or multi-point Terzaghi differential settlement manometer (structure settlement)        | Serata; Galileo                                                       | Readout and hoses can be permanent or portable      | Direct                          | Yes                        | Up to 50 ft of settlement; distances up to 1000 ft between reference points | $\pm 0.25$ in. | Susceptible to barometric pressure variation, heating due to sunlight, temperature variations, and vandalism; water cannot be used in freezing conditions | Hoses must be free of air bubbles, dirt, algae; little difficulty to repair or replace hoses; survey elevation of readout stations before each observation | Install reference points on structure; provide protection for readout and hoses if permanent installation                                                           | Simple; two technicians for portable system, one for permanent installation; repeat measurement for each data point, and allow ample time for stilling oscillations | None               | Convert pressure differences or graduated scale reading to elevation | Multiple points and terminal point apparatus \$150 to \$500; deairing unit \$300 to \$800                                                             |
| Single point simple hose manometer (structure or surface settlement)                                 | Soil and rock instrumentation; also user fabricated, Dunncliff (1977) | Permanent for monitoring period; may be recoverable | Direct                          | No, if hose is long enough | Up to 20 ft of settlement                                                   | $\pm 0.50$ in. | As above                                                                                                                                                  | Hoses must be free of air bubbles, dirt, algae; difficult to repair or replace hoses; survey elevation of readout station before each observation          | Hose placed in trench of uniform grade below frost depth and buried; provide protection for readout device; readout must be installed below lowest point along hose | Simple; one person to take reading                                                                                                                                  | None               | As above                                                             | Readout \$150; tubing \$0.30/ft deairing unit \$300 to \$800                                                                                          |
| Single point or multi-point electrical contact type hose manometer (structure or surface settlement) | Soil and Rock Instrumentation; Soil Instruments                       | As above                                            | Direct                          | As Above                   | Up to 3 ft of settlement                                                    | $\pm 0.10$ in. | As above; problems with electronics likely; mercury is used in freezing temperatures                                                                      | As above                                                                                                                                                   | As above; install readout at same elevation as manometer hose                                                                                                       | Simple; one person to adjust readout, establish electric contact, and take reading                                                                                  | Battery            | As above                                                             | 100 ft long manometer with readout, electronics, mercury and nitrogen regulation, single point \$250, multi-point \$450; deairing unit \$300 to \$800 |
| Single point overflow type manometer (structure or surface settlement)                               | Telemac; Soil Instruments; Galileo                                    | As above                                            | Direct                          | As Above                   | Up to 3 ft of settlement                                                    | $\pm 0.20$ in. | Susceptible to barometric pressure variation, heating due to sunlight, temperature variations, freezing conditions and vandalism                          | As above                                                                                                                                                   | As above; overflow cell is buried; readout must be installed below lowest point along hose                                                                          | Simple; one person to add water, confirm overflow and get reading                                                                                                   | None               | Convert graduated standpipe or pressure gage reading to elevation    | Overflow cell \$32; graduated standpipe \$35; tubing \$25/100 ft; deairing unit \$300 to \$800                                                        |
| Full profile overflow type manometer (structure or surface settlement)                               | Telemac                                                               | Permanent for monitoring period; recoverable        | Direct                          | As Above                   | Up to 10 ft of settlement                                                   | $\pm 0.10$ in. | As above                                                                                                                                                  | As above                                                                                                                                                   | Casing is placed in trench and buried; readout and pulley system installed in pit with protection provided                                                          | One person to move probe, add water, confirm overflow and get reading                                                                                               | None               | As above                                                             | Readout: manual \$3000; digital \$4500                                                                                                                |

TABLE A.2 - INSTRUMENT CAPABILITIES  
-Settlement Devices (Continued)-

Sheet 2 of 2

| INSTRUMENT                                                                                         | AVAILABILITY                     | INSTRUMENT CHARACTERISTICS                          | DATA COLLECTION CHARACTERISTICS |                       | RANGE                     | ACCURACY  | SENSITIVITY TO ENVIRONMENT                                                                                                                           | CALIBRATION AND MAINTENANCE                                                                                                                           | EASE/COST OF INSTALLATION                                                                        | EASE/COST OF OPERATION                                                          | POWER REQUIREMENTS                                     | EASE/COST OF DATA REDUCTION                                                                                                           | COST OF INSTRUMENT HARDWARE *                                                               |
|----------------------------------------------------------------------------------------------------|----------------------------------|-----------------------------------------------------|---------------------------------|-----------------------|---------------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
|                                                                                                    |                                  |                                                     | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                           |           |                                                                                                                                                      |                                                                                                                                                       |                                                                                                  |                                                                                 |                                                        |                                                                                                                                       |                                                                                             |
| Full profile air balloon in liquid filled tube settlement device (structure or surface settlement) | Soil Instruments                 | Probe and readout are portable                      | Direct                          | As Above              | Up to 10 ft of settlement | ±0.60 in. | Susceptible to variations in temperature and pressure; cannot be used in freezing conditions; possible electric problems with transducer and readout | Periodic calibration of transducer; calibrate steel tape with reference tape or bar; survey elevation at each readout station before each observation | Tube placed along trench, kept straight, brought to surface on gentle curve, and buried          | One person to move probe and take readings;                                     | Battery                                                | Convert electric readouts to elevation                                                                                                | Available with electromagnetic torpedo to monitor horizontal movement \$1500; casing \$3/ft |
| Full profile two liquid pressure balance manometer (structure or surface settlement)               | User fabricated; O'Rourke (1977) | Permanent for monitoring period; may be recoverable | Direct or Remote                | As Above              | Up to 20 ft of settlement | ±0.25 in. | As above;                                                                                                                                            | As above; calibration risers along tube allow for in-situ calibration along profile                                                                   | Tubing with calibration risers placed along trench of uniform grade below frost depth and buried | One person to move two liquid interface along tube, calibrate and take readings | None for manual readout; battery for automatic readout | Convert readings on pressure gage to elevation for manual readout. Automatic readout gives scaled chart recording of tubing elevation | Tubing \$0.30/ft; manual readout \$4000; automatic readout \$5500                           |

TABLE A.3 - INSTRUMENT CAPABILITIES

•Tiltmeters•

Sheet 1 of 1

| INSTRUMENT                                                                                                                   | AVAILABILITY                                         | INSTRUMENT CHARACTERISTICS                                               | DATA COLLECTION CHARACTERISTICS |                       | RANGE             | ACCURACY                    | SENSITIVITY TO ENVIRONMENT                                                                                                                                                      | CALIBRATION AND MAINTENANCE           | EASE/COST OF INSTALLATION                                                    | EASE/COST OF OPERATION                                                                                            | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                   | COST OF INSTRUMENT HARDWARE                |
|------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------|-----------------------|-------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------------|-------------------------------------------------------------------------------|--------------------------------------------|
|                                                                                                                              |                                                      |                                                                          | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                   |                             |                                                                                                                                                                                 |                                       |                                                                              |                                                                                                                   |                    |                                                                               |                                            |
| Electrolytic type tiltmeter<br><br>(ground tilt)                                                                             | BAC                                                  | Portable; long service records; permanent installation for best accuracy | Remote                          | Yes                   | 0.5 to 1.0 degree | 1.0 to 2.0 seconds of arc   | Sensitive to temperature; possible electric problems including zero drift due to residual instability of metals and cements; permanent installation may be subject to vandalism | Check for zero drift                  | Install base plates on reference stations                                    | One person with moderate training to take reading; portable device must be mounted on base plate for each reading | Battery            | Convert digital readout to tilt angle                                         | readout \$1500; stations to \$100 each     |
| Spirit level type tiltmeter<br><br>(ground tilt)                                                                             | Galileo                                              | Portable; rugged; long operating life                                    | Direct                          | Yes                   | 0.5 to 1.0 degree | 5.0 to 10.0 seconds of arc  | Moderately sensitive to temperature; reference points may be subject to vandalism                                                                                               | Check zero by readings at 180 degrees | As above                                                                     | Simple; one person to mount level and read                                                                        | None               | Simple; direct readout of tilt angle is given                                 | readout \$1200; stations to \$100 each     |
| Vibrating wire type tiltmeter<br><br>(ground tilt)                                                                           | Talemac; Mathak                                      | Portable; rugged; long term stability                                    | Remote                          | Yes                   | 1.5 degree        | 0.3 to 10.0 seconds of arc  | Relatively insensitive to temperature or moisture; reference points may be subject to vandalism                                                                                 | None                                  | As above                                                                     | One person to mount tiltmeter and take readings; time and training required depends on readout device used        | Battery            | Convert vibrating frequency, analog reading, or digital readout to tilt angle | Tiltmeter \$1200; readout \$3000 to \$4500 |
| Force balance servo-accelerometer type tiltmeter<br><br>(ground tilt)                                                        | Sinco; Terra; Technology; Schaevitz; Geo-testing     | Portable; moderately delicate                                            | Remote                          | Yes                   | ±30 degrees       | 10.0 to 80.0 seconds of arc | As above                                                                                                                                                                        | None                                  | As above                                                                     | One person with moderate training to mount tiltmeter and take reading                                             | Battery            | Convert digital readout to tilt angle                                         | Tiltmeter \$2900; readout \$1100           |
| Rod extensometer with micrometer and spirit level<br><br>(ground tilt)                                                       | Micro Precision Engr.; Galileo                       | Portable; rugged                                                         | Remote                          | Yes                   | 0.5 to 1.0 degree | 5.0 to 10.0 seconds of arc  | Moderately sensitive to temperature; reference points may be subject to vandalism                                                                                               | Check zero by readings at 180 degrees | Reference points embedded in soil, rock or structure                         | One person with moderate training to mount bar, adjust level and read                                             | None               | Simple; direct readout of tilt angle is given                                 | \$3500                                     |
| Rod extensometer with leveling bubble and leveling screw, and linear potentiometer, LVDT, or dial gauge<br><br>(ground tilt) | User fabricated; Hendron et al. (1975), Nason (1971) | Permanent for monitoring period                                          | Direct                          | Yes                   | 5.0 degrees       | 500 seconds of arc          | Susceptible to corrosion and vandalism unless protected                                                                                                                         | None                                  | Extensometer mounted on reference points embedded in soil, rock or structure | Simple; one person to adjust screw and take reading                                                               | None               | Convert leveling screw reading to tilt angle                                  | \$1500 to \$3500                           |

TABLE A.4 - INSTRUMENT CAPABILITIES  
-Strain/Displacement Monitoring Instruments-

Sheet 1 of 3

| INSTRUMENT                                                                                      | AVAILABILITY                                                                                | INSTRUMENT CHARACTERISTICS                                                             | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                                                                    | ACCURACY                                       | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                              | CALIBRATION AND MAINTENANCE                                                                                            | EASE/COST OF INSTALLATION                                                                                                                                                                              | EASE/COST OF OPERATION                                                                                                                  | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                     | COST OF INSTRUMENT                                                            |
|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------|-----------------------|--------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
|                                                                                                 |                                                                                             |                                                                                        | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                                                          |                                                |                                                                                                                                                                                                                         |                                                                                                                        |                                                                                                                                                                                                        |                                                                                                                                         |                    |                                                                                 |                                                                               |
| Rod extensometer with dial gauge<br><br>(ground or structure strain and crack movement)         | Terrametrics; Structural Behavior Engineering Laboratories or user fabricated; Mason (1971) | Permanent for monitoring period; recoverable; rugged and dependable                    | Direct                          | Yes                   | Displacement ranges to 1.0 in.; resettable gauge length 10 in. to 20 in.; if user fabricated gauge length may be 10 feet | Sensitivity of 0.0001 in.                      | Susceptible to vandalism unless protected; sensitive to temperature                                                                                                                                                     | Calibrate with standard reference bar; easy to replace                                                                 | Embed reference points in soil, rock or structure and attach bar; provide protection for instrument                                                                                                    | Simple; one person to read; can use camera recorder and replace film periodically                                                       | Battery for camera | Convert dial readings to displacement; temperature correction                   | \$100 to \$800                                                                |
| Steel tape extensometer<br><br>(ground or structure strain, convergence)                        | Sinco; Inrad; Terrametrics; Interfels; Silttest                                             | Portable; dependable                                                                   | Direct                          | Yes                   | Displacement ranges of 0.01 in. to 100 ft; gauge length 2 ft to 100 ft                                                   | $\pm 0.01$ in.                                 | Reference points susceptible to damage; sensitive to temperature                                                                                                                                                        | Problems with tape breaking; calibrate with standard reference bar; oil periodically and check tensioning device       | Embed reference points in soil, rock or structure                                                                                                                                                      | Simple; one or two people to attach extensometer to reference points, apply tension and read; two people need two hours for 15 readings | None               | Direct readout of distance makes data reduction simple; temperature corrections | \$500 to \$1500                                                               |
| Invar wire extensometer<br><br>(ground or structure strain, convergence)                        | Telemac; Kern                                                                               | Portable                                                                               | Remote                          | Yes                   | Displacement ranges of 2.5 in. to 4.0 in; gauge length of 3 ft to 150 ft                                                 | $\pm 0.0008$ in. to 0.002 in.                  | Reference points susceptible to damage; insignificant temperature effects                                                                                                                                               | Calibrate with standard reference bar; check periodically and check tensioning device as well as zero drift of readout | as above                                                                                                                                                                                               | as above                                                                                                                                | 12 VDC             | Digital readout of distance makes data reduction simple                         | \$4800                                                                        |
| Steel ruler<br><br>(structure crack movement)                                                   | Readily available                                                                           | Rugged and dependable                                                                  | Direct                          | Yes                   | Displacement ranges of 0.03 in. to 36.0 in.; gauge length to 36.0 in.                                                    | $\pm 0.06$ in.                                 | Reference points susceptible to damage; sensitive to temperature                                                                                                                                                        | Calibrate with standard reference bar                                                                                  | as above                                                                                                                                                                                               | Very simple                                                                                                                             | None               | Direct readout of distance makes data reduction simple; temperature correction  | \$70                                                                          |
| Rod extensometer with LVDT<br><br>(ground and structure strain and crack movement)              | User fabricated; Kennedy (1971)                                                             | Permanent for monitoring period; may be recoverable; suitable for long-term monitoring | Remote                          | No                    | Displacement ranges of 0.10 in. to 6 in.; gauge length 5 ft. to 10 ft.                                                   | $\pm 0.001$ in. possible; infinite resolution; | Electronics not very sensitive to vibration or temperature, but susceptible to changes in line resistance, cable length, or input voltage variance; may be subject to corrosion, vandalism and sensitive to temperature | Check for zero drift; easy to replace; calibrate with standard reference bar                                           | Embed reference points in soil, rock or structure, and attach bar; provide protection for instrument; establish zero reading; enclose in telescoping casing for monitoring convergence (at wire level) | Simple; one person to take reading                                                                                                      | None               | As above                                                                        | LVDT \$200; transducer amplifier and recorder readout \$800; cable \$14/20 ft |
| Rod extensometer with machinist's scale<br><br>(ground and structure strain and crack movement) | User fabricated; Utter and Tesco (1965)                                                     | May be permanent for monitoring period or may be portable                              | Direct                          | Yes                   | Displacement ranges of 0.1 in. to 10 ft; typical gauge length 3 ft to 10 ft                                              | Sensitivity of 0.01 in.                        | Susceptible to corrosion, vandalism and sensitive to temperature                                                                                                                                                        | Clean periodically; calibrate with standard reference bar; easy to repair                                              | Embed reference points in soil, rock or structure; provide protection for instrument                                                                                                                   | Simple; one person to take direct reading                                                                                               | None               | As above                                                                        | Materials and labor \$500                                                     |

TABLE A.4 - INSTRUMENT CAPABILITIES  
-Strain/Displacement Monitoring Instruments (Continued)-

Sheet 2 of 3

| INSTRUMENT                                                                                                                                 | AVAILABILITY                                                           | INSTRUMENT CHARACTERISTICS                                                             | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                                                   | ACCURACY                                               | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                                     | CALIBRATION AND MAINTENANCE                                                                                             | EASE/COST OF INSTALLATION                                                                                                                                                              | EASE/COST OF OPERATION                                                        | POWER REQUIREMENTS          | EASE/COST OF DATA REDUCTION                                                                                                                                       | COST OF INSTRUMENT                                                                                                                                  |
|--------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------|-----------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                            |                                                                        |                                                                                        | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                                         |                                                        |                                                                                                                                                                                                                                |                                                                                                                         |                                                                                                                                                                                        |                                                                               |                             |                                                                                                                                                                   |                                                                                                                                                     |
| Rod extensometer with micrometer<br><br>(surface or structure strains) and crack movement                                                  | Microprecision Engineering<br>Livermore, CA<br>Burland and Moore, 1973 | Portable                                                                               | Direct                          | Yes                   | Displacement ranges of 0.001 in. to 3.0 in.; typical gauge length 10 ft                                 | $\pm 0.005$ in.; sensitivity of 0.0004 in.             | Reference points susceptible to damage; sensitive to temperature unless Invar                                                                                                                                                  | Clean periodically; calibrate with standard reference bar; easy to repair                                               | Embed reference points in soil, rock, or structure                                                                                                                                     | One or two people to move bar, adjust micrometer and take reading             | Penlight battery            | Direct readout of distance makes data reduction simple; temperature correction                                                                                    | Materials and labor \$600                                                                                                                           |
| Telescoping tube extensometer with machinist's scale<br><br>(convergence)                                                                  | User fabricated; Utter and Tesch (1965)                                | Portable                                                                               | Direct                          | Yes                   | Displacement range 12.0 in.; typical gauge length 10 ft                                                 | Sensitivity of 0.01 in.                                | As above                                                                                                                                                                                                                       | As above; check spring tension                                                                                          | Embed reference points in roof, floor, and walls of mine                                                                                                                               | One to move rod and take readings                                             | None                        | As above                                                                                                                                                          | Materials and labor \$500                                                                                                                           |
| Invar telescoping tube extensometer with dial gauge or micrometer<br><br>(convergence; surface strain)                                     | Gisco; Senata                                                          | Portable                                                                               | Direct                          | Yes                   | Displacement range 2.0 in.; gauge lengths of 3.0 ft to 25.0 ft                                          | Sensitivity of 0.001 in.                               | Reference points susceptible to damage; invar tube has low temperature sensitivity                                                                                                                                             | Clean periodically; calibrate with standard reference bar; easy to repair                                               | As above                                                                                                                                                                               | As above                                                                      | None                        | Direct readout of distance makes data reduction simple                                                                                                            | 3 ft to 6 ft gauge length \$650, 17 ft to 25 ft gauge length \$895                                                                                  |
| Rod extensometer with spring-tensioned vibrating wire strain gauge in telescoping casing<br><br>(convergence; surface or structure strain) | Maihak; Telemec, Galileo                                               | Permanent for monitoring period; may be recoverable; suitable for long term monitoring | Remote                          | No                    | Displacement ranges to 10 in.; gauge lengths to 50 ft                                                   | $\pm 0.004$ in.                                        | Sensors are waterproofed at factory and safe in moderate water pressure; vibrating wire is temperature compensated but rod is sensitive to temperature unless made of Invar; may be subject to vandalism                       | Calibrate with reference bar or tape in field; easy to repair or replace if accessible; usually no maintenance required | Install in trench or between anchors embedded in soil or rock; use good practice to maintain dry circuitry for electrical connections; tension anchorage cable; establish zero reading | One person; training and time required depends on type of readout device used | AC main or battery operated | Depends on readout device used; convert vibrating frequency; micrometer reading; dial reading or digital readout to displacement; possible temperature correction | Readout \$1500-\$4500; Extensometer 1 in displacement \$525; 1/8 in displacement \$700; cable \$0.40/ft                                             |
| Telescoping rod extensometer with linear potentiometer<br><br>(surface or structure strain)                                                | Sineco Soil Instruments                                                | Permanent for monitoring period; may be recoverable                                    | Remote                          | No                    | Displacement ranges of 0.5 in. to 2.0 ft; gauge length of 5 ft to 25 ft common; greater length possible | $\pm 0.01$ in.; sensitivity of 0.0005 in. to 0.006 in. | Electronics susceptible to moisture, changes in line resistance, changes in cable length, input voltage variance, and temperature variation; Invar rod may be used to reduce temperature sensitivity; may be subject to damage | As above; also have problems with zero drift                                                                            | Install in trench or between anchors embedded in soil, rock, or structure; establish zero reading; anchors \$15 to \$30                                                                | One person to read; straight forward signal conditioning                      | Battery powered             | Depends on readout device used; direct digital readout of distance, or convert voltage to distance; temperature correction possible                               | 6 in displacement potentiometer \$250; telescoping rod 5 ft gauge length \$110 25 ft gauge length \$199 voltage-type readout \$400; cable \$0.60/ft |
| (convergence)                                                                                                                              | User fabricated; Hinsley and King (1966)                               | Permanent; cannot usually be recovered; robust mechanically                            | Remote                          | No                    | Displacement range of 15 in.; gauge lengths to 25 ft common; greater length possible                    | $\pm 0.02$ in.                                         | As above                                                                                                                                                                                                                       | As above                                                                                                                | Embed rod anchors in roof and floor or mine. Use mechanical or grouted anchors.                                                                                                        | As above                                                                      | As above                    | As above                                                                                                                                                          | As above                                                                                                                                            |

TABLE A.4 - INSTRUMENT CAPABILITIES  
-Strain/Displacement Monitoring Instruments (Continued)-

Sheet 3 of 3

| INSTRUMENT                                                                            | AVAILABILITY                                                 | INSTRUMENT CHARACTERISTICS                                                    | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                                                   | ACCURACY                                    | SENSITIVITY TO ENVIRONMENT                                                                                                                                         | CALIBRATION AND MAINTENANCE                                                    | EASE/COST OF INSTALLATION                     | EASE/COST OF OPERATION                                                        | POWER REQUIREMENTS          | EASE/COST OF DATA REDUCTION                                                                                                  | COST OF INSTRUMENT HARDWARE                                        |
|---------------------------------------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------|-----------------------|---------------------------------------------------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|
|                                                                                       |                                                              |                                                                               | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                                         |                                             |                                                                                                                                                                    |                                                                                |                                               |                                                                               |                             |                                                                                                                              |                                                                    |
| Sonic pulse linear displacement transducer strain gauge<br>(structure crack movement) | Tempo Instruments                                            | Permanent for monitoring period; may be recoverable; completely solid state   | Remote                          | No                    | Displacement ranges of 12 in. to 60 in.; gauge length 15 in. to 63 in.                                  | $\pm 0.024$ in. to 0.12 in.                 | Sealed from industrial environment; low temperature sensitivity; magnetic fields generated by 60 Hz to 140 Hz equipment will not have effect; subject to vandalism | Includes provision for external fine zero-position adjustment; can be replaced | Attach to structure; establish zero reading   | One person; straight-forward signal conditioning                              | 15 VDC or 115 VAC 60 Hz     | Convert sonic pulse travel time to strain; temperature correction                                                            |                                                                    |
| Dial indicator mechanical strain gauge<br>(structure crack movement)                  | Weidman Division; W.H. Mayes; LNEC; Sattler; Demec; Galileo; | Portable                                                                      | Direct                          | Yes                   | Displacement ranges of 0.0025 in. to 2.5 in.; 0.2 in. typical; resettable; gauge length 2 in. to 50 in. | Sensitivity of 5 to 10 $\mu$ strain at best | Sensitive to temperature; reference points susceptible to damage                                                                                                   | May be calibrated in field with portable standard bar                          | Embed permanent reference points in structure | One person; accuracy depends on skill of operator                             | None                        | Convert dial reading to strain; temperature correction                                                                       | \$675 to \$750                                                     |
| Vibrating wire strain gauge<br>(structure crack movement)                             | Telemec; Mainak; Irad; Galileo; Terrametrics; Deakin         | Permanent for monitoring period; may be recoverable; good long term stability | Remote                          | No                    | Displacement ranges of 0.0025 in. to 0.10 in.; gauge length 1 in. to 14 in.                             | Sensitivity 1 to 2 $\mu$ strain             | Not affected by moist, wet environment; corrosion-resistant; low temperature sensitivity; may be subject to vandalism                                              | Moderate problems with zero drift; can be replaced                             | Attach to structure; establish zero reading   | One person; training and time required depends on type of readout device used | AC main or battery operated | Depends on readout device used; convert vibrating frequency, micro-meter reading, dial reading, or digital readout to strain | Gauge \$60 to \$140; Cable \$0.40 per ft; readout \$1500 to \$4500 |
| Scratch strain gauge<br>(structure crack movement)                                    | Prewitt Associates                                           | Permanent for monitoring period; may be recoverable; very durable and stable  | Direct                          | Yes                   | Displacement ranges of 12 in. to 0.10 in.; gauge length 8 in. to 100 in.                                | Sensitivity of 30 $\mu$ strain              | Waterproof; corrosion-resistant; shock resistant; moderate temperature correction; may be subject to vandalism                                                     | Can be replaced                                                                | Attach to structure                           | One person to replace scratch disk                                            | None                        | Read scratch disc with calibrated microscope or optical scanner and computer;                                                | Gauge \$170 to \$290; Scratch disks \$6 microscope \$200           |



TABLE A.5 - INSTRUMENT CAPABILITIES

-Extensometers-

Sheet 1 of 4

| INSTRUMENT                                                                                                                                                              | AVAILABILITY                                                            | INSTRUMENT CHARACTERISTICS                                                                      | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                                                                                    | ACCURACY                                                                             | SENSITIVITY TO ENVIRONMENT                                                                                                            | CALIBRATION AND MAINTENANCE                                                                                                          | EASE/COST OF INSTALLATION                                                                                                                                                                                                                                                       | EASE/COST OF OPERATION                                                                                       | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                             | COST OF INSTRUMENT HARDWARE                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------|------------------------|----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                         |                                                                         |                                                                                                 | REMOTE OR DIRECT                | ENTER SUBSIDIANCE AREA |                                                                                                          |                                                                                      |                                                                                                                                       |                                                                                                                                      |                                                                                                                                                                                                                                                                                 |                                                                                                              |                    |                                                                                         |                                                                                                                                                                                                                                |
| Single point borehole extensometer (SPBX) wire type, weight-anchored and weight-tensioned with dial gauge (subsurface vertical deformation, roof strata separation)     | User-fabricated; Lofgren (1969)                                         | Permanent for monitoring period; remains operational for many years; may be recoverable; rugged | Direct                          | Yes                    | Displacement range 2.0 in., resettable; boreholes to 2200 ft                                             | Sensitivity of 0.001 in.; accuracy reduced for wires over 30 ft. long                | Wire is susceptible to creep and temperature; susceptible to vandalism                                                                | None; dial gauge easy to replace if damaged                                                                                          | Subsurface: weight-tensioned wire is anchored in bottom of borehole; borehole cased to within one foot of bottom if necessary; keep wire from getting kinked or bent                                                                                                            | Simple; one person to read dial; Survey elevation of borehole collar                                         | None               | Simple; dial reading converted to displacement                                          | Materials and labor for surface station \$500; wire \$0.04 to \$0.08 per foot casing \$3/ft                                                                                                                                    |
| SPBX wire type, weight-anchored and weight-tensioned, with rotary potentiometer (subsurface vertical settlement, also surface settlement if anchored below mined level) | Sinco                                                                   | Permanent for monitoring period; may be recoverable                                             | Remote                          | No                     | Displacement range up to 9 ft                                                                            | <0.02 in.; sensitivity of 0.001 in.; accuracy reduced for wires more than 30 ft long | As above; sensing unit can be recessed to protect it from damage                                                                      | None; may be difficult to repair or replace sensor after it is buried                                                                | Subsurface: install telescoping casing in borehole; weight-tensioned wire placed in borehole; keep wire from getting kinked or bent                                                                                                                                             | Simple; one person to get reading; straight forward signal conditioning; Survey elevation of borehole collar | Battery            | Simple; convert readout to displacement                                                 | Sensing unit and weights \$310; readout \$486; remote terminal station \$97.50 electrical cable \$0.30/ft; casing \$6/ft; wire \$0.04 to \$0.08/ft                                                                             |
| Multi-point borehole extensometer (MPBX) wire type, weight-tensioned with pulley and dial gauge (subsurface vertical deformation or roof strata separation)             | Interfels Galileo; also user fabricated, Sellers (1966), Maddell (1964) | Permanent installation; measuring head may be recoverable                                       | Direct                          | Yes                    | Displacement ranges of 0.5 in. to 2.0 in., resettable, anchors may be up to 1000 ft from measuring head  | Sensitivity of 0.004 in. to 0.04 in.; accuracy reduced for wires over 30 ft long     | Wire is susceptible to creep, and sensitive to temperature; problems with system friction; measuring head may be subject to vandalism | None; easy to repair or replace pulley and dial gauge assembly                                                                       | Casing not required; surface: wires run through telescoping casing and attached to plates in trench; subsurface and mine level: each wire runs through a flexible tube and is attached to an anchor; then each is installed in borehole; skill required when working with wires | Simple; one person to read dial; Survey elevation of borehole collar                                         | None               | Simple; convert dial reading to displacement                                            | Measuring head anchors, wire, and casing \$4000/1000 ft                                                                                                                                                                        |
| MPBX wire type, spring-tensioned or cantilever-tensioned with dial gauge or micrometer (subsurface vertical deformation or roof strata separation)                      | Terrametrics; Peter Smith Instruments                                   | As above                                                                                        | Direct                          | Yes                    | Displacement range 3 in., resettable if spring-tensioned; anchor may be up to 500 ft from measuring head | Sensitivity of 0.001 in.; accuracy reduced for wires more than 30 ft long            | As above                                                                                                                              | Adjust wire tension after installation in borehole; adjust spring tension periodically; difficult to replace sensing head if damaged | As above                                                                                                                                                                                                                                                                        | As above                                                                                                     | None               | Convert dial reading to displacement; correct for variable spring or cantilever tension | Dial gauge \$123; sensing head with 8 cantilevers \$700; head with 6 coiled springs \$1135; anchors \$15 to \$50 each; wire \$0.04 to \$0.08/ft; tubing for wire \$0.07 to \$0.50/ft; setting rod extensions \$20 to \$40 each |

TABLE A.5 - INSTRUMENT CAPABILITIES

-Extensometers (Continued)-

Sheet 2 of 4

| INSTRUMENT                                                                                                                                          | AVAILABILITY                                                      | INSTRUMENT CHARACTERISTICS                          | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                                                 | ACCURACY                                 | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                                               | CALIBRATION AND MAINTENANCE                                                                                                       | EASE/COST OF INSTALLATION                                                                                                                             | EASE/COST OF OPERATION                                                                                             | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                                                         | COST OF INSTRUMENT HARDWARE                                                                                                                                             |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|-----------------------------------------------------|---------------------------------|-----------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------|---------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                     |                                                                   |                                                     | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                                       |                                          |                                                                                                                                                                                                                                          |                                                                                                                                   |                                                                                                                                                       |                                                                                                                    |                    |                                                                                                                     |                                                                                                                                                                         |
| Single point borehole extensometer (SPBX) rod type, with rotary potentiometer; (subsurface vertical deformation)                                    | User fabricated; Burn (1959)                                      | Permanent for monitoring period; may be recoverable | Remote                          | No                    | Displacement range of 27.0 in. or more; rods up to 120 ft long have been used                         | ±0.05 in.                                | Rod susceptible to temperature variation; electrical equipment is sensitive to temperature, changes in line resistance, cable length, input voltage variance, zero drift, and moisture; susceptible to damage unless buried or protected | Difficult to repair or replace sensor if recessed                                                                                 | Subsurface and mine level; anchor attached to moveable rod inside guide pipe; pre-assembled before installed in borehole; installation tools required | Simple; one person to take reading; straight forward signal conditioning; Survey elevation of borehole collar      | Battery            | Convert voltage or digital readout to displacement                                                                  | Readout \$500; potentiometer \$200; cable \$0.80/ft; rods \$1.50/ft; anchors \$15 to \$90 each; fabrication labor \$400; installation tools \$300; guide pipe \$1.50/ft |
| SPBX or multi point borehole extensometer (MPBX) rod type, with linear potentiometer (subsurface vertical deformation, mine roof strata separation) | Terra Technology; Interfels; Sincro; Irad                         | As above                                            | Remote                          | No                    | Displacement range of 1.0 in. to 6.0 in.; some are resettable                                         | Sensitivity of 0.0005 in. to 0.001 in.   | As above                                                                                                                                                                                                                                 | Resetting may be required; flexible rod type has spring which must be adjusted; difficult to repair or replace sensor if recessed | As above; some types not suitable for use at mine level; rods may or may not be in guide pipes; installation tools available                          | As above                                                                                                           | Battery            | As above                                                                                                            | Readout \$400; potentiometer \$250; rods \$2/ft; anchor \$15 to \$90 each; installation tools \$300; cable \$0.80/ft; guide pipe \$1.50/ft                              |
| SPBX or MPBX rod type, with LVDT (subsurface vertical deformation, mine roof strata separation)                                                     | Interfels                                                         | As above                                            | Remote                          | No                    | Displacement range up to 0.5 in; lengths up to 600 ft have been used                                  | High; sensitivity of 0.0005 to 0.005 in. | As above                                                                                                                                                                                                                                 | Difficult to repair or replace sensor if recessed                                                                                 | Subsurface and mine level; anchors attached to moveable rods inside guide pipes; assembly installed in borehole                                       | As above                                                                                                           | Battery            | As above                                                                                                            | LVDT \$374/rod; rods \$1.50/ft; anchors \$15 to \$90 each; readout \$1000; guide pipe \$1.50/ft                                                                         |
| MPBX, rod type with reed switches, LVDT and magnetic rings (mine roof strata separation)                                                            | Developmental Woodward-Clyde Consultants (1976b); (Burland, 1972) | As above                                            | Remote                          | No                    | Displacement range up to 6.0 in.                                                                      | ±0.001 in.                               | As above                                                                                                                                                                                                                                 | Simple calibration before each reading, difficult to repair or replace sensor and rod if recessed                                 | Mine level; ring magnets installed along borehole; install reed switches along rod at 0.5 in. below mating ring magnet; installation tools needed     | As above                                                                                                           | Battery            | As above                                                                                                            | Ring magnets \$22 to \$60; rod with reed switches \$20/ft; cable \$1/ft; LVDT \$200 each; readout \$1000; installation tools \$100; guide pipe \$1.50/ft                |
| SPBX, rod type with vibrating wire strain gauges; (subsurface vertical deformation, roof strata separation)                                         | Mohak; Telemac                                                    | As above; good long term stability                  | Remote                          | No                    | Displacement range 0.5 in. to 8.0 in. standard rod length 30 ft to 50 ft; additional length available | ±0.0007 in. to 0.03 in.                  | Rod susceptible to temperature variation; electronics are stable with respect to time, temperature and environment; susceptible to damage unless buried or protected                                                                     | Difficult to repair or replace sensor if recessed                                                                                 | Subsurface and mine level; anchors attached to moveable rods inside guide pipes; pre-assembled before installed in borehole                           | One person; training and time required depends on type of readout device used; Survey elevation of borehole collar | Battery            | Depends on readout device used; convert vibrating frequency, micrometer reading, or digital readout to displacement | 50 foot rod \$750-\$925; readout \$1500-\$4500; terminal box \$28-\$46; cable \$0.50/ft                                                                                 |
| SPBX or MPBX, rod type with dial gauge or micrometer (subsurface vertical deformation, roof strata separation)                                      | Irad; Telemac; Interfels                                          | As above                                            | Direct                          | Yes                   | Displacement range 2.0 in. resettable; standard rod length 10 ft to 50 ft.                            | ±0.10 in.; sensitivity of 0.001 in.      | Rod susceptible to temperature variation; measuring head susceptible to damage unless protected                                                                                                                                          | May need to reset dial gauge or micrometer                                                                                        | As above; installation tools available                                                                                                                | Simple; one person to read dial; Survey elevation of borehole collar                                               | None               | Convert dial reading to displacement                                                                                | Dial gauge \$130; rods with guide tube \$ 5/ft; anchors \$15 to \$90 each; installation tools \$100                                                                     |

TABLE A.5 - INSTRUMENT CAPABILITIES

•Extensometers (Continued)•

Sheet 3 of 4

| INSTRUMENT                                                                                                                                          | AVAILABILITY                                                       | INSTRUMENT CHARACTERISTICS                                                                                  | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                    | ACCURACY                                                                                     | SENSITIVITY TO ENVIRONMENT                                                                                                                             | CALIBRATION AND MAINTENANCE                                                                                                       | EASE/COST OF INSTALLATION                                                                                                                                                                                                           | EASE/COST OF OPERATION                                                                                             | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                                                                                         | COST OF INSTRUMENT HARDWARE                                                                                                                                                  |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|---------------------------------|-----------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                     |                                                                    |                                                                                                             | REMOTE OR DIRECT                | ENTER SUBSIDIARY AREA |                                                                          |                                                                                              |                                                                                                                                                        |                                                                                                                                   |                                                                                                                                                                                                                                     |                                                                                                                    |                    |                                                                                                                                                     |                                                                                                                                                                              |
| MPBX wire type, spring-tensioned with rotary potentiometer (subsurface vertical deformation, roof strata separation convergence)                    | Sinco; user fabricated arrangement for convergence at mine level   | Permanent installation; sensing head may be recoverable; problems have been noted over long term monitoring | Remote                          | No                    | Displacement range 1.0 in., resettable                                   | ±0.02 in.; sensitivity of 0.002 in.; accuracy reduced for wires more than 30 ft long         | As above                                                                                                                                               | Adjust wire tension after installation; calibrate readout with sensing head; difficult to replace if sensing head damaged         | As above; enclose instrument in telescoping casing for monitoring convergence at mine level                                                                                                                                         | As above                                                                                                           | Battery            | Convert voltage readout to displacement                                                                                                             | Readout \$400; sensing head for 6 anchors \$1180; wire \$0.35/ft; anchors \$55 to \$90 each; installation tools \$275                                                        |
| MPBX wire type, cantilever-tensioned or spring-tensioned with vibrating wire strain gauge (subsurface vertical deformation, roof strata separation) | Telemac; user fabricated arrangement for convergence at mine level | Permanent installation; sensing head may be recoverable; long term stability                                | Remote                          | No                    | Displacement ranges of 0.5 in. to 2.0 in.                                | High; sensitivity of 0.0002 in. to 0.01 in.; accuracy reduced for wires more than 30 ft long | Wire is susceptible to creep and sensitive to temperature; problems with system friction; sensing head may be subject to vandalism                     | As above                                                                                                                          | Subsurface and mine level; all wires are individually guided in tubing; anchor systems are shop mounted and ready for introduction into borehole; enclose instrument in telescoping casing for monitoring convergence at mine level | One person; training and time required depends on type of readout device used; Survey elevation of borehole collar | Battery            | Depends on readout device used; convert vibrating frequency micrometer reading, or digital readout to displacement; possible temperature correction | Readout \$1500 to \$4500; sensing head for 6 anchors \$1725; anchor system 100 ft long \$1250; field calibration tool \$140; electrical cable \$1.95/ft; switching box \$240 |
| MPBX wire type, cantilever-tensioned with bonded resistance strain gauges (subsurface vertical deformation or roof strata separation)               | Terrametrics                                                       | As above; problems reported with long term monitoring                                                       | Remote                          | No                    | Displacement range 1.0 in.; anchor may be up to 500 ft from sensing head | Sensitivity of 0.0005 in.; accuracy reduced for wires over 30 ft long                        | As above; electrical equipment is sensitive to temperature, changes in line resistance, cable length, input voltage variance, zero drift, and moisture | Adjust wire tension after installation; calibrate readout and cantilever deflection; difficult to replace sensing head if damaged | As above                                                                                                                                                                                                                            | Simple; one person to read; straight forward signal conditioning; Survey elevation of borehole collar              | None               | Convert voltage or digital readout to displacement                                                                                                  | Readout \$1125; cable \$3.75/ft; sensing head with 8 cantilevers \$1220; other accessories                                                                                   |

TABLE A.5 - INSTRUMENT CAPABILITIES

•Extensometers (Continued)•

Sheet 4 of 4

| INSTRUMENT                                                                                                                                                     | AVAILABILITY                       | INSTRUMENT CHARACTERISTICS                                                                                    | DATA COLLECTION CHARACTERISTICS |                          | RANGE                                                                              | ACCURACY                                                                                       | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                                        | CALIBRATION AND MAINTENANCE                                                                         | EASE/COST OF INSTALLATION                                                                                                                                                                         | EASE/COST OF OPERATION                                                                                                                             | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                             | COST OF INSTRUMENT                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------|--------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                |                                    |                                                                                                               | REMOTE OR DIRECT                | ENTER OR SUBSIDENCE AREA |                                                                                    |                                                                                                |                                                                                                                                                                                                                                   |                                                                                                     |                                                                                                                                                                                                   |                                                                                                                                                    |                    |                                                                                         |                                                                                                                                                                             |
| Full profile borehole extensometer (FPBK) with reed switch torpedo with casing and magnets<br><br>(subsurface vertical deformation, surface horizontal strain) | Soil Instruments; Terra Technology | Torpedo, and readout are portable                                                                             | Direct                          | Yes                      | 100 ft cable; or series of 10 ft rods                                              | $\pm 0.10$ in. with calibrated cable<br>$\pm 0.01$ in. with rods and vernier winding mechanism | Probe is waterproof; calibrated cable or rods sensitive to temperature                                                                                                                                                            | Calibrate with standard reference tape or bar; problems with probe when battery starts losing power | On surface: casing with magnets placed along trench and embedded; subsurface: casing with magnets installed in borehole, placing tool available for boreholes                                     | One person with simple training to move torpedo mounted on cable or rods and to determine location of magnets; Survey elevation of borehole collar | Battery            | Direct readout of distance makes data reduction simple; possible temperature correction | Torpedo, cable and indicator \$1600; rods and readout \$22/10 ft; vernier winding mechanism \$185; magnetic rings \$22 to \$60; casing \$4/10 ft; placing tool \$50         |
| FPBK with electromagnetic torpedo and flexible casing with metal rings<br><br>(subsurface vertical deformation, surface horizontal strain)                     | Sinco; Idel; Mathak; Telerac       | Torpedo and readout are portable                                                                              | Direct                          | Yes                      | 250 ft cable                                                                       | $\pm 0.10$ in.; sensitivity of 0.01 in.                                                        | Probe is waterproof; steel tape is sensitive to temperature                                                                                                                                                                       | As above                                                                                            | On surface: casing with metal rings placed along trench and embedded; subsurface: casing with metal rings installed in borehole                                                                   | One person with simple training to move torpedo and determine location of magnets; Survey elevation of borehole collar                             | Battery            | As above                                                                                | Torpedo, 250 ft cable with steel tape and indicator \$825; corrugated casing with sensing rings and rigid PVC casing \$4.35/ft; extra rings \$5 each; couplings \$6.55 each |
| FPBK with latch-type probe with telescoping casing<br><br>(subsurface vertical deformation)                                                                    | Sinco                              | Probe is portable and rugged                                                                                  | Direct                          | Yes                      | Each 5 ft or 10 ft section of casing can be displaced up to 12 in; use 200 ft tape | Sensitivity of 0.02 in.                                                                        | Steel tape is sensitive to temperature; dirt in casing may foul probe and make it difficult to latch on to bottom of casing section                                                                                               | Calibrate with standard reference tape or bar; clean periodically                                   | Subsurface: telescoping casing installed in borehole, requires tedious effort                                                                                                                     | One person with simple training to move probe, latch it on to bottom of casing sections, read tape; Survey elevation of borehole collar            | None               | As above                                                                                | Telescoping casing \$6 / ft; latch probe \$125; 200 ft tape \$123                                                                                                           |
| FPBK, radioactive bullets and gamma-gamma density logger<br><br>(subsurface vertical deformation)                                                              | Schlumberger                       | Probe and readout are portable                                                                                | Direct                          | Yes                      | Boreholes 500 ft to 600 ft deep                                                    | $\pm 0.5$ in. to 13.0 in.                                                                      | Affected by radio interference; cable or tape may be sensitive to temperature                                                                                                                                                     | Calibrate with standard reference tape or bar; problems with probe when battery starts losing power | Subsurface or mine level: radioactive bullets injected into sides of borehole; borehole must be kept open                                                                                         | One person with simple training to move logger and locate bullets; Survey elevation of borehole collar                                             | Battery            | As above                                                                                |                                                                                                                                                                             |
| FPBK, time domain reflectometry<br><br>(subsurface vertical deformation)                                                                                       | Hewlett-Packard; Tektronix         | Permanent for monitoring period; readout is portable; significant potential for long-term monitoring problems | Remote                          | No                       | Coaxial cable up to 4900 ft                                                        | Sensitivity of 0.25 in.                                                                        | Sensitive to bad electrical connections which make it difficult to locate disruptions along coaxial cable; susceptible to changes in line resistance, cable length, input voltage variance, and temperature variation along cable | Calibrated before and after installation; zero drift very likely                                    | Surface: coaxial cable placed in trench and embedded; subsurface or mine level: coaxial cable grouted into borehole; calibrate system before and after installation; establish initial conditions | Simple; one person to take reading; straight forward signal conditioning; Survey elevation of borehole collar                                      | Battery or AC main | Experienced personnel to recognize variations in readings and interpret results         | Signal conditioner and readout \$2000; 1/8 in. 50-ohm coaxial cable \$6; 50-ohm borehole cable \$10/6 ft                                                                    |

TABLE A.6 - INSTRUMENT CAPABILITIES  
-Inclinometers-

Sheet 1 of 2

| INSTRUMENT                                                                                                                                      | AVAILABILITY                            | INSTRUMENT CHARACTERISTICS                                                                                    | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                                                              | ACCURACY                                      | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                          | CALIBRATION AND MAINTENANCE                                                                                                                         | EASE/COST OF INSTALLATION                                                                                                                                | EASE/COST OF OPERATION                                                                                               | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                    | COST OF INSTRUMENT HARDWARE                                                                                                         |
|-------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------|------------------------|------------------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------------|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                 |                                         |                                                                                                               | REMOTE OR DIRECT                | ENTER SURVEILANCE AREA |                                                                                    |                                               |                                                                                                                                                                                                     |                                                                                                                                                     |                                                                                                                                                          |                                                                                                                      |                    |                                                                                |                                                                                                                                     |
| Full profile borehole inclinometer (FPBI) servo-accelerometer torpedo<br><br>(subsurface horizontal deformation, surface settlement)            | Sinco, Geotesting, Terra Technology     | Portable; moderately delicate<br><br>Note: different torpedo required for horizontal or vertical measurements | Direct                          | Yes                    | ±30 degrees<br><br>(±90 degree models available)                                   | 20 to 30 sec.<br>(.005 ft per 100 ft depth)   | Factory waterproofed; relatively insensitively to temperature and moisture; top of casing subject to vandalism; readout must be kept dry; casing may twist and lower accuracy unless spiral checked | Let torpedo stabilize in casing for 5 minutes before taking readings; take readings at 180 degrees to correct for errors; keep vital bearings clean | Surface: install flexible casing in horizontal trench and bury, install pulley assembly in pit; subsurface: install flexible casing in vertical borehole | Simple; one person to move torpedo and take reading; 10 minutes for 15 readings; 2 insertions for movement on 2 axes | Battery            | Convert readout to displacement; correct for zero drift                        | Torpedo \$3000 to \$3400; readout \$1130 to \$1300; cable \$1 to \$3.50/ft; casing \$3.25/ft; cable-torpedo connector \$140         |
| Multi point borehole inclinometer (MPBI) with fixed servo-accelerometer sensors<br><br>(subsurface horizontal deformation)                      | Sinco                                   | Permanent for monitoring period; moderately delicate; recoverable                                             | Remote                          | No                     | ±30 degrees                                                                        | As above                                      | As above, but entire casing assembly can be buried for protection; problems with zero drift                                                                                                         | Difficult to remove for repair or replacement; accuracy lost if removed from casing                                                                 | Install sensors in flexible casing in vertical borehole                                                                                                  | Simple; one person to take reading                                                                                   | 775 VAC            | Convert digital readout to displacement                                        | Sensors \$2500 each; readout \$1300 to \$4000; cable \$3.50/ft; rods \$2/ft; casing \$3.25/ft                                       |
| MPBI with fixed deflectionometers consisting of pendulum-mounted electrical resistance strain gauges<br><br>(subsurface horizontal deformation) | Terrametrics; Geosistimes               | Permanent for monitoring period; recoverable                                                                  | Remote                          | No                     | ±30 degrees, maximum instrument length is 180 ft with 8 downhole deflectionometers | 2 min. only monitors displacement on one axis | As above, but entire casing assembly can be buried for protection; problems with zero drift, line resistance, input voltage variance                                                                | Difficult to remove or replace; accuracy lost if removed from casing                                                                                | Install sensors in flexible casing in vertical borehole, installation tools available                                                                    | Simple; one person to take readings                                                                                  | Battery            | As above                                                                       | Sensors \$455 each; cable \$0.27/ft; readout box and cable \$1295; extra readout cable \$64/5 ft; installation tools \$450 to \$700 |
| FPBI linear potentiometer and pendulum torpedo<br><br>(subsurface horizontal deformation)                                                       | Sinco                                   | Portable; long experience record                                                                              | Direct                          | Yes                    | ±12 to ±25 degrees                                                                 | 1 min. to 10 min.                             | Factory waterproofed; insensitive to temperature; top of casing may be subject to vandalism; casing may twist and reduce accuracy                                                                   | Take readings at 90 degrees to correct for errors; keep torpedo clean                                                                               | Install flexible casing in vertical borehole                                                                                                             | Simple; one person to move torpedo and take readings; 4 insertions for movement on 2 axes                            | Battery            | Complicated calculations to convert voltage or digital readout to displacement | Torpedo and readout \$2550; cable \$1.50/ft; cable-torpedo connector \$140; casing \$3.25/ft                                        |
| MPBI with fixed electrolytic level sensors<br><br>(surface settlement)                                                                          | User-fabricated, Cooke and Price (1973) | Permanent for monitoring period; recoverable                                                                  | Remote                          | No                     | ±30 minutes; can be mechanically extended to 6 degrees down, 3 degrees up          | 3 min.                                        | Sensitive to moisture, changes in line resistance and cable length; temperature does not affect calibration, but zero reading is sensitive to temperature variation and twist of casing             | None; difficult to remove sensors for repair or replacement                                                                                         | Install sensors in flexible casing along trench and bury                                                                                                 | Simple; one person to adjust levels and take reading                                                                 | Battery or AC main | Convert voltage or digital readout to displacement                             |                                                                                                                                     |

TABLE A.6 - INSTRUMENT CAPABILITIES  
-Inclinometers (Continued)-

Sheet 2 of 2

| INSTRUMENT                                                                                                | AVAILABILITY                          | INSTRUMENT CHARACTERISTICS                       | DATA COLLECTION CHARACTERISTICS |                       | RANGE       | ACCURACY           | SENSITIVITY TO ENVIRONMENT                                                                                                                         | CALIBRATION AND MAINTENANCE                                             | EASE/COST OF INSTALLATION                                            | EASE/COST OF OPERATION                                                                        | POWER REQUIREMENTS                          | EASE/COST OF DATA REDUCTION                                                                              | COST OF INSTRUMENT HARDWARE                                                                          |
|-----------------------------------------------------------------------------------------------------------|---------------------------------------|--------------------------------------------------|---------------------------------|-----------------------|-------------|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
|                                                                                                           |                                       |                                                  | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |             |                    |                                                                                                                                                    |                                                                         |                                                                      |                                                                                               |                                             |                                                                                                          |                                                                                                      |
| Inclinometer mounted on ground-elevation cart<br><br>(surface settlement)                                 | Developmental; Panek and Tesch (1975) | Portable; bulky and requires large storage space | Direct                          | Yes                   |             | 3 min.             | Electronics sensitive to moisture and temperature                                                                                                  | Keep survey course free of obstacles; make 6 runs to correct for errors | Railroad track or course surfaced with blacktop or concrete required | Simple; two people to drive tractor and monitor equipment; make 3 runs in each direction      | Tractor; equipment runs off tractor battery | Computer required                                                                                        | Estimate-tractor \$2000; inclinometer and recorder \$7000; fabrication and fitting to tractor \$8000 |
| FBPI with pendulum-mounted vibrating wire strain gauge torpedo<br><br>(subsurface horizontal deformation) | Telenac                               | Portable                                         | Direct                          | Yes                   | ±15 degrees | 20 sec. to 10 min. | Factory waterproofed and sealed; stable with respect to temperature, moisture and zero drift; top of casing subject to vandalism; casing may twist | Keep torpedo clean; take readings at 180 degrees to correct for errors  | Install flexible casing in vertical borehole                         | Simple; one person to move torpedo and take readings; 2 insertions for movement on 2 axes     | Battery                                     | Convert digital readout to displacement                                                                  | Torpedo \$2550; cable \$1.65/ft; readout \$4500; casing \$4/ft                                       |
| FBPI with LVDT and pendulum torpedo<br><br>(subsurface horizontal deformation)                            | Galileo                               | Portable                                         | Direct                          | Yes                   | ±12 degrees | 3 min. to 10 min.  | Factory waterproofed and sealed but electronics are sensitive to moisture and temperature; top of casing subject to vandalism; casing may twist    | Take readings at 90 degrees to correct for errors                       | As above                                                             | Simple; one person to move torpedo and monitor equipment; 4 insertions for movement on 2 axes | Battery                                     | Borehole profile is recorded and displayed on chart recorder; or convert digital readout to displacement | Torpedo \$2000; readout and cable \$1500; casing \$4/ft.                                             |
| FBPI with pneumatic force balance torpedo<br><br>(subsurface horizontal deformation)                      | Developmental                         | Portable                                         | Direct                          | Yes                   |             | 30 sec.            | No electrical problems; susceptible to leaks; top of casing subject to vandalism; casing may twist                                                 | Check for leaks in system                                               | As above                                                             | Simple; one person to move probe, make adjustments, take reading                              | Compressed air                              | Complicated calculations to convert air pressure to displacement                                         |                                                                                                      |
| FBPI with camera and compass face with pendulum torpedo<br><br>(subsurface horizontal deformation)        | Eastman                               | Portable; moderately delicate                    | Direct                          | Yes                   |             | 3 min.             | Insensitive to temperature and moisture; top of casing subject to vandalism; casing may twist                                                      | Maintain camera in good working condition                               | As above                                                             | Simple; one person to move torpedo and take pictures                                          | Battery                                     | Complicated calculations to determine displacement from photographs                                      | Torpedo \$4500; casing \$3 to \$3.50/ft                                                              |

TABLE A.7 - INSTRUMENT CAPABILITIES

-Geophysical Instruments-

Sheet 1 of 1

| INSTRUMENT                                                                                 | AVAILABILITY                                                                         | INSTRUMENT CHARACTERISTICS                                      | DATA COLLECTION CHARACTERISTICS<br>—ISTICS—<br>REMOTE OR DIRECT |                                                   | RANGE                                                                                                                                                                        | ACCURACY                                                                                                                                                                               | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                               | CALIBRATION AND MAINTENANCE                                                                                                                                 | EASE/COST OF INSTALLATION                                                                                                                                                                                                | EASE/COST OF OPERATION                                                                                                                                   | POWER REQUIREMENTS                                                              | EASE/COST OF DATA REDUCTION                                                                                                                                                 | COST OF INSTRUMENT HARDWARE                                                                      |
|--------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Microseismic<br><br>(extent of subsurface fracturing, rock noise)                          | Equipment and professional services are available; W. Nold Co.; Solitest; Geospaces; | Durable and reusable; may be permanent during monitoring period | Remote                                                          | Yes, if head-phones used; No, if tele-metry used. | In metal ore mines can detect micro-seismic events up to 500 ft from geophone; in soft rock, effective range less than 300 ft; has been used in bore-holes up to 800 ft deep | Subsurface: get profile of density of events vs. depth, but not exact location of upper limit of subsidence; mine used in metal mines to locate over-stress pillars within 10 to 20 ft | Equipment durable; may be subject to electrical problems; if geologic discontinuity exists between microseismic event and geophone, event may not be detected, difficult to separate events from background noise        | Need accurate knowledge of location of geophones; need to know seismic velocity of roof rock for locating noise source; need bore-hole data for calibration | At least two boreholes, cased or uncased, ground coupling by water-fill or grout backfill in bore-hole accurately determine location of boreholes and geophones in borehole                                              | Register the number of microseismic events over a short period of time; simple if use head-phone set; complicated if use analog-digital recording device | Continuous power or battery; depending on readout                               | Experience required to separate micro-seismic events from background noise using headphones; using sophisticated recording devices the background noise may be filtered out | Single channel headphone set \$5000; seven channel automated unit \$32,000; geophones \$200 each |
| P-wave reflection<br><br>(extent of subsurface fracturing)                                 | As above                                                                             | As above                                                        | Remote                                                          | yes                                               | Used to depths of 6000 ft; the lateral extent of the subsurface feature which can be detected is a function of the frequency used                                            | May be possible to locate subsurface interfaces within 3 ft; may be difficult or impossible to detect the upper limit of subsidence                                                    | Distortion may block out first arrival; geologic discontinuities, gravel or boulders can cause scatter waves; may be subject to electrical problems                                                                      | As above                                                                                                                                                    | Shot points must be in bedrock, need several small blasts per reading, use 24 to 48 geophone groups (of 6 to 100 geophones each); place over points accurately surveyed; geophone sets must be set out in straight lines | Need experts to deal with explosives; can use weight-drop trucks instead; need expert to determine in field if good data is being recorded               | Explosives or trucks for wave sources; continuous power for recording equipment | Borehole data and computer; geophysicist to analyze data; data processing can run \$1000 or more per set of observations                                                    | \$100,000                                                                                        |
| S-wave reflection (Vibroseis method)<br><br>(extent of subsurface fracturing)              | As above                                                                             | As above                                                        | Remote                                                          | Yes                                               | As above                                                                                                                                                                     | Possibly as above                                                                                                                                                                      | As above; lower amplitude of signal at surface allows method to be used in large cities                                                                                                                                  | As above; adjust frequency of source signal in field to get best signal-to-noise ratio                                                                      | As above; except truck mounted vibrator used instead of explosives for signal source                                                                                                                                     | Use trucks and highly trained personnel                                                                                                                  | Trucks; continuous power for recording equipment                                | Borehole data, computer and geophysicist required                                                                                                                           |                                                                                                  |
| P-wave crosshole (Traveltime method)<br><br>(extent of subsurface fracturing)              | As above                                                                             | As above                                                        | Remote                                                          | Yes                                               | Distances up to 1000 ft between impulse source and geophone; used in bore-holes up to 800 ft deep                                                                            | At least 10 percent of true travel time over 100 ft path in rock having $V_p$ 10000 fps; accuracy determination of upper limit of subsidence will depend on number of sampling depths  | Premature timer stop due to high noise level, low amplitude first arrival may not trigger stop; geologic discontinuity between impulse source and geophone may affect travel time; may be subject to electrical problems | Need to know accurate location of bore-holes and geophones; need to know seismic velocity of roof strata and rock profile                                   | At least two bore-holes, cased or uncased; accurately determine location of boreholes, geophones, and impulse source                                                                                                     | Experts to deal with explosives; experts to determine in field if good data is being recorded                                                            | Drop hammer or explosives; continuous power for recorder                        | Borehole data, computer and geophysicist required                                                                                                                           |                                                                                                  |
| S-wave cross-hole (travel-time difference method)<br><br>(extent of subsurface fracturing) | As above                                                                             | As above                                                        | Remote                                                          | Yes                                               | Distances of 20 ft to 30 ft between impulse source and geophones; boreholes up to 500 ft deep have been used                                                                 | Polarity of impulse can be changed for accurate time measurement; accuracy of determination of subsidence will depend on number of sampling depths                                     | Geologic discontinuity between impulse and geophone will affect travel time; refracted waves may affect accuracy; don't need to know time of first arrival, may be subject to electrical problems                        | As above                                                                                                                                                    | At least three boreholes; geophones must have good contact with sides of borehole                                                                                                                                        | Experts to determine in field if good data is being recorded                                                                                             | Continuous power for recorder                                                   | Borehole data, and geophysicist to analyze data                                                                                                                             |                                                                                                  |

TABLE A.8 - INSTRUMENT CAPABILITIES  
-Rock Stress Instruments-

Sheet 1 of 4

| INSTRUMENT                                                                                                                                   | AVAILABILITY                                    | INSTRUMENT CHARACTERISTICS                                                                                                                  | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                                | ACCURACY                                                        | SENSITIVITY TO ENVIRONMENT                                                                                                              | CALIBRATION AND MAINTENANCE                                                                                                                                                                    | EASE/COST OF INSTALLATION                                                                                                                    | EASE/COST OF OPERATION                                                                                                                                                                     | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                            | COST OF INSTRUMENT HARDWARE |
|----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|------------------------|------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|------------------------------------------------------------------------|-----------------------------|
|                                                                                                                                              |                                                 |                                                                                                                                             | REMOTE OR DIRECT                | ENTER SUBSISTENCE AREA |                                                      |                                                                 |                                                                                                                                         |                                                                                                                                                                                                |                                                                                                                                              |                                                                                                                                                                                            |                    |                                                                        |                             |
| Solid inclusion stressmeter with strain gauge rosettes bonded to steel sphere<br><br>(absolute pillar stress, change in pillar stress)       | Developmental; Nichols, et al. (1968)           | Permanent for monitoring period; may be recoverable; if overcoring used, one time measurement; potential problems with long term monitoring | Remote                          | No                     | 4500 psi                                             | ±20 percent measure stress increase along 3 axes                | Sensitive to changes in line resistance, cable length, input voltage; susceptible to zero drift; problems with temperature and moisture | Dummy gauges for temperature correction; need to know hydraulic pressure used to install gauge; laboratory calibrate necessary only if the gauge modulus is less than 3 times the rock modulus | Drill crew and technician; gauge connected into borehole; overcore to measure absolute stress                                                | Highly trained personnel to measure absolute stress; moderately trained personnel to measure stress change; straight forward signal conditioning; primarily used to monitor stress changes | Battery            | Complicated calculations; convert voltage or digital readout to stress |                             |
| Rigid inclusion stressmeter with magnetostriuctive gauge<br><br>(absolute pillar stress, change in pillar stress)                            | Developmental; Roberts (1974); Fairhurst (1967) | As above                                                                                                                                    | Remote                          | No                     | 10,000 psi; borehole depths to 100 ft have been used | ±15 percent; measure stress increase or decrease along one axis | As above                                                                                                                                | As above                                                                                                                                                                                       | Drill crew and highly trained technician; gauge is hydraulically installed in borehole and pre-stressed; overcore to measure absolute stress | As above                                                                                                                                                                                   | As above           | As above                                                               |                             |
| Rigid inclusion stressmeter with strain gauges bonded to hydraulically pressured diaphragm<br><br>(change in pillar stress, absolute stress) | Developmental; Roberts (1974); Fairhurst (1967) | As above                                                                                                                                    | Remote                          | No                     | As above                                             | As above                                                        | As above                                                                                                                                | As above                                                                                                                                                                                       | As above                                                                                                                                     | As above                                                                                                                                                                                   | As above           | As above                                                               |                             |
| Rigid inclusion stressmeter with internally bonded strain gauges in recess<br><br>(absolute pillar stress, change in pillar stress)          | Developmental; Roberts (1974)                   | As above                                                                                                                                    | Remote                          | No                     | As above                                             | As above                                                        | As above                                                                                                                                | As above                                                                                                                                                                                       | As above                                                                                                                                     | As above                                                                                                                                                                                   | As above           | As above                                                               |                             |



TABLE A.8 - INSTRUMENT CAPABILITIES  
-Rock Stress Instruments (Continued)-

Sheet 2 of 4

| INSTRUMENT                                                                                                | AVAILABILITY                            | INSTRUMENT CHARACTERISTICS                                                               | DATA COLLECTION CHARACTERISTICS |                         | RANGE                                                            | ACCURACY                                                       | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                        | CALIBRATION AND MAINTENANCE                                                                                                                                                      | EASE/COST OF INSTALLATION                                                                                            | EASE/COST OF OPERATION                                                                                       | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                                                                                              | COST OF INSTRUMENT HARDWARE                                                                                                                                                                               |
|-----------------------------------------------------------------------------------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------|---------------------------------|-------------------------|------------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------|--------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                           |                                         |                                                                                          | REMOTE OR DIRECT                | ENTER SUBSTOR-ENCE AREA |                                                                  |                                                                |                                                                                                                                                                                                                   |                                                                                                                                                                                  |                                                                                                                      |                                                                                                              |                    |                                                                                                                          |                                                                                                                                                                                                           |
| CSIR Multi-component borehole deformation gauge with three strain gauge rosettes (absolute pillar stress) | Corner House Laboratories, South Africa | Permanent installation of strain gauge rosettes; significant electronics are recoverable | Remote                          | Yes                     | Borehole depth to at least 20 ft. has been used                  | ±10 percent                                                    | Possible to obtain results even in moderately jointed rock provided that rosettes are not placed over cracks; susceptible to changes in line resistance, cable length, input voltage variance, moisture and drift | Accuracy depends on good cement bond; borehole simulator can be used to increase accuracy; laboratory determination of rock modulus; use dummy gauges for temperature correction | Drill crew and highly trained technician                                                                             | Highly trained personnel to monitor readout from gauge and reference gauges; Overcore to get absolute stress | Battery            | Complicated calculations; obtain stress ellipsoid from one borehole; convert strain to stress                            |                                                                                                                                                                                                           |
| CSIR doorstopper strain gauge rosette (absolute pillar stress)                                            | As above                                | Permanent installation of strain gauge rosettes; significant electronics are recoverable | Remote                          | Yes                     | Borehole depths over 150 ft. have been used                      | ±6.5 percent                                                   | As above                                                                                                                                                                                                          | As above                                                                                                                                                                         | As above, overcore same size as borehole; need three boreholes to obtain stress ellipsoid                            | As above                                                                                                     | Battery            | Complicated calculations; convert strain to stress                                                                       | Doorstopper strain gauge rosette and readout \$2000                                                                                                                                                       |
| USBM borehole deformation gauge with cantilever-mounted strain gauges (absolute pillar stress)            | Irad, Terra-metrics                     | Recoverable after each test                                                              | Remote                          | Yes                     | 15000 psi; borehole depths up to 100 ft. have been used          | ±25 percent sensitivity of 13.5 psi                            | Problems with waterproofing; not suitable for highly fractured or highly stressed rock prone to rockburst; susceptible to changes in line resistance, cable length, input voltage variance and zero drift         | Laboratory calibration of rock modulus; laboratory calibration of gauge before each use                                                                                          | Drill crew and highly trained technician; \$500 to \$5000 per borehole; installation tools available                 | As above                                                                                                     | Battery            | As above                                                                                                                 | Gauge \$1800 to \$2000; readout \$950; 20 ft cable \$90; modulus chamber \$1500; installation tools \$1400                                                                                                |
| White pines borehole deformation gauge with LVDT (absolute pillar stress)                                 | Solltest; Pemh and Scott (1964)         | As above                                                                                 | Remote                          | Yes                     | Used up to 3000 psi; borehole depths up to 30 ft. have been used | ±15 percent                                                    | As above                                                                                                                                                                                                          | As above                                                                                                                                                                         | Driller and highly trained technician; installation tools required                                                   | As above                                                                                                     | Battery            | As above                                                                                                                 | Gauge and readout \$3000                                                                                                                                                                                  |
| Vibrating wire stress meter (change in pillar stress)                                                     | Irad                                    | As above                                                                                 | Remote                          | No                      | 10,000 psi in hard rock; 6000 psi in soft rock                   | ±10 percent; only measures rock stress change in one direction | Stable with respect to temperature, moisture, zero drift                                                                                                                                                          | Acts as rigid inclusion; don't need rock modulus; thermistors required for temperature correction                                                                                | Drill crew and highly trained technician; monitor pressure used to install in borehole; installation tools available | One person time and training required depends on readout device used; monitor stress change only             | Battery            | Convert change in vibrating frequency, micrometer reading or digital readout to change in stress; temperature correction | Gauge and 40 ft cable \$85; extra cable \$0.10/ft; extra platen assembly \$15; setting tools \$1200 to \$2900; setting rod extensions \$600; thermistor and readout \$130; gauge readout \$1500 to \$4500 |

TABLE A.8 - INSTRUMENT CAPABILITIES  
•Rock Stress Instruments (Continued)•

Sheet 3 of 4

| INSTRUMENT                                                                            | AVAILABILITY          | INSTRUMENT CHARACTERISTICS                                                    | DATA COLLECTION CHARACTERISTICS |                       | RANGE                                                                           | ACCURACY                                                                                                                      | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                 | CALIBRATION AND MAINTENANCE                                                                                                        | EASE/COST OF INSTALLATION                                                                                  | EASE/COST OF OPERATION                                                                                    | POWER REQUIREMENTS                                   | EASE/COST OF DATA REDUCTION                             | COST OF INSTRUMENT HARDWARE                                                                  |
|---------------------------------------------------------------------------------------|-----------------------|-------------------------------------------------------------------------------|---------------------------------|-----------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------|
|                                                                                       |                       |                                                                               | REMOTE OR DIRECT                | ENTER SUBSIDENCE AREA |                                                                                 |                                                                                                                               |                                                                                                                                                                                            |                                                                                                                                    |                                                                                                            |                                                                                                           |                                                      |                                                         |                                                                                              |
| Cylindrical hydraulic borehole pressure cell<br><br>(change in pillar stress)         | Terrametrics; Serata  | Permanent for monitoring period; may be recoverable; good long term stability | Direct                          | Yes                   | 1000 to 7000 psi                                                                | ±20 percent; measures average change in stress acting over borehole                                                           | Not sensitive to blasting; fissures and fractures may negate results; susceptible to vandalism and accidental damage; open joints or fractures along borehole will lead to rupture of cell | Check for leaks in system; correct for compressibility of system by dilating cell in metal cylinders before installing in borehole | Driller and highly trained technician; borehole must be drilled to precise dimensions                      | As above, but principally used to determine modulus of rigidity in situ                                   | As above                                             | As above                                                | 4000 psi cell \$167; pressure gauge \$80; pump \$280 to \$815                                |
| FlatJack in slot<br><br>(absolute pillar stress, change in pillar stress)             | Terrametrics, Telemac | Permanent installation; good long term stability                              | Direct                          | Yes                   | 10000 psi; minimum pressure 1500 psi; can be used only in vicinity of rock face | ±20 percent; only measures rock stress in one direction perpendicular to plane of FlatJack; accuracy less for absolute stress | Not sensitive to blasting; fissures and fractures may negate results; susceptible to vandalism and accidental damage                                                                       | Check for leaks in system; void in mortar will lead to rupture of cell                                                             | Driller and highly trained technician; mortar must set 20 to 28 days before taking reading                 | No overcoring needed; monitoring period about 2 to 3 weeks per FlatJack for absolute stress determination | Oil pressure<br>Battery required for absolute stress | Convert oil pressure in FlatJack to rock pressure       | 300 psi cell \$300; pressure gauge \$80; pump \$280 to \$815                                 |
| Flat, encapsulated, hydraulic borehole pressure cell<br><br>(change in pillar stress) | Terrametrics          | Permanent for monitoring period; may be recoverable; good long term stability | Direct                          | Yes                   | 4000 psi; borehole depth up to 50 ft                                            | As above; sensitivity of 10 to 23 psi                                                                                         | As above                                                                                                                                                                                   | As above; determine response of pressure cell in particular rock medium for calibration                                            | As above; can be encapsulated at factory, but this requires that borehole be drilled to precise dimensions | One person moderately trained to take readings; monitor stress changes only                               | Oil pressure                                         | Convert change in oil pressure to change in rock stress | Unencapsulated cell \$155; encapsulated cell \$167; pressure gauge \$80; pump \$280 to \$815 |

TABLE A.8 - INSTRUMENT CAPABILITIES  
Rock Stress Instruments (Continued).

Sheet 4 of 4

| INSTRUMENT                                                                                             | AVAILABILITY                                 | INSTRUMENT CHARACTERISTICS                                                                  | DATA COLLECTION CHARACTERISTICS |                        | RANGE                                         | ACCURACY                                                                                                              | SENSITIVITY TO ENVIRONMENT                                                                                                                                                                                                                                                                                                                                          | CALIBRATION AND MAINTENANCE                                                                                                                                                                     | EASE/COST OF INSTALLATION                                                                                                  | EASE/COST OF OPERATION                                                                                                                                                                                                                                             | POWER REQUIREMENTS       | EASE/COST OF DATA REDUCTION                      | COST OF INSTRUMENT HARDWARE                                                       |
|--------------------------------------------------------------------------------------------------------|----------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------|------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------------------------------|-----------------------------------------------------------------------------------|
|                                                                                                        |                                              |                                                                                             | REMOTE OR DIRECT                | ENTER SURROUNDING AREA |                                               |                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                 |                                                                                                                            |                                                                                                                                                                                                                                                                    |                          |                                                  |                                                                                   |
| Photoelastic biaxial glass plug stress gauge<br><br>(absolute pillar stress, change in pillar stress)  | Terrametrics                                 | Permanent installation; no deterioration of fringe pattern after rests of one to two months | Direct                          | Yes                    | 2500 to 3000 psi; borehole depths to 25 ft    | ±25 percent; sensitivity of 7.5 to 15.0 psi                                                                           | Stable with respect to temperature and moisture; in highly fractured rock fringe pattern may be difficult to interpret due to highly variable conditions; best suited for rocks under high load which display appreciable elastic rebound upon relief; gauges in roof may become useless due to failure of rocks around them or due to damage from mining operation | Calibrate fringe pattern using deformer in same rock sample; accuracy depends on good cement bond; errors due to differences in coefficient of expansion between gauge or gauge-cement and rock | Drill crew and technician; cement plug to borehole; overcore necessary to measure absolute stress; setting tools available | Overcore to get absolute stress; need access to view gauge; measurement of low orders of fringe (less than 1/4 fringe) requires experience; measures either stress change or absolute stress but not both; moderately trained personnel to measure absolute stress | Battery for light source | Convert fringe pattern to stress acting on gauge | Plug \$85 to \$156; light \$112; hand-viewer \$600 to \$1100; setting tool \$3315 |
| Photoelastic uniaxial glass plug stress gauge<br><br>(absolute pillar stress, change in pillar stress) | Developmental; Hawkes (1968); Roberts (1974) | Permanent for monitoring period; good long term stability                                   | Direct                          | Yes                    | Up to 16000 psi; borehole depths to 25 ft     | ±25 percent; for use in areas, such as pillars, where stress directions are roughly known; sensitivity of 7.5 to 15.0 | As above                                                                                                                                                                                                                                                                                                                                                            | As above                                                                                                                                                                                        | Drill crew and technician; plug wedged into borehole; overcore necessary to measure absolute stress                        | As above                                                                                                                                                                                                                                                           | As above                 | As above                                         |                                                                                   |
| Hiramatsu and Oka photometer stress gauge<br><br>(absolute pillar stress, change in pillar stress)     | Developmental; Hiramatsu and Oka (1964)      | Permanent installation; good long term stability                                            | Direct                          | Yes                    | Up to 14000 psi; borehole depths up to 1.0 ft | ±20 percent; sensitivity of 7.5 to 15.0 psi                                                                           | As above                                                                                                                                                                                                                                                                                                                                                            | As above                                                                                                                                                                                        | As above but cemented into borehole                                                                                        | As above                                                                                                                                                                                                                                                           | As above                 | As above                                         |                                                                                   |
| Photoelastic biaxial epoxy disc stress gauge<br><br>(absolute pillar stress)                           | Terrametrics; Roberts (1974)                 | As above                                                                                    | Direct                          | Yes                    | Borehole depths up to 1.0 ft                  | ±25 percent; sensitivity of 7.5 to 15.0 psi                                                                           | As above                                                                                                                                                                                                                                                                                                                                                            | As above                                                                                                                                                                                        | As above; back of borehole must be dried before attaching disc; setting tools available                                    | As above                                                                                                                                                                                                                                                           | As above                 | As above                                         | Overcoring kit for NX borehole \$6675; disc \$29 to \$41; handviewer \$200        |

TABLE A.9 - INSTRUMENT CAPABILITIES

•Support Load Cells•

Sheet 1 of 1

| INSTRUMENT                                                     | AVAILABILITY                   | INSTRUMENT CHARACTERISTICS                                               | DATA COLLECTION CHARACTERISTICS |                        | RANGE                 | ACCURACY                          | SENSITIVITY TO ENVIRONMENT                                                                                                                                   | CALIBRATION AND MAINTENANCE                                           | EASE/COST OF INSTALLATION                                                | EASE/COST OF OPERATION                                                        | POWER REQUIREMENTS      | EASE/COST OF DATA REDUCTION                                                              | COST OF INSTRUMENT HARDWARE                            |
|----------------------------------------------------------------|--------------------------------|--------------------------------------------------------------------------|---------------------------------|------------------------|-----------------------|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------|-------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------|
|                                                                |                                |                                                                          | REMOTE OR DIRECT                | ENTER SUBSISTENCE AREA |                       |                                   |                                                                                                                                                              |                                                                       |                                                                          |                                                                               |                         |                                                                                          |                                                        |
| Vibrating wire load cell<br><br>(support load)                 | Telemac; Mathak                | Permanent for monitoring period; may be recoverable; long term stability | Remote                          | No                     | To 200 tons and above | Sensitivity: 0.15 ton             | Stable with respect to temperature, moisture and zero drift; load eccentricity has little effect; may be subject to vandalism                                | None; must be factory repaired or replaced if damaged<br><br>As above | Install between rock surface and lagging or beneath base plates of props | One person; training and time required depends on type of readout device used | Battery                 | Depends on readout device used; multiply readout by calibration constant to get pressure | Cell \$1500; cable \$0.50/ft; readout \$1500 to \$4500 |
| Bonded resistance strain gauge load cell<br><br>(support load) | Terrametrics                   | Permanent for monitoring period; may be recoverable                      | Remote                          | No                     | 150 to 1250 tons      | Sensitivity: 0.03 ton to 0.25 ton | Electronics sensitive to changes in line resistance, cable length, input, voltage variance, temperature, moisture; blast resistant; susceptible to vandalism | As above                                                              | As above                                                                 | Simple; one person to take reading; straight forward signal conditioning      | Battery                 | As above                                                                                 | Cell \$1500; readout \$1600; cable \$2.15/ft           |
| Hydraulic load cell<br><br>(support load)                      | Gloetzl; Terrametrics; Telemac | Permanent installation; long term stability                              | Direct                          | Yes                    | To 200 tons and above | Sensitivity: 0.2 ton              | Stable with respect to temperature and moisture; if leak develops, cell is lost                                                                              | As above                                                              | As above; pump required for installation                                 | Very simple; one person to take reading                                       | Compressed air or oil   | Convert oil or air pressure in cell to support stress per calibration constant           | Cell \$1000 pressure gauge \$80; pump \$280 to \$815   |
| Photoelastic load cell                                         | Terrametrics                   | Permanent for monitoring period; may be recoverable                      | Direct                          | Yes                    | 50 tons               | Sensitivity 0.5 tons              | Moderately stable with respect to temperature and moisture                                                                                                   | As above                                                              | Install between rock surface and props                                   | One person moderately trained to read fringes                                 | Small battery for light | Convert number of fringes to load                                                        | \$350 each; handviewer \$100 to \$500                  |

TABLE A.10- INSTRUMENT CAPABILITIES

•Rock Bolt Load Devices•

Sheet 1 of 2

| INSTRUMENT                                                                   | AVAILABILITY | INSTRUMENT CHARACTERISTICS                                               | DATA COLLECTION CHARACTERISTICS |                        | RANGE               | ACCURACY                             | SENSITIVITY TO ENVIRONMENT                                                                                                              | CALIBRATION AND MAINTENANCE                           | EASE/COST OF INSTALLATION | EASE/COST OF OPERATION                                                                               | POWER REQUIREMENTS    | EASE/COST OF DATA REDUCTION                                                          | COST OF INSTRUMENT HARDWARE                                            |
|------------------------------------------------------------------------------|--------------|--------------------------------------------------------------------------|---------------------------------|------------------------|---------------------|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|---------------------------|------------------------------------------------------------------------------------------------------|-----------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------|
|                                                                              |              |                                                                          | REMOTE OR DIRECT                | ENTER SUBSISTENCE AREA |                     |                                      |                                                                                                                                         |                                                       |                           |                                                                                                      |                       |                                                                                      |                                                                        |
| Vibrating wire compression type dynamometer<br><br>(rock bolt load)          | Maihak       | Permanent for monitoring period; may be recoverable; long term stability | Remote                          | No                     | 20 tons to 300 tons | $\pm 0.2$ to $\pm 3$ tons            | Stable with respect to temperature, moisture, and zero drift; may be subject to damage                                                  | None; must be factory repaired or replaced if damaged | Installed with rock bolt  | One person; training and time required depends on type of readout device used                        | Battery               | Depends on readout device used; multiply readout by calibration constant to get load | 20 ton cell \$650; cable \$1/ft; readout \$3000 to \$4500              |
| Vibrating wire tension type dynamometer<br><br>(rock bolt load)              | Telemac      | As above                                                                 | Remote                          | No                     | 5 tons to 100 tons  | high; sensitivity of 0.01 to 0.2 ton | As above, but not as susceptible to damage                                                                                              | As above                                              | As above                  | As above                                                                                             | Battery               | As above                                                                             | 5 ton cell \$450; 100 ton cell \$1550; readout and cable as above      |
| Hydraulic compression type cell<br><br>(rock bolt load)                      | Terrametrics | As above                                                                 | Direct                          | Yes                    | Up to 15 tons       | Sensitivity of 0.05 ton              | Stable with respect to temperature and moisture; if leak develops, cell is lost; may be subject to damage                               | As above                                              | As above                  | Very simple; one person to take reading; near access to cell required                                | Compressed air or oil | Convert oil or air pressure in cell to load                                          | 15 ton cell \$102; gauge \$80; pump \$280 to \$815                     |
| Photoelastic compression type cell<br><br>(rock bolt load)                   | Terrametrics | Permanent for monitoring period; principal parts recoverable             | Direct                          | Yes                    | Up to 16 tons       | $\pm 0.08$ to $\pm 0.35$ ton         | Stable with respect to temperature and moisture; may be subject to damage; water and dust proof caps available                          | None; easy to replace glass plug if damaged           | As above                  | One person; technique required to count fringes of order less than one; near access to cell required | None                  | Convert fringe pattern to load                                                       | 16 ton cell \$168; viewer \$200 to \$1065                              |
| Bonded resistance strain gauge compression type cell<br><br>(rock bolt load) | Terrametrics | Permanent for monitoring period; may be recoverable                      | Remote                          | No                     | 20 tons to 300 tons | Sensitivity of 0.01 to 1.5 tons      | Electronics sensitive to changes in line resistance, cable length, input voltage variance, temperature, moisture; susceptible to damage | None; must be factory repaired or replaced if damaged | As above                  | Simple; one person to take readings; straight forward signal conditioning                            | Battery               | Depends on readout device used; multiply readout by calibration constant to get load | 20 ton cell \$250; 300 ton cell \$994; readout \$1125; cable \$3.75/ft |

TABLE A.10 - INSTRUMENT CAPABILITIES  
 •Rock Bolt Load Devices (Continued)•

Sheet 2 of 2

| INSTRUMENT                                                                | AVAILABILITY | INSTRUMENT CHARACTERISTICS                          | DATA COLLECTION CHARACTERISTICS |                        | RANGE               | ACCURACY                | SENSITIVITY TO ENVIRONMENT                                                                                             | CALIBRATION AND MAINTENANCE | EASE/COST OF INSTALLATION | EASE/COST OF OPERATION                                   | POWER REQUIREMENTS | EASE/COST OF DATA REDUCTION                          | COST OF INSTRUMENT HARDWARE                             |
|---------------------------------------------------------------------------|--------------|-----------------------------------------------------|---------------------------------|------------------------|---------------------|-------------------------|------------------------------------------------------------------------------------------------------------------------|-----------------------------|---------------------------|----------------------------------------------------------|--------------------|------------------------------------------------------|---------------------------------------------------------|
|                                                                           |              |                                                     | REMOTE OR DIRECT                | ENTER SUSCEP-ENCE AREA |                     |                         |                                                                                                                        |                             |                           |                                                          |                    |                                                      |                                                         |
| Bonded resistance strain gauge instrumented bolts<br><br>(rock bolt load) | Strainert    | Permanent for monitoring period; may be recoverable | Remote                          | No                     | 15 tons to 50 tons  | $\pm 0.15$ to 0.50 ton  | As above but not as susceptible to damage                                                                              | As above                    | As above                  | As above                                                 | Battery            | As above                                             | 50 ton bolt \$145 to \$225, readout and cable as above  |
| Elastic disc and dial gauge compression type cell<br><br>(rock bolt load) | Interfels    | Permanent for monitoring period; recoverable        | Direct                          | Yes                    | 17 tons to 250 tons | $\pm 0.09$ to 11.25 ton | Stable with respect to temperature and moisture; susceptible to damage, but dial gauge can be removed between readings | None                        | As above                  | Simple: one person to attach dial gauge and take reading | None               | Convert dial reading to load using calibration chart | 17 ton cell \$100; 250 ton cell \$800; dial gauge \$100 |

APPENDIX B  
MATRIX OF INSTRUMENT  
CAPABILITIES





TABLE B.1  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM A: SUBSIDENCE DETECTION'

|                                                                                                 | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>VERTICAL SETTLEMENT                                                           | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level with wood rod                                                                      | 66               | 3            | 3                             | 1                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 3                  | 0                                |
| Precision Level with Invar rod                                                                  | 68               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| Rotating Beam Laser Level<br>with rod detector                                                  | 55               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 1     | 2                              | 1                  | 0                                |
| Theodolite with wood rod<br>(as level)                                                          | 66               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| Theodolite and Stadia Rod                                                                       | 60               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 0                                |
| EDM Tachymeter<br>(portable reflectors)                                                         | 54               | 2            | 3                             | 1                                  | 3     | 3        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 0                                |
| S.P. Simple Hose Manometer                                                                      | 62               | 2            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                                                  | 49               | 2            | 1                             | 2                                  | 1     | 2        | 1                             | 2                              | 1                            | 3                         | 2     | 2                              | 2                  | 0                                |
| S.P. Overflow type Manometer                                                                    | 58               | 3            | 1                             | 2                                  | 1     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Overflow type Manometer                                                                    | 62               | 2            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Two Liquid Pressure Balance<br>Manometer                                                   | 54               | 1            | 1                             | 2                                  | 3     | 3        | 2                             | 2                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| F.P. Air Balloon in Liquid Filled<br>Tube Settlement Device                                     | 46               | 2            | 1                             | 2                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Borehole Inclinator with<br>Servo-accelerometer torpedo<br>(horiz. casing in trench)       | 47               | 3            | 2                             | 1                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| M.P. Borehole Inclinator with<br>fixed Electrolytic levels<br>(horiz. casing in trench)         | 39               | 1            | 1                             | 2                                  | 3     | 0        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| S.P. Borehole Ext., Wire Type Weight<br>Anchored, Weight Tensioned with<br>Rotary Potentiometer | 44               | 2            | 0                             | 2                                  | 3     | 3        | 1                             | 2                              | 0                            | 2                         | 2     | 2                              | 1                  | 0                                |
| Ground Elevation Cart                                                                           | 39               | 0            | 3                             | 1                                  | 3     | 1        | 1                             | 2                              | 2                            | 2                         | 1     | 0                              | 0                  | 0                                |
|                                                                                                 |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

TABLE B.2  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM B: STRUCTURE PERFORMANCE'

|                                                                | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|----------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| STRUCTURAL DIFFERENTIAL<br>VERTICAL SETTLEMENT                 | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level and wood rod                                      | 66               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 2                            | 2                         | 3     | 2                              | 3                  | 0                                |
| Precision Level and Invar rod                                  | 71               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 2                            | 2                         | 3     | 2                              | 2                  | 0                                |
| Theodolite (as level)                                          | 66               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 2                            | 2                         | 3     | 2                              | 1                  | 0                                |
| Rotating Beam Laser Level                                      | 58               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 2                            | 2                         | 1     | 2                              | 1                  | 0                                |
| Precision Theodolite and tape<br>(triangulation)               | 70               | 3            | 3                             | 2                                  | 3     | 3        | 3                             | 3                              | 2                            | 2                         | 3     | 1                              | 1                  | 1                                |
| EDM Tachymeter<br>(fixed reflectors)                           | 58               | 2            | 3                             | 2                                  | 3     | 1        | 1                             | 3                              | 2                            | 3                         | 1     | 3                              | 0                  | 1                                |
| EDM Tachymeter<br>(portable reflectors)                        | 54               | 2            | 3                             | 1                                  | 3     | 1        | 1                             | 3                              | 2                            | 2                         | 1     | 3                              | 0                  | 1                                |
| Infrared EDM and Theodolite<br>(trilateration)                 | 55               | 3            | 3                             | 2                                  | 3     | 1        | 2                             | 3                              | 2                            | 2                         | 1     | 1                              | 0                  | 1                                |
| Rod Extensometer with Micrometer<br>and Spirit level Tiltmeter | 62               | 2            | 3                             | 1                                  | 1     | 2        | 2                             | 2                              | 2                            | 2                         | 3     | 2                              | 2                  | 2                                |
| Close-range structure<br>Photogrammetry                        | 56               | 3            | 3                             | 3                                  | 3     | 1        | 2                             | 2                              | 2                            | 1                         | 3     | 0                              | 1                  | 1                                |
| M.P. Terzaghi Differential<br>Settlement Manometer             | 61               | 2            | 2                             | 2                                  | 3     | 1        | 2                             | 2                              | 2                            | 2                         | 3     | 2                              | 3                  | 0                                |
| S.P. Simple Hose<br>Manometer                                  | 62               | 2            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 2                            | 3                         | 3     | 2                              | 3                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                 | 61               | 2            | 1                             | 2                                  | 3     | 2        | 1                             | 2                              | 2                            | 3                         | 2     | 2                              | 3                  | 0                                |
| F.P. Overflow-type<br>Manometer                                | 64               | 3            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 2                            | 3                         | 3     | 2                              | 3                  | 0                                |
| F.P. Two liquid pressure balance<br>Manometer                  | 51               | 1            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 2                            | 2                         | 3     | 2                              | 1                  | 0                                |
|                                                                |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |
|                                                                |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

[illegible]



[illegible]

TABLE B.3  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM C: MINE STABILITY'

(CONTINUED)

|                                                                                    | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|------------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| MINE CONVERGENCE                                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| Spirit Level with wood rod                                                         | 72               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 1                             |
| Precision Level with Invar rod                                                     | 74               | 3            | 3                          | 1                               | 3     | 2        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 1                             |
| Theodolite and Tape                                                                | 69               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 1                             |
| Steel Tape Extensometer                                                            | 72               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 0                             |
| Invar Wire Extensometer                                                            | 69               | 2            | 3                          | 1                               | 3     | 3        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 0                             |
| EDM Tachymeter (portable reflectors)                                               | 57               | 2            | 3                          | 1                               | 3     | 2        | 1                          | 3                           | 2                         | 2                      | 1     | 3                           | 0               | 1                             |
| Infrared EDM and Theodolite                                                        | 59               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 1     | 2                           | 1               | 0                             |
| Close range mine photography                                                       | 55               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 2                           | 2                         | 1                      | 2     | 0                           | 1               | 0                             |
| S.P.B.X. Wire Type with Spring Tensioned Rotary Potentiometer (telescoping casing) | 44               | 2            | 0                          | 2                               | 0     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 0                             |
| Rod Extensometer with Spring Tensioned Vibrating Wire (telescoping casing)         | 53               | 3            | 1                          | 3                               | 2     | 3        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 1               | 0                             |
| Telescoping Rod Extensometer with Linear Potentiometer                             | 51               | 1            | 0                          | 2                               | 3     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 0                             |
| Invar Telescoping Tube Extensometer with dial gauge                                | 62               | 2            | 1                          | 1                               | 1     | 3        | 3                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 0                             |
| Telescoping Tube Extensometer with machinist's scale                               | 64               | 1            | 1                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 0                             |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: S.P.B.X. - Single Point Borehole Extensometer

[illegible]

[illegible]



TABLE B.3  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM C: MINE STABILITY'  
(CONTINUED)

[illegible]

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'

|                                                                                                 | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>VERTICAL SETTLEMENT                                                           | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level with wood rod                                                                      | 69               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 3                  | 2                                |
| Precision Level with Invar rod                                                                  | 77               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 3                                |
| Rotating Beam Laser Level<br>with rod detector                                                  | 58               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 1     | 2                              | 1                  | 1                                |
| Theodolite with wood rod<br>(as level)                                                          | 69               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 3                                |
| Theodolite and Stadia Rod                                                                       | 69               | 3            | 3                             | 1                                  | 3     | 0        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 3                                |
| EDM Tachymeter<br>(portable reflectors)                                                         | 60               | 2            | 3                             | 1                                  | 3     | 2        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 3                                |
| S.P. Simple Hose Manometer                                                                      | 56               | 2            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                                                  | 58               | 2            | 1                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 3                         | 2     | 2                              | 2                  | 0                                |
| S.P. Overflow type Manometer                                                                    | 61               | 3            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Overflow type Manometer                                                                    | 59               | 2            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Two Liquid Pressure Balance<br>Manometer                                                   | 51               | 1            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| F.P. Air Balloon in Liquid Filled<br>Tube Settlement Device                                     | 46               | 2            | 1                             | 2                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Borehole Inclinator with<br>Servo-accelerometer torpedo<br>(horiz. casing in trench)       | 47               | 3            | 2                             | 1                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| M.P. Borehole Inclinator with<br>fixed Electrolytic levels<br>(horiz. casing in trench)         | 39               | 1            | 1                             | 2                                  | 3     | 0        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| S.P. Borehole Ext., Wire Type Weight<br>Anchored, Weight Tensioned with<br>Rotary Potentiometer | 47               | 2            | 0                             | 2                                  | 3     | 2        | 1                             | 2                              | 0                            | 2                         | 2     | 2                              | 1                  | 1                                |
| Ground Elevation Cart                                                                           | 36               | 0            | 3                             | 1                                  | 3     | 0        | 1                             | 2                              | 2                            | 2                         | 1     | 0                              | 0                  | 0                                |
|                                                                                                 |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS  
(CONTINUED)

|                                                                   | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND-SURFACE<br>HORIZONTAL STRAIN<br>(LINES)                    | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Steel Tape                                                        | 78               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 3                            | 2                         | 3     | 2                              | 3                  | 1                                |
| Invar Tape                                                        | 81               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 3                            | 2                         | 3     | 2                              | 3                  | 1                                |
| Steel Tape Extensometer                                           | 72               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 2                                |
| Invar Wire Extensometer                                           | 69               | 2            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 2                                |
| Infrared EDM and theodolite<br>(traverse)                         | 59               | 3            | 3                             | 1                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 1     | 2                              | 0                  | 2                                |
| Infrared EDM and theodolite<br>(trilateration)                    | 60               | 3            | 3                             | 2                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 1     | 2                              | 0                  | 2                                |
| EDM Tachymeter<br>(portable reflectors)                           | 60               | 2            | 3                             | 1                                  | 3     | 2        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 3                                |
| Precision Theodolite and Tape<br>(triangulation)                  | 70               | 3            | 3                             | 2                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 1                              | 1                  | 2                                |
| Theodolite and Stadia Rod                                         | 63               | 3            | 3                             | 1                                  | 3     | 0        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 3                                |
| Precision Theodolite and Invar<br>Subtense Bar                    | 68               | 3            | 3                             | 1                                  | 3     | 2        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 2                                |
| Reduction Tachymeter and<br>Stadia Rod                            | 65               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| Aerial Photogrammetry                                             | 38               | 3            | 3                             | 3                                  | 3     | 0        | 2                             | 2                              | 2                            | 0                         | 0     | 0                              | 0                  | 0                                |
| F.P. Inclinator with Reed Switch<br>Torpedo (Horizontal casing)   | 54               | 2            | 2                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Inclinator with Electro-<br>magnetic Torpedo (Horiz. casing) | 58               | 3            | 2                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 2                  | 0                                |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

|                                                                                   | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|-----------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| SUBSURFACE VERTICAL DEFORMATION                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Dial Gauge                 | 48               | 1            | 1                          | 1                               | 2     | 2        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 0                             |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Rotary Potentiometer       | 53               | 2            | 0                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type Weight Tensioned with Dial Gauge                               | 59               | 2            | 1                          | 1                               | 2     | 3        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 1                             |
| M.P.B.X, Wire Type, Spring or Cantilever Tensioned with Dial Gauge                | 61               | 2            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 1                             |
| M.P.B.X, Wire Type, Cantilever Tensioned with Bonded Electrical Res. Strain Gauge | 44               | 2            | 0                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type with Spring Tensioned Rotary Potentiometer                     | 53               | 2            | 0                          | 2                               | 2     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 2                             |
| M.P.B.X, Wire Type with Spring or Cantilever Tensioned Vibrating Wire             | 47               | 2            | 1                          | 3                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 2                             |
| F.P.B.X, With Electromagnetic Torpedo                                             | 58               | 3            | 2                          | 1                               | 3     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 3               | 1                             |
| F.P.B.X, With Reed Switch Torpedo                                                 | 53               | 2            | 2                          | 1                               | 3     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| F.P.B.X, With Latch Type Probe                                                    | 51               | 2            | 2                          | 1                               | 1     | 2        | 2                          | 2                           | 0                         | 2                      | 3     | 2                           | 3               | 0                             |
| F.P.B.X, With Time Domain Reflectometry                                           | 36               | 2            | 2                          | 3                               | 3     | 0        | 1                          | 2                           | 0                         | 0                      | 2     | 0                           | 2               | 0                             |
| F.P.B.X, With Radioactive Bullets                                                 | 44               | 2            | 2                          | 1                               | 3     | 0        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with Dial Gauge                                                 | 60               | 3            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 1                             |
| M.P.B.X, Rod Type with Linear Potentiometer                                       | 49               | 3            | 0                          | 2                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Rod Type with LVDT                                                       | 46               | 2            | 1                          | 2                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 1                             |
| M.P.B.X, Rod Type with Vibrating Wire Strain Gauges                               | 50               | 2            | 1                          | 3                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 2                             |
|                                                                                   |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: F.P.B.X. - Full Profile Borehole Extensometer  
M.P.B.X. - Multi Point Borehole Extensometer  
S.P.B.X. - Single Point Borehole Extensometer

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

|                                                                 | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|-----------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| SUBSURFACE HORIZONTAL DEFORMATION                               | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| F.P.B.I. with Linear Potentiometer Torpedo                      | 38               | 2            | 0                          | 1                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with Servo-Accelerometer Torpedo                       | 50               | 3            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| M.P.B.I. with fixed Servo-Accelerometers                        | 44               | 2            | 1                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 0               | 0                             |
| F.P.B.I. with bonded electrical resistance strain gauge torpedo | 38               | 2            | 0                          | 1                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with fixed bonded strain gauge deflectometer           | 36               | 2            | 0                          | 2                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 0               | 0                             |
| F.P.B.I. with vibrating wire strain gauge torpedo               | 48               | 2            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with LVDT Torpedo                                      | 39               | 2            | 2                          | 1                               | 3     | 0        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with Pneumatic Torpedo                                 | 44               | 0            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with camera and compass Torpedo                        | 48               | 2            | 3                          | 1                               | 3     | 1        | 2                          | 3                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: F.P.B.I. - Full Profile Borehole Inclinator  
M.P.B.I. - Multi Point Borehole Inclinator

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

[illegible]



TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

|                                                                                    | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|------------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| MINE CONVERGENCE                                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| Spirit Level with wood rod                                                         | 78               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 3                             |
| Precision Level with Invar rod                                                     | 77               | 3            | 3                          | 1                               | 3     | 2        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 2                             |
| Theodolite and Tape                                                                | 72               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 2                             |
| Steel Tape Extensometer                                                            | 78               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 2                             |
| Invar Wire Extensometer                                                            | 75               | 2            | 3                          | 1                               | 3     | 3        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 2                             |
| EDM Tachymeter (portable reflectors)                                               | 63               | 2            | 3                          | 1                               | 3     | 2        | 1                          | 3                           | 2                         | 2                      | 1     | 3                           | 0               | 3                             |
| Infrared EDM and Theodolite                                                        | 65               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 1     | 2                           | 1               | 2                             |
| Close range mine photography                                                       | 55               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 2                           | 2                         | 1                      | 2     | 0                           | 1               | 0                             |
| S.P.B.X. Wire Type with Spring Tensioned Rotary Potentiometer (telescoping casing) | 47               | 2            | 0                          | 2                               | 0     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 1                             |
| Rod Extensometer with Spring Tensioned Vibrating Wire (telescoping casing)         | 58               | 3            | 1                          | 3                               | 2     | 3        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 1               | 1                             |
| Telescoping Rod Extensometer with Linear Potentiometer                             | 57               | 1            | 0                          | 2                               | 3     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 2                             |
| Invar Telescoping Tube Extensometer with dial gauge                                | 68               | 2            | 1                          | 1                               | 1     | 3        | 3                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 2                             |
| Telescoping Tube Extensometer with machinist's scale                               | 67               | 1            | 1                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 1                             |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: S.P.B.X. - Single Point Borehole Extensometer

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

|                                                                                        | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|----------------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| MINE ROOF STRATA SEPARATION                                                            | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| M.P.B.X, Wire Type Weight Tensioned with Dial Gauge                                    | 61               | 2            | 1                          | 1                               | 2     | 3        | 1                          | 3                           | 0                         | 3                      | 3     | 2                           | 3               | 1                             |
| M.P.B.X, Wire Type Spring Tensioned with Dial Gauge                                    | 63               | 2            | 1                          | 1                               | 2     | 3        | 2                          | 3                           | 0                         | 3                      | 3     | 2                           | 3               | 1                             |
| M.P.B.X, Wire Type Cantilever Tensioned with Bonded Electrical Resistance Strain Gauge | 44               | 2            | 0                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type with Spring Tensioned Rotary Potentiometer                          | 47               | 2            | 0                          | 2                               | 2     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type with Spring or Cantilever Tensioned Vibrating Wire                  | 50               | 2            | 1                          | 3                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 2                             |
| M.P.B.X, Rod Type with Dial Gauge                                                      | 67               | 3            | 1                          | 1                               | 2     | 3        | 2                          | 3                           | 0                         | 3                      | 3     | 2                           | 3               | 1                             |
| M.P.B.X, Rod Type with Linear Potentiometer                                            | 57               | 3            | 0                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Rod Type with LVDT                                                            | 52               | 2            | 1                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 1                             |
| M.P.B.X, Rod Type with Vibrating Wire Strain Gauges                                    | 53               | 2            | 1                          | 3                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 1                             |
| M.P.B.X, Rod Type with Reed Switches and LVDT                                          | 48               | 0            | 1                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 1                             |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                        |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: M.P.B.X. - Multi Point Borehole Extensometer

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.4  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM D: PERFORMANCE OF SUPPORTED SYSTEMS'

(CONTINUED)

[illegible]

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'

|                                                                                                 | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>VERTICAL SETTLEMENT                                                           | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level with wood rod                                                                      | 66               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 3                  | 1                                |
| Precision Level with Invar rod                                                                  | 74               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 2                                |
| Rotating Beam Laser Level<br>with rod detector                                                  | 55               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 1     | 2                              | 1                  | 0                                |
| Theodolite with wood rod<br>(as level)                                                          | 66               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 2                                |
| Theodolite and Stadia Rod                                                                       | 66               | 3            | 3                             | 1                                  | 3     | 0        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 2                                |
| EDM Tachymeter<br>(portable reflectors)                                                         | 61               | 2            | 3                             | 2                                  | 3     | 2        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 3                                |
| S.P. Simple Hose Manometer                                                                      | 56               | 2            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                                                  | 52               | 2            | 1                             | 2                                  | 1     | 3        | 1                             | 2                              | 1                            | 3                         | 2     | 2                              | 2                  | 0                                |
| S.P. Overflow type Manometer                                                                    | 55               | 3            | 1                             | 2                                  | 1     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Overflow type Manometer                                                                    | 59               | 2            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Two Liquid Pressure Balance<br>Manometer                                                   | 51               | 1            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| F.P. Air Balloon in Liquid Filled<br>Tube Settlement Device                                     | 46               | 2            | 1                             | 2                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Borehole Inclinator with<br>Servo-accelerometer torpedo<br>(horiz. casing in trench)       | 47               | 3            | 2                             | 1                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| M.P. Borehole Inclinator with<br>fixed Electrolytic levels<br>(horiz. casing in trench)         | 39               | 1            | 1                             | 2                                  | 3     | 0        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| S.P. Borehole Ext., Wire Type Weight<br>Anchored, Weight Tensioned with<br>Rotary Potentiometer | 44               | 2            | 0                             | 2                                  | 3     | 2        | 1                             | 2                              | 0                            | 2                         | 2     | 2                              | 1                  | 0                                |
| Ground Elevation Cart                                                                           | 36               | 0            | 3                             | 1                                  | 3     | 0        | 1                             | 2                              | 2                            | 2                         | 1     | 0                              | 0                  | 0                                |
|                                                                                                 |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

|                                                                   | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>HORIZONTAL STRAIN<br>(LINES)                    | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Steel Tape                                                        | 81               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 3                            | 2                         | 3     | 2                              | 3                  | 2                                |
| Invar Tape                                                        | 83               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 3                            | 2                         | 3     | 2                              | 3                  | 2                                |
| Steel Tape Extensometer                                           | 75               | 3            | 3                             | 1                                  | 3     | 3        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 3                                |
| Invar Wire Extensometer                                           | 72               | 2            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 3                                |
| Infrared EDM and theodolite<br>(traverse)                         | 82               | 3            | 3                             | 1                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 1     | 2                              | 0                  | 3                                |
| Infrared EDM and theodolite<br>(trilateration)                    | 63               | 3            | 3                             | 2                                  | 3     | 2        | 2                             | 3                              | 1                            | 2                         | 1     | 2                              | 0                  | 3                                |
| EDM Tachymeter<br>(portable reflectors)                           | 60               | 2            | 3                             | 1                                  | 3     | 2        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 3                                |
| Precision Theodolite and Tape<br>(triangulation)                  | 70               | 3            | 3                             | 2                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 1                              | 1                  | 2                                |
| Theodolite and Stadia Rod                                         | 60               | 3            | 3                             | 1                                  | 3     | 0        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 2                                |
| Precision Theodolite and Invar<br>Subtense Bar                    | 68               | 3            | 3                             | 1                                  | 3     | 2        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 2                                |
| Reduction Tachymeter and<br>Stadia Rod                            | 65               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| Aerial Photogrammetry                                             | 44               | 3            | 3                             | 3                                  | 3     | 0        | 2                             | 2                              | 2                            | 0                         | 3     | 0                              | 0                  | 0                                |
| F.P. Inclinator with Reed Switch<br>Torpedo (Horizontal casing)   | 54               | 2            | 2                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Inclinator with Electro-<br>magnetic Torpedo (Horiz. casing) | 59               | 3            | 2                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 2                  | 0                                |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |
|                                                                   |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile



TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

|                                                                                   | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|-----------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| SUBSURFACE VERTICAL DEFORMATION                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Dial Gauge                 | 50               | 1            | 1                          | 1                               | 2     | 2        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 0                             |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Rotary Potentiometer       | 51               | 2            | 0                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 1     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type Weight Tensioned with Dial Gauge                               | 56               | 2            | 1                          | 1                               | 2     | 3        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 0                             |
| M.P.B.X, Wire Type, Spring or Cantilever Tensioned with Dial Gauge                | 58               | 2            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 0                             |
| M.P.B.X, Wire Type, Cantilever Tensioned with Bonded Electrical Res. Strain Gauge | 41               | 2            | 0                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Wire Type with Spring Tensioned Rotary Potentiometer                     | 50               | 2            | 0                          | 2                               | 2     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type with Spring or Cantilever Tensioned Vibrating Wire             | 41               | 2            | 1                          | 3                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 0                             |
| F.P.B.X, With Electromagnetic Torpedo                                             | 58               | 3            | 2                          | 1                               | 3     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 3               | 1                             |
| F.P.B.X, With Reed Switch Torpedo                                                 | 53               | 2            | 2                          | 1                               | 3     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| F.P.B.X, With Latch Type Probe                                                    | 53               | 2            | 2                          | 1                               | 1     | 2        | 2                          | 2                           | 0                         | 2                      | 3     | 2                           | 3               | 0                             |
| F.P.B.X, With Time Domain Reflectometry                                           | 36               | 2            | 2                          | 3                               | 3     | 0        | 1                          | 2                           | 0                         | 0                      | 2     | 0                           | 2               | 0                             |
| F.P.B.X, With Radioactive Bullets                                                 | 44               | 2            | 2                          | 1                               | 3     | 0        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with Dial Gauge                                                 | 57               | 3            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with Linear Potentiometer                                       | 43               | 3            | 0                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with LVDT                                                       | 40               | 2            | 1                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 0                             |
| M.P.B.X, Rod Type with Vibrating Wire Strain Gauges                               | 44               | 2            | 1                          | 3                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 1                             |
|                                                                                   |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: F.P.B.X. - Full Profile Borehole Extensometer  
M.P.B.X. - Multi Point Borehole Extensometer  
S.P.B.X. - Single Point Borehole Extensometer

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'

(CONTINUED)

|                                                                 | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|-----------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| SUBSURFACE HORIZONTAL DEFORMATION                               | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| F.P.B.I. with Linear Potentiometer Torpedo                      | 38               | 2            | 0                          | 1                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with Servo-Accelerometer Torpedo                       | 50               | 3            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| M.P.B.I. with fixed Servo-Accelerometers                        | 44               | 2            | 1                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 0               | 0                             |
| F.P.B.I. with bonded electrical resistance strain gauge torpedo | 38               | 2            | 0                          | 1                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with fixed bonded strain gauge deflectometer           | 36               | 2            | 0                          | 2                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 0               | 0                             |
| F.P.B.I. with vibrating wire strain gauge torpedo               | 48               | 2            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with LVDT Torpedo                                      | 39               | 2            | 2                          | 1                               | 3     | 0        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with Pneumatic Torpedo                                 | 44               | 0            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
| F.P.B.I. with camera and compass Torpedo                        | 48               | 2            | 3                          | 1                               | 3     | 1        | 2                          | 3                           | 0                         | 2                      | 2     | 1                           | 1               | 0                             |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                 |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: F.P.B.I. - Full Profile Borehole Inclinator  
M.P.B.I. - Multi Point Borehole Inclinator

(CONTINUED)

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

|                                                                                    | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | -3              | 3                             |
|------------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| MINE CONVERGENCE                                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| Spirit Level with wood rod                                                         | 72               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 1                             |
| Precision Level with Invar rod                                                     | 77               | 3            | 3                          | 1                               | 3     | 2        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 2                             |
| Theodolite and Tape                                                                | 72               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 2                             |
| Steel Tape Extensometer                                                            | 81               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 2                      | 3     | 2                           | 3               | 3                             |
| Invar Wire Extensometer                                                            | 78               | 2            | 3                          | 1                               | 3     | 3        | 3                          | 3                           | 2                         | 2                      | 3     | 2                           | 2               | 3                             |
| EDM Tachymeter (portable reflectors)                                               | 63               | 2            | 3                          | 1                               | 3     | 2        | 1                          | 3                           | 2                         | 2                      | 1     | 3                           | 0               | 3                             |
| Infrared EDM and Theodolite                                                        | 68               | 3            | 3                          | 1                               | 3     | 2        | 2                          | 3                           | 2                         | 2                      | 1     | 2                           | 1               | 3                             |
| Close range mine photography                                                       | 55               | 3            | 3                          | 1                               | 3     | 3        | 2                          | 2                           | 2                         | 1                      | 2     | 0                           | 1               | 0                             |
| S.P.B.X. Wire Type with Spring Tensioned Rotary Potentiometer (telescoping casing) | 44               | 2            | 0                          | 2                               | 0     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 0                             |
| Rod Extensometer with Spring Tensioned Vibrating Wire (telescoping casing)         | 61               | 3            | 1                          | 3                               | 2     | 3        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 1               | 2                             |
| Telescoping Rod Extensometer with Linear Potentiometer                             | 60               | 1            | 0                          | 2                               | 3     | 2        | 1                          | 2                           | 2                         | 2                      | 2     | 2                           | 2               | 3                             |
| Invar Telescoping Tube Extensometer with dial gauge                                | 62               | 2            | 1                          | 1                               | 1     | 3        | 3                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 0                             |
| Telescoping Tube Extensometer with machinist's scale                               | 64               | 1            | 1                          | 1                               | 3     | 3        | 2                          | 3                           | 2                         | 3                      | 3     | 2                           | 2               | 0                             |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |
|                                                                                    |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: S.P.B.X. - Single Point Borehole Extensometer

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

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TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES  
SYSTEM E: PERFORMANCE OF CAVING SYSTEMS'  
(CONTINUED)

[illegible]

[illegible]

TABLE B.5  
MATRIX OF INSTRUMENT CAPABILITIES

(CONTINUED)

[illegible]

TABLE B.6  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM F: PERFORMANCE OF FILLED MINES'

|                                                                                                 | Weighting Factor | 2            | 2                             | 1                                  | 3     | 3        | 2                             | 2                              | 3                            | 3                         | 2     | 2                              | 3                  | 3                                |
|-------------------------------------------------------------------------------------------------|------------------|--------------|-------------------------------|------------------------------------|-------|----------|-------------------------------|--------------------------------|------------------------------|---------------------------|-------|--------------------------------|--------------------|----------------------------------|
| GROUND SURFACE<br>VERTICAL SETTLEMENT                                                           | TOTAL            | Availability | Instrument<br>Characteristics | Data Collection<br>Characteristics | Range | Accuracy | Sensitivity<br>to Environment | Calibration<br>and Maintenance | Ease/Cost of<br>Installation | Ease/Cost<br>of Operation | Power | Ease/Cost of<br>Data Reduction | Instrument<br>Cost | No. of Applications<br>in System |
| Spirit Level with wood rod                                                                      | 66               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 3                  | 1                                |
| Precision Level with Invar rod                                                                  | 71               | 3            | 3                             | 1                                  | 3     | 3        | 3                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 1                                |
| Rotating Beam Laser Level<br>with rod detector                                                  | 55               | 3            | 3                             | 1                                  | 3     | 3        | 1                             | 2                              | 1                            | 2                         | 1     | 2                              | 1                  | 0                                |
| Theodolite with wood rod<br>(as level)                                                          | 63               | 3            | 3                             | 1                                  | 3     | 1        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 1                                |
| Theodolite and Stadia Rod                                                                       | 60               | 3            | 3                             | 1                                  | 3     | 0        | 2                             | 3                              | 1                            | 2                         | 3     | 2                              | 2                  | 1                                |
| EDM Tachymeter<br>(portable reflectors)                                                         | 54               | 2            | 3                             | 1                                  | 3     | 2        | 1                             | 3                              | 1                            | 2                         | 1     | 3                              | 0                  | 1                                |
| S.P. Simple Hose Manometer                                                                      | 56               | 2            | 1                             | 2                                  | 3     | 1        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| S.P. Electrical contact-type<br>Hose Manometer                                                  | 58               | 2            | 1                             | 2                                  | 3     | 3        | 1                             | 2                              | 1                            | 3                         | 2     | 2                              | 2                  | 0                                |
| S.P. Overflow type Manometer                                                                    | 61               | 3            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Overflow type Manometer                                                                    | 59               | 2            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 3                         | 3     | 2                              | 2                  | 0                                |
| F.P. Two Liquid Pressure Balance<br>Manometer                                                   | 51               | 1            | 1                             | 2                                  | 3     | 2        | 2                             | 2                              | 1                            | 2                         | 3     | 2                              | 1                  | 0                                |
| F.P. Air Balloon in Liquid Filled<br>Tube Settlement Device                                     | 48               | 2            | 1                             | 2                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 2                              | 1                  | 0                                |
| F.P. Borehole Inclinator with<br>Servo-accelerometer torpedo<br>(horiz. casing in trench)       | 47               | 3            | 2                             | 1                                  | 3     | 1        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| M.P. Borehole Inclinator with<br>fixed Electrolytic levels<br>(horiz. casing in trench)         | 39               | 1            | 1                             | 2                                  | 3     | 0        | 1                             | 2                              | 1                            | 2                         | 2     | 1                              | 1                  | 0                                |
| S.P. Borehole Ext., Wire Type Weight<br>Anchored, Weight Tensioned with<br>Rotary Potentiometer | 49               | 2            | 0                             | 2                                  | 3     | 2        | 1                             | 2                              | 0                            | 2                         | 2     | 2                              | 1                  | 1                                |
| Ground Elevation Cart                                                                           | 36               | 0            | 3                             | 1                                  | 3     | 0        | 1                             | 2                              | 2                            | 2                         | 1     | 0                              | 0                  | 0                                |
|                                                                                                 |                  |              |                               |                                    |       |          |                               |                                |                              |                           |       |                                |                    |                                  |

KEY: F.P. - Full Profile  
M.P. - Multi Point  
S.P. - Single Point

TABLE B.6  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM F: PERFORMANCE OF FILLED MINES'  
(CONTINUED)

|                                                                                   | Weighting Factor | 2            | 2                          | 1                               | 3     | 3        | 2                          | 2                           | 3                         | 3                      | 2     | 2                           | 3               | 3                             |
|-----------------------------------------------------------------------------------|------------------|--------------|----------------------------|---------------------------------|-------|----------|----------------------------|-----------------------------|---------------------------|------------------------|-------|-----------------------------|-----------------|-------------------------------|
| SUBSURFACE VERTICAL DEFORMATION                                                   | TOTAL            | Availability | Instrument Characteristics | Data Collection Characteristics | Range | Accuracy | Sensitivity to Environment | Calibration and Maintenance | Ease/Cost of Installation | Ease/Cost of Operation | Power | Ease/Cost of Data Reduction | Instrument Cost | No. of Applications in System |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Dial Gauge                 | 51               | 1            | 1                          | 1                               | 2     | 3        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 0                             |
| S.P.B.X, Wire Type, Weight Anchored Wt. Tensioned with Rotary Potentiometer       | 55               | 2            | 0                          | 2                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 1                             |
| M.P.B.X, Wire Type Weight Tensioned with Dial Gauge                               | 56               | 2            | 1                          | 1                               | 2     | 3        | 1                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 0                             |
| M.P.B.X, Wire Type, Spring or Cantilever Tensioned with Dial Gauge                | 58               | 2            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 3               | 0                             |
| M.P.B.X, Wire Type, Cantilever Tensioned with Bonded Electrical Res. Strain Gauge | 41               | 2            | 0                          | 2                               | 0     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Wire Type with Spring Tensioned Rotary Potentiometer                     | 55               | 2            | 0                          | 2                               | 2     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Wire Type with Spring or Cantilever Tensioned Vibrating Wire             | 44               | 2            | 1                          | 3                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 0                             |
| F.P.B.X, With Electromagnetic Torpedo                                             | 60               | 3            | 2                          | 1                               | 3     | 2        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 3               | 0                             |
| F.P.B.X, With Reed Switch Torpedo                                                 | 53               | 2            | 2                          | 1                               | 3     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| F.P.B.X, With Latch Type Probe                                                    | 56               | 2            | 2                          | 1                               | 1     | 3        | 2                          | 2                           | 0                         | 2                      | 3     | 2                           | 3               | 0                             |
| F.P.B.X, With Time Domain Reflectometry                                           | 39               | 2            | 2                          | 3                               | 3     | 1        | 1                          | 2                           | 0                         | 0                      | 2     | 0                           | 2               | 0                             |
| F.P.B.X, With Radioactive Bullets                                                 | 41               | 2            | 2                          | 1                               | 3     | 1        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with Dial Gauge                                                 | 57               | 3            | 1                          | 1                               | 2     | 3        | 2                          | 2                           | 0                         | 3                      | 3     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with Linear Potentiometer                                       | 44               | 3            | 0                          | 2                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 2               | 0                             |
| M.P.B.X, Rod Type with LVDT                                                       | 43               | 2            | 1                          | 2                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 0                             |
| M.P.B.X, Rod Type with Vibrating Wire Strain Gauges                               | 44               | 2            | 1                          | 3                               | 1     | 3        | 1                          | 2                           | 0                         | 2                      | 2     | 2                           | 1               | 0                             |
|                                                                                   |                  |              |                            |                                 |       |          |                            |                             |                           |                        |       |                             |                 |                               |

KEY: F.P.B.X. - Full Profile Borehole Extensometer  
M.P.B.X. - Multi Point Borehole Extensometer  
S.P.B.X. - Single Point Borehole Extensometer

TABLE B.6  
MATRIX OF INSTRUMENT CAPABILITIES  
'SYSTEM F: PERFORMANCE OF FILLED MINES'  
(CONTINUED)

[illegible]

Key: S.P.B.X. - Single Point Borehole Extensometer

APPENDIX C

REFERENCES





APPENDIX C

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APPENDIX D  
LIST OF MANUFACTURERS AND DISTRIBUTORS





APPENDIX D

LIST OF MANUFACTURERS AND DISTRIBUTORS

Manufacturers and distributors whose literature was used to prepare the tables in the main body of this report are listed below.

AGA Corporation  
80 Mark Dr.  
San Rafael, California

Bison Instruments, Incorporated  
5708 West 36th Street  
Minneapolis, Minnesota

British Aircraft Corp.-USA (BAC)  
339 J Davis Hy.  
Arlington-, Virginia

Carlson Instruments  
1190-C Dell Ave.  
Campbell, California

Chesterman - See Surveyors Service Co.

Corner House Laboratories (Pty.) Ltd.  
Private Bag I  
Emmarentia, Johannesburg  
South Africa

Cubic Corp.  
9233 Balboa  
San Diego, California

Deakin - See SINCO

Diffraeto Limited  
Box 2093  
Windsor, Ontario NBY 4R5

Eagle - See Surveyors Service Co.

Eastman International Company GMBH  
3005 Hannover-Westerfeld  
Carl Zeiss-Strasse 16  
Germany

Galileo - See Officine Galileo

Geosistemas, S. A.  
Calle Oriente 23 1/3, No. 36  
Mexico 9, D.F., Mexico

Geo Space Corporation  
P. O. Box 36374/5803 Glenmant Dr.  
Houston, Texas

Geotesting, Incorporated  
P. O. Box 4339  
San Rafael, California

Geostrumenti, S. R. L.  
20090 Segrate (Milano)  
Via XXV Aprile, 10  
Italy

Gisco Instrument and Supply Co.  
4665 Joliet St.  
Denver, Colorado

Franz Glotzl, Baumesstechnik  
D-7501 Forcneim  
BHF bei Karlsruhe  
West Germany

Gurley - See Surveyors Service Co.

Hewlett-Packard (H.P.)  
1501 Page Mill Road  
Palo Alto, California

Interfels GMBH  
Schwarzstrabe 27  
A-5020 Salzburg  
Austria

Irad Gage, Incorporated  
14 Parkhurst St.  
Lebanon, New Hampshire

Jenoptik - See AGA Corporation

Kern - See Gisco

Keuffel & Esser Company  
20 Whippany Rd.  
Morristown, New Jersey

Laser Alignment  
6330 - 28th St., S.E.  
Grand Rapids, Michigan

The Leitz Company  
829 Cowan Rd.  
Burlingame, California

LNEC - See Interfels

Lufkin - See Surveyors Service Co.

H. Maihak A. G.  
2000 Hamburg 39  
Germany

W. H. Mayes & Son, Ltd (Demec Gauge)  
Vans, Hart Estate  
Arthur Rd.  
Windsor, Berkshire, England

MG Laser Systems  
2352 Charleston Rd.  
Mountain View, California

Micro-Measurements  
Box 306/38905 Chase Rd.  
Romulus, Michigan

Micro Precision Engineering  
943 Ventura Ave.  
Livermore, California

Nimbus Instruments  
2791 Del Monte St.  
West Sacramento, California

Walter Nold Company  
24 Birch Rd.  
Natick, Massachusetts

Officine Galileo S.P.A.  
Div. Strumentazione  
50134 Firenze  
Via Carlo Bini  
Italy

Path - See Surveyors Service Co.

Pelton Company, Incorporated (PELCO)  
P. O. Box 1415  
Ponca City, Oklahoma

Precision International - See Surveyors  
Service Co.

Prewitt Associates  
Scratch Stram Gauge Division  
P. O. Box 365  
Lexington, Kentucky

Sattec - See Telemac

Schaevitz Engineering  
U. S. Route 30 & Union Ave.  
Pennsauken, New Jersey

Seismograph Service Corporation  
Birdwell Division  
P. O. Box 1590  
Tulsa, Oklahoma

Serata Geomechanics, Incorporated  
1229 - 8th St.  
Berkeley, California

Slope Indicator Company (SINCO)  
3668 Albion Place North  
Seattle, Washington

Peter Smith Instrumentation Ltd.  
Gosforth Industrial Estate  
Newcastle Upon Tyne NE3 1 x F  
England

Soil & Rock Instrumentation  
30 Tower Rd.  
Newton Upper Falls, Massachusetts

Soil Instruments Limited  
Townsend Lane  
London, NW9, 8TR, England

Soiltest, Incorporated (See also GISCO)  
2205 Lee St.  
Evanston, Illinois

Strainert Company  
Union Hill Industrial Park  
West Conshohocken, Pennsylvania

Structural Behavior Engineering  
Laboratories, Inc.  
P. O. Box 9847  
Phoenix, Arizona

Surveyors Service Company  
P. O. Box 1500/2942 Century Place  
Costa Mesa, California

Tektronix  
P. O. Box 500  
Beaverton, Oregon 97005

Teledyne Geotech  
16027 West 5th Ave.  
Golden, Colorado

Telemac International, Incorporated  
5450 Cote des Neiges  
Room 416  
Montreal, Canada

Tellurometer - U.S.A.  
A Division of Plessey, Inc.  
89 Marcus Blvd.  
Hauppauge, New York

Tempo Instruments  
51 East Bethpage  
Plainview, New York

Terrametrics  
16027 West 5th Ave.  
Golden, Colorado

Terra Technology Corporation  
3018 Western Ave.  
Seattle, Washington

Texas Instruments, Incorporated  
P. O. Box 66027  
Houston, Texas

Universal Camera Division  
P. O. Box 23167  
Phoenix, Arizona

Weidman Division  
Warner and Swasey Corporation  
7 Salt Creek Lane  
Hinsdale, Illinois 60521

David White - See Surveyors Service Co.

Wild - See Surveyors Service Co.

Carl Zeiss  
Oberkochen  
West Germany



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APPENDIX E  
SUPPLEMENTARY LIST OF  
MANUFACTURERS AND DISTRIBUTORS



# APPENDIX E

## SUPPLEMENTARY LIST OF MANUFACTURERS AND DISTRIBUTORS

Since the list of manufacturers and distributors given in Appendix D is not comprehensive, the following reprints are included as a supplement to this report.

(from "Water Power," February, 1974)

# Instrumentation

a special survey

*Instrumentation for civil- and mechanical-engineering applications has grown increasingly complex during recent years, and it has now reached a point where practising engineers have difficulty in keeping up to date with new products and their capabilities. In the next pages we have tried to assist readers by providing firstly a list of the more prominent manufacturers, classified under product types, and secondly, brief details of their latest equipment. Such a survey cannot hope to be truly comprehensive, but we hope it will be of value in keeping hydroelectric engineers informed of new developments*

### Hydraulic

Automatic Systems Laboratories Ltd,  
Construction House, Grovebury  
Road, Leighton Buzzard, Bedfordshire LU7 8SX, U.K.

Huggenberger AG,  
Hohlstrasse 176, CH-8004 Zürich,  
Switzerland.

KDG Instruments Ltd,  
Fleming Way, Crawley, Sussex  
RH10 2QE, UK.

Leupold & Stevens Instruments Inc,  
PO Box 688, 600 NW Meadow  
Drive, Beaverton, Oregon 97005,  
USA.

(European representative:  
GK Instruments, 3 Commerce  
Way, Leighton Buzzard, Bedfordshire, UK.)

H. Maihak AG,  
2000 Hamburg 39, Semperstrasse,  
38, W Germany.

Metrosol s.r.l.,  
Via Almerigo da Schio 8, 20146  
Milan, Italy.

Franz Rittmeyer Ltd,  
CH-6300 Zug 2, Switzerland.

Robertson Research International  
Ltd,  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.,  
3668 Albion Place N, Seattle,  
Washington 98103, USA.

Socosor,  
6 place de la République Dominicaine,  
75827 Paris, Cedex 17,  
France.

Terrametrics,  
16027 West 5th Avenue, Golden,  
Colorado 80401, USA.

### Optical

Eastman International Company,  
3005 Hannover-Westerfeld, Carl-  
Zeiss-Strasse 16, W Germany.

Huggenberger AG,  
Hohlstrasse 176, CH-8004 Zürich,  
Switzerland.

Kern & Co Ltd,  
5001 Aarau, Switzerland.

Rank Precision Industries,  
Analytical Division,  
Westwood Industrial Estate, Ramsgate Road, Margate, Kent CT9 4JL, UK.

Robertson Research International  
Ltd,  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.,  
3668 Albion Place N, Seattle,  
Washington 98103, USA.

Survey & General Instrument Co  
Ltd,  
Fircroft Way, Edenbridge, Kent,  
UK.

Terrametrics,  
16027 West 5th Avenue, Golden,  
Colorado 80401, USA.

Wild Heerbrugg AG,  
CH 9435 Heerbrugg, Switzerland.

### Dam Monitoring

Dynamic Logic Ltd,  
Great Hollands Square, Bracknell,  
Berkshire, UK.

Gage Technique Ltd,  
PO Box 30, Trowbridge, Wiltshire  
BA14 8YD, UK.

Geostrumenti s.r.l.,  
20090 Segrate (Milano), Via XXV  
Aprile 10, Italy.

Hewlett-Packard Company, Civil  
Engineering Products,  
PO Box 301, Loveland, Colorado  
80537, USA.

Leupold & Stevens Instruments Inc,  
PO Box 688, 600 NW Meadow  
Drive, Beaverton, Oregon 97005,  
USA.

(European representative:  
G.K. Instruments, 3 Commerce

Way, Leighton Buzzard, Bedfordshire, UK.)

H. Maihak AG,  
2000 Hamburg 39, Semperstrasse  
38, W Germany.

Metrosol s.r.l.,  
Via Almerigo da Schio 8, 20146  
Milan, Italy.

Nimbus Instruments,  
2791 Del Monte Street, West  
Sacramento, California 95691,  
USA.

Robertson Research International  
Ltd,  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.,  
3668 Albion Place N, Seattle,  
Washington 98103, USA.

Socosor,  
6 place de la République Dominicaine,  
75827 Paris, Cedex 17,  
France.

Soil Instruments Ltd,  
Townsend Lane, London NW9  
8TR, UK.

W. F. Sprengnether Instrument Co.  
4567 Swan Avenue, St Louis,  
Missouri 63110, USA.

Survey & General Instrument Co Ltd,  
Fircroft Way, Edenbridge, Kent,  
UK.

Telemac, s.r.l.,  
17 Rue Alfred Roll, Paris 17e,  
France.

Terra Technology (Division)  
Corporation,  
3018, Western Avenue, Seattle,  
Washington 98121, USA.

Terrametrics,  
16027 West 5th Avenue, Golden,  
Colorado 80401, USA.

Welwyn Electric Ltd,  
Strain Measurement & Equipment  
Division, Armstrong Road, Basingstoke RG24 0QA, UK.

Wykeham Farrance Engineering Ltd,  
Weston Road, Slough SL1 4HW,  
UK.

SUPPLEMENTARY LIST OF MANUFACTURERS AND DISTRIBUTORS (continued)

# instrumentation

## Electronic and Data Processing

Automatic Systems Laboratories Ltd.  
Construction House, Grovebury  
Road, Leighton Buzzard, Bedfordshire LU7 8SX, UK.

Bell & Howell Ltd, Electronic & Instruments Division,  
Lennox Road, Basingstoke, Hampshire, UK.

Dynamic Logic Ltd.  
Great Hollands Square, Bracknell,  
Berkshire, UK.

Fielden Electronics Ltd.  
P.O. Box 6, Paston Road, Wythenshawe, Manchester M22 4TX, UK.

Fisher Research Laboratory,  
P.O. Box 490, Belmont, California 94002, USA.

Gage Technique Ltd.  
P.O. Box 30, Trowbridge, Wiltshire BA14 8YD, UK.

Geosumenti s.r.l.  
20090 Segrate (Milano), Via XXV Aprile 10, Italy.

Hewlett-Packard Company,  
Civil Engineering Products,  
P.O. Box 301, Loveland, Colorado 80537, USA.

A/S Kongsberg Våpenfabrikk.  
Postbox 25, N-3601 Kongsberg, Norway.

Metrolabs Systems Inc.  
P.O. Box 1307, Norman, Oklahoma 73069, USA.

Mycalex Instruments Ltd,  
Charlton Kings Industrial Estate,  
Cirencester Road, Cheltenham GL53 8DZ, UK.

Franz Rittmeyer Ltd.  
CH-6300 Zug 2, Switzerland.

Robertson Research International Ltd.  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.  
3668 Albion Place N, Seattle, Washington 98103, USA.

Soil Instruments Ltd,  
Townsend Lane, London NW9 8TR, UK.

W. F. Sprengnether Instrument Co.  
4567 Swan Avenue, St Louis, Missouri 63110, USA.

Survey & General Instrument Co Ltd,  
Firecroft Way, Edenbridge, Kent, UK.

Teledyne Gurley,  
514 Fulton Street, Troy, New York 12181, USA.

Terra Technology (Division) Corporation,  
3018, Western Avenue, Seattle, Washington 98121, USA.

Terrametrics,  
16027 West 5th Avenue, Golden, Colorado 80401, USA.

Rock and Soil Mechanics  
Eastman International Company,  
3005 Hannover-Westerfeld, Carl-Zeiss-Strasse 16, W Germany.

Engineering Laboratory Equipment Ltd.  
Durrants Hill Trading Estate,  
Apsley, Hemel Hempstead, Hertfordshire, UK.

Gage Technique Ltd.  
P.O. Box 30, Trowbridge, Wiltshire BA14 8YD, UK.

Geotechnik,  
3 Hannover, Gabelborgerstrasse 5, W Germany.

Geonor A/S,  
P.O. Box 99, Raa, Oslo 7, Norway.

Huggenberger AG,  
Hohlstrasse 176, CH-8004 Zürich, Switzerland.

H. Mailhak AG,  
2000 Hainburg 39, Semperstrasse 39, W Germany.

Nimbus Instruments,  
2791 Del Monte Street, West Sacramento, California 95691, USA.

Robertson Research International Ltd.  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.  
3668 Albion Place N, Seattle, Washington 98103, USA.

Socesor,  
6 place de la République Dominicaine, 75827 Paris, Cedex 17, France.

Soil Instruments Ltd,  
Townsend Lane, London NW9 8TR, UK.

Soiltest International Inc.  
2205 Lee Street, Evanston, Illinois 60202, USA.

Telame s.r.l.,  
17 Rue Alfred Roll, Paris 17e, France.

Terra Technology (Division) Corporation,  
3018, Western Avenue, Seattle, Washington 98121, USA.

Terrametrics,  
16027 West 5th Avenue, Golden, Colorado 80401, USA.

Terratest,  
P.O. Box No. 8, Wigston, Leicester LE8 2TL, UK.

Walter Nold Co.  
24, Birch Road, Natick, Massachusetts 01760, USA.

Wykeham Farrance Engineering Ltd,  
Weston Road, Slough SL1 4HW, UK.

## Others

Gage Technique Ltd,  
P.O. Box 30, Trowbridge, Wiltshire BA14 8YD, UK.

Geosumenti s.r.l.  
20090 Segrate (Milano), Via XXV Aprile 10, Italy.

Hottinger Baldwin Messtechnik GmbH,  
61 Darmstadt, Im Tiefen See 45, Post Box 4151, W Germany.

Huggenberger AG,  
Hohlstrasse 176, CH-8004 Zürich, Switzerland.

Metrosol s.r.l.,  
Via Almerigo da Schio 8, 20146 Milan, Italy.

Rank Precision Industries, Analytical Division,  
Westwood Industrial Estate, Ramsgate Road, Margate, Kent CT9 4JL, UK.

B. Rhodes & Son Ltd,  
Danes Road, Crow Lane, Romford RM7 0HR, Essex, UK.

Robertson Research International Ltd.  
'Ty'n-y-Coed', Llanrhos, Llandudno, N Wales, UK.

Slope Indicator Co.  
3668 Albion Place N, Seattle, Washington 98103, USA.

Socesor,  
6 place de la République Dominicaine, 75827 Paris, Cedex 17, France.

Soiltest International Inc.  
2205 Lee Street, Evanston, Illinois 60202, USA.

Terratest,  
P.O. Box No. 8, Wigston, Leicester LE8 2TL, UK.

Walter Nold Company,  
24 Birch Road, Natick, Massachusetts 01760, USA.



SUPPLEMENTARY LIST OF MANUFACTURERS AND DISTRIBUTORS (continued)

(from Cording et al, 1975)

LISTING OF INSTRUMENTATION SPECIALISTS,  
SUPPLIERS AND MANUFACTURERS

ABEM Instrument Group, Craelius Svenska Diamant, Fack, S-101 10 Stockholm,  
Sweden  
Adlab Ltd. P. O. Box 1, Farnworth, Bolton, BL4 7SM, Lancashire, England  
Ailtech, 19535 East Walnut Drive, City of Industry, California, 91748 USA  
American Instruments, 8030 Georgia Avenue, Silver Spring, Maryland  
20910, USA  
B.C. Ames Co., 131 Lexington St., Waltham, Massachusetts 02154, USA  
Ampower Corp., 1 Marine Plaza, North Bergen, New Jersey 07047, USA  
Atkins Technical, Inc., P.O. Box 14405 University Station, Gainesville,  
Florida, 32601, USA  
Automation Industries, Inc., Shelter Rock Road, Danbury, Connecticut  
06810, USA  
  
BEVAC, Route d'Yverdon 18, CH-1033 Cheseaux-sur-Lausanne, Switzerland  
Bison Instruments, Inc. 5708 W. 36th Street, Minneapolis, Minnesota,  
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Geo-Testing, Inc., P.O. Box 4339, San Rafael, California, 94903, USA  
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GISCO (Geophysical Instrument and Supply Co.), 900 Broadway, Denver, Colorado,  
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Honeywell Industrial Division, Fort Washington, Pa. 19034, USA or  
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77018, USA  
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Dr. Ing. Heinz Idel, Potthoffs Borde 15, 43 Essen, West Germany.  
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Plasticrafts, Inc., 2800 North Speer Blvd., Denver, Colorado, 80211, USA  
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U.S. Supplier: Soil and Rock Instrumentation, Inc.  
  
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North Wales, England  
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Sensotec, Inc., 1400 Holley Ave., Columbus, Ohio, 43212, USA  
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Michigan, 49507, USA  
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