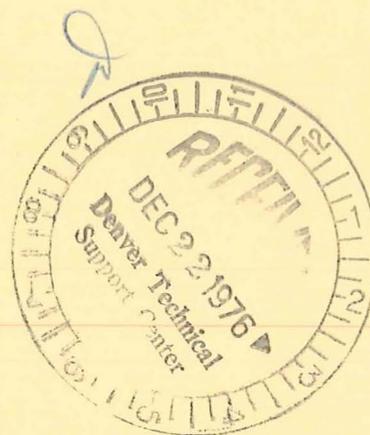


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Field Measurements and Corresponding
Finite-Element Analysis of Closure
During Shaft Sinking
at the Lucky Friday Mine



UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8193

**Field Measurements and Corresponding
Finite-Element Analysis of Closure
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at the Lucky Friday Mine**

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UNITED STATES DEPARTMENT OF THE INTERIOR

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FIELD MEASUREMENTS AND CORRESPONDING FINITE-ELEMENT ANALYSIS OF CLOSURE DURING SHAFT SINKING AT THE LUCKY FRIDAY MINE

by

A. E. Gooch¹ and J. P. Conway¹

ABSTRACT

The Bureau of Mines conducted research in an attempt to provide a more sound basis for recommending improved artificial support during deepening of the main shaft of the Lucky Friday mine in the Coeur d'Alene mining district of northern Idaho. Field measurements of closure across the short axis of the 13- by 26-foot shaft were as high as 16 inches. Elastic/plastic finite-element (F/E) analyses were made, reducing the values of large-scale in situ rock mass properties until field closure measurements generally corresponded to displacements in the F/E analyses. Resulting plots of rock mass displacements, stresses, and areas of plastic failure display the results of creating openings (shaft, in this case) in deep mines in difficult ground conditions requiring artificial support.

INTRODUCTION

Efficient support of underground openings is a major problem in deep mines. Efficiency in the larger sense considers general underground-environment safety as well as cost effectiveness. Support concerns the size, shape, orientation, and purpose of openings, as well as the actual physical support media.

Reports on underground-support research are many. Significant "break-throughs" are few and far between, but the continuing individual detailed research efforts are gradually improving the efficiency of support systems.

Timber support has remained basically the same for decades. More recently, rock bolting has extensively replaced timber. Although there has been rather steady improvement in bolts, bolt anchorage, and installation methods, bolting patterns, lengths, and diameters have remained fundamentally the same. When the decision is made to bolt, it is done typically according to a standard mine procedure. Patterns, length, and anchorage selection are based on past experience and are the same regardless of the specifics of a particular opening such as bedding, size, shape, and orientation. When the operator has no sound criteria to guide him, his experience can be costly.

¹Mining engineer.

The research reported here is on ground support in a deep shaft. The test mine was limited by the constraints of the existing shaft, which was being deepened; this precluded the option of new shaft design. Because of excessive closure,² the mine operators asked the Bureau of Mines to monitor the shaft as sinking progressed.

Subsequent research demonstrated how the state of stress, strain, and deformation around an opening can be investigated quantitatively in conjunction with appropriate field measurements and previous knowledge of the rock mass. Although the finite-element analyses in this particular case were done after the fact, they show that a predictive capability exists if carried out in a timely manner.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the cooperation given by the officials and personnel at Hecla's Lucky Friday mine in the Coeur d'Alene mining district near Mullan, Idaho, without which this research would not have been possible.

SHAFT SUPPORT

The shaft is a 26- by 13-foot (open ground) rectangle, and ground conditions are difficult, requiring jacket sets to provide for relieving the main shaft timber before distortion from uncontrollable ground displacement. When the operators felt that ground conditions improved, resin-grouted bolts were

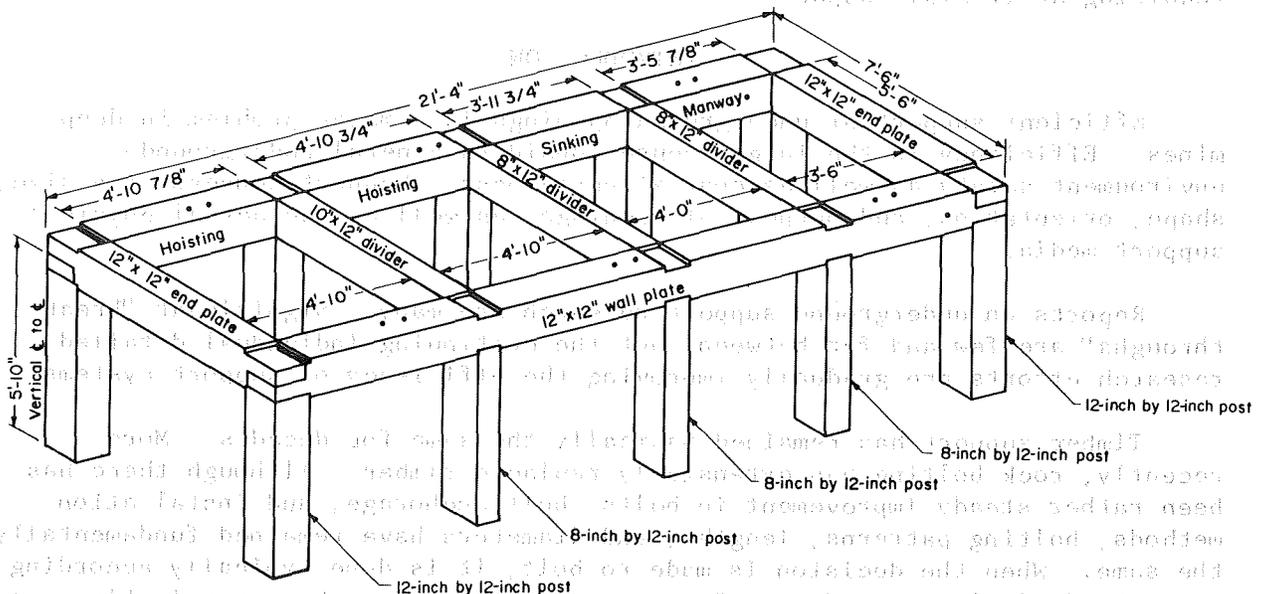
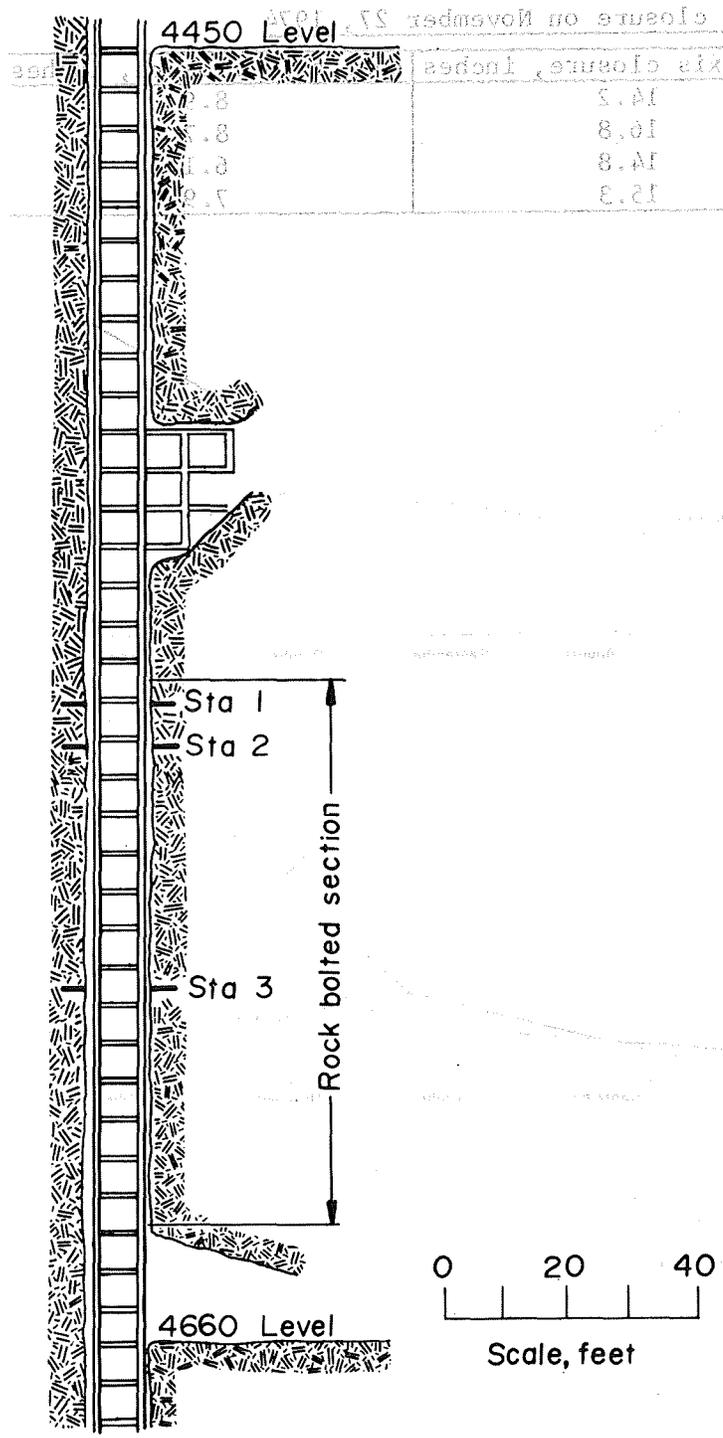


FIGURE 1. - Lucky Friday mine standard shaft sets below 4050 level.

²Closure in this report is total measured displacement along the two horizontal axes of the opening.



installed instead of jacket sets. The bolt system was four 3/4-inch-diameter rebar bolts in a single mat along the short dimension and two mats with eight bolts along the long dimension. Shaft timbers are on 5-foot 10-inch centers. An 8-foot, resin-grouted bolt pattern was installed between each set. Figure 1 illustrates standard shaft timber.

MEASUREMENTS

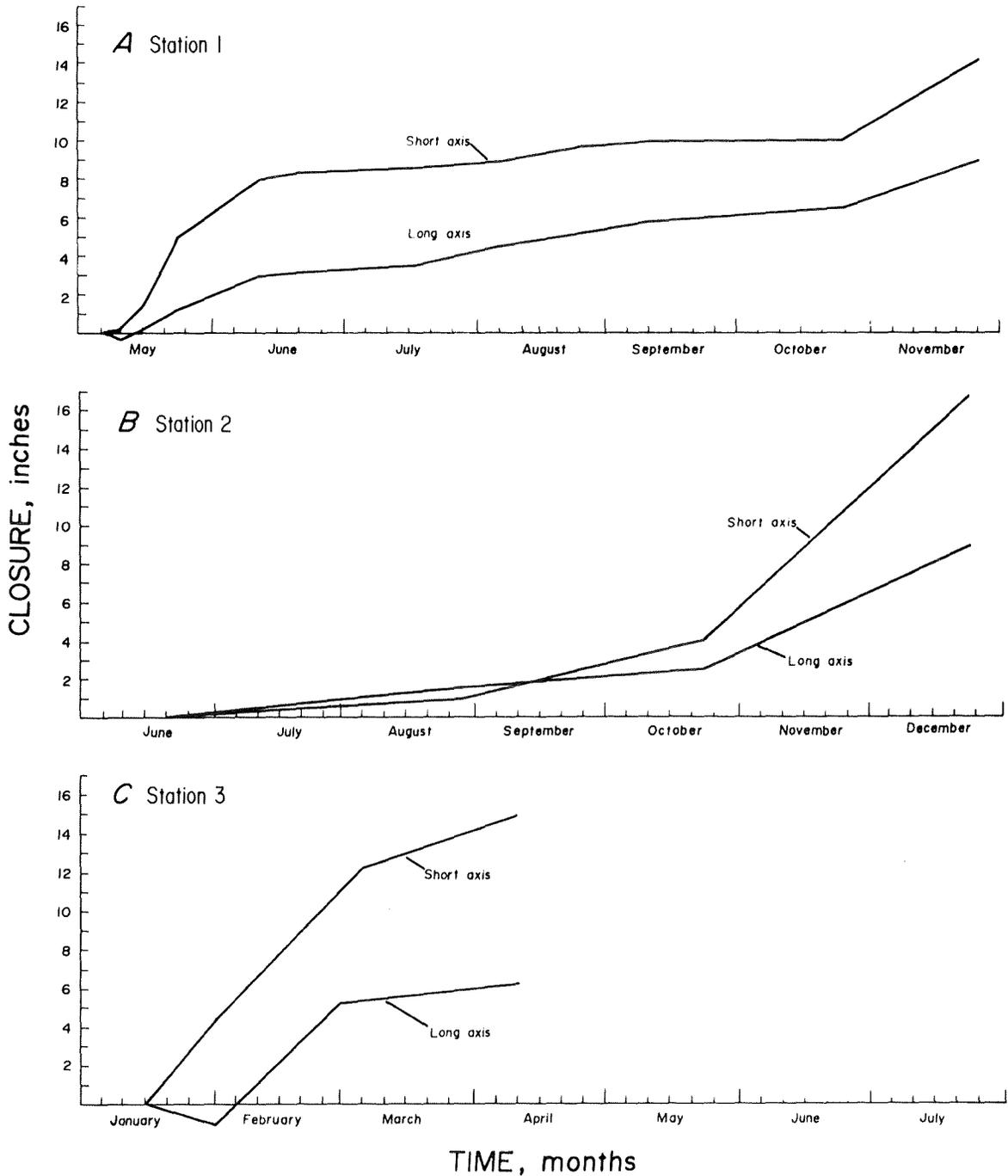
Between May 1974 and April 1975, closure was measured in the shaft while sinking proceeded between the 4450 and 4660 levels. The 4660 level is actually 4687 feet below surface. Measurements were made with a tape extensometer from points anchored about 4 feet into the shaft walls. Figure 2 shows the position of these points. Measured closure was excessive, as shown by the closure versus time plots in A, B, and C of figure 3. The predominant closure as shown in figure 3A occurred during sinking activity and was relatively small from July through October during a period of no sinking. The closure rate increased again when sinking began in October, indicating that ground conditions were still unstable. As the shaft deepened, the walls were laced off making these closure points unavailable for measurement. Total closures and period of measurement are shown in table 1.

FIGURE 2. - Lucky Friday shaft vertical section.

Figure 2. Lucky Friday shaft vertical section.

TABLE 1. - Shaft closure on November 27, 1974

Station	Period measured	Short axis closure, inches	Long axis closure, inches
1.....	5/6-11/27/74	14.2	8.9
2.....	6/20-12/23/74	16.8	8.7
3.....	1/15-4/10/75	14.8	6.1
Average	-	15.3	7.9



TIME, months
 FIGURE 3. - Field closure plots.

FINITE-ELEMENT ANALYSES

To provide a comprehensive picture of the state of stress and displacement in the rock/support system, finite element (F/E) analyses were made. An essence of the analyses was the alteration of rock mass properties to show a magnitude of closure in the F/E analyses generally equal to the closure measured in the field. Of the parameters concerned with the problem, the large-scale rock mass properties are the least known and may be altered using a consistent procedure (5).³

Program Description

The program was a modification of one developed by Douglas Dahl (2) for an elastic/plastic analysis. It is described in previous work in underground-opening analyses (4-5). The specific features of this F/E analysis are--

1. Two-dimensional plain strain analysis (6).
2. Each material is homogeneous and isotropic.
3. Elastic/perfectly plastic material properties with Mohr-Coulomb yield criteria.

Program input, in addition to mesh description, consisted of sets of elastic and plastic properties for each desired material. Elastic properties entered are modulus of elasticity (E), Poisson's ratio (μ), and shear modulus (G), computed from $G = \frac{E}{2(1 + \mu)}$. Maximum strength (plastic) properties entered are compressive strength (C_o), tensile strength (T_o), and shear strength (S_o), computed from $S_o = \frac{(C_o)(T_o)}{(C_o + T_o)}$ (2). The desired angle of internal friction (ϕ), is determined by appropriate material property input values of C_o and T_o , from $\sin \phi = \frac{C_o - T_o}{C_o + T_o}$ (2). An important program input (ϕ) is often more predictable than C_o and T_o in a large-scale rock mass.

Boundary conditions require nodal points to be fixed, restrained in the X or Y direction only, or free. Load may be applied in the X and Y direction at nodal points, or may be entered as an initial stress field with any combination of X and Y stresses.

Program output consists of--

1. Complete elastic analysis at the total load.
2. Analysis of elements that fail (plastic) as load increases through increments to the total load.

³Underlined numbers in parentheses refer to items in the list of references at the end of this report.

3. Final complete elastic-plastic analysis at total load.

Model Description

Figure 4 illustrates the finite-element mesh and delineates areas within which material property input may be specified in any single run, independent of properties of adjoining areas. Symmetry across each of the X and Y axes is modeled to allow a quarter section mathematical model to represent the problem, the opening thus representing a 6-1/2- by 13-foot quarter section. The condition of symmetry is fulfilled by specifying zero displacement along one axis and freedom of movement along the other. This condition is illustrated by the roller boundaries along the X and Y axes in figure 4. Total load is assumed to be a 5,000-psi initial stress field representing approximately a 5,000-foot depth (1 psi/ft). This is represented by 5,000-psi stresses along each of the coordinate axes, in compression, that is applied (in compression) toward each of the restraining boundaries ($X = 0$ and $Y = 0$). The outer boundaries (max X and max Y) are unrestrained. The result is a uniform stress field if there were no opening (shaft) in the model. The total load was divided into 10 increments, each increment representing a percentage of the total load.

Material 1 provides for representation of the 8-foot "bolts" or a pin restraining rock movement, simulating a grouted bolt. Long thin elements are

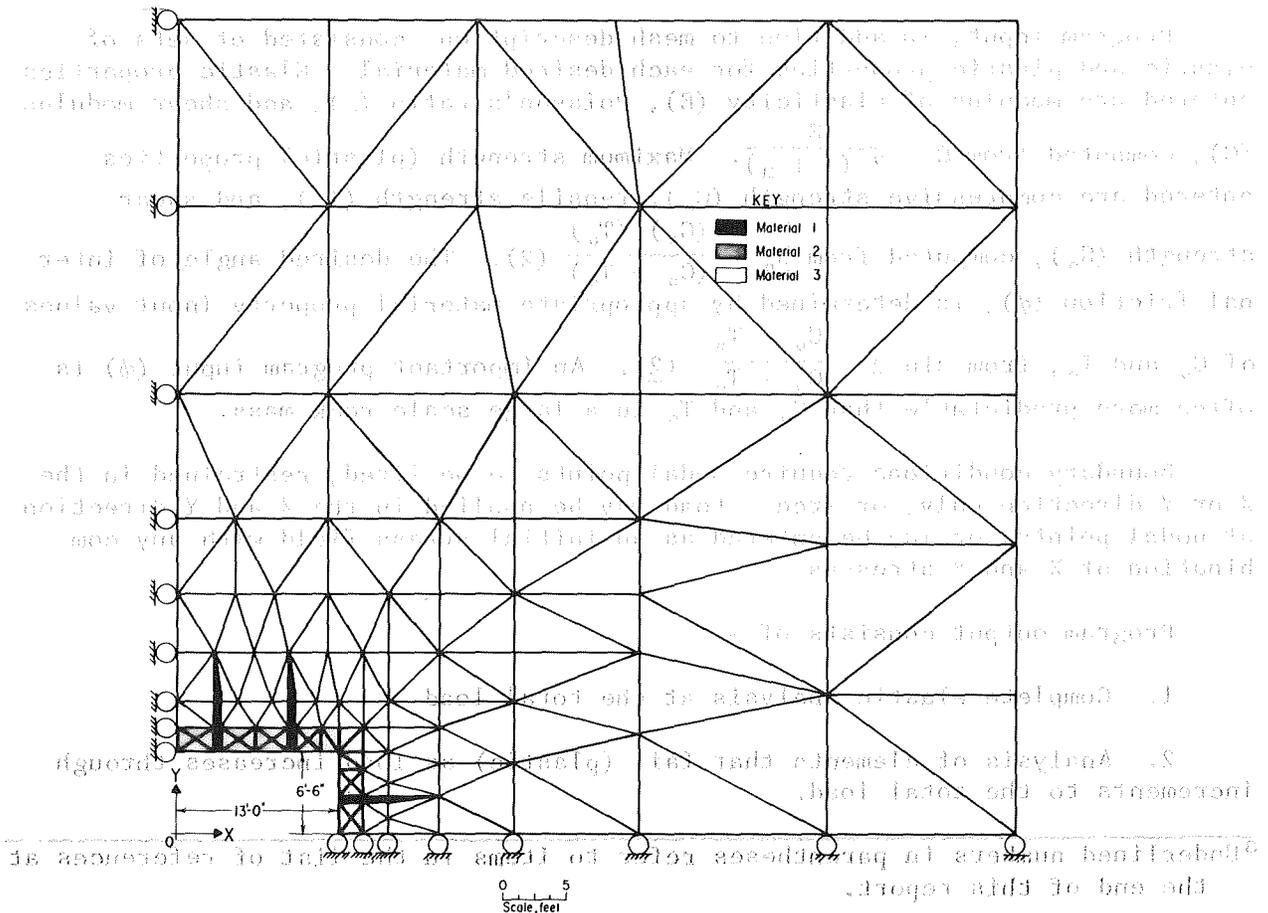


FIGURE 4. - Finite-element mesh and material property boundaries.

used, dimensionally exceeding the "rule of thumb" length/width ratio of 5. Thin elements have produced good results when loads are in tension or compression; however, poor bending behavior is obtained. In this analysis, the bolts are subjected primarily to axial loads. The importance of the bolt material model is not in an analysis of the bolt itself, but rather the influence of the bolt material as a restraint on the adjacent rock mass.

(1) Note that since the bolt material is specified prior to loading, the bolt is, in effect, in place before the cut. The bolt therefore realizes its maximum support potential.

(2) Material 2 outlines an area representing a weaker inner 2 feet of rock adjacent to the opening. Recent Bureau of Mines work has shown that the inner 2 feet of rock is fractured and may be considered a "no tensile strength" material in the Revett formation (3).

(3) Material 3 represents the remainder of the rock mass, considered homogeneous beyond the inner 2 feet.

In all analyses, a ratio of C_0 to T_0 in the rock materials was maintained to give a resultant ϕ angle of 52° (1).

F/E Bolt Models

Material properties were varied to represent two different strength bolt materials that restrain rock movement. The relationships of elastic and strength properties in the F/E model to the corresponding field condition is based on the existing field bolt pattern (see introduction). A 1-inch-thick finite-element model corresponds to a thickness of 3 feet in the field, so two 3/4-inch bolts in the field are represented by two 3- by 1-inch bolts in the model. The subsequent computations consider 13 feet, or half of the long axis of the shaft (fig. 4),

where E = modulus of elasticity, pounds per square inch,
 P = total axial load, pounds,
 A = cross section area, bolts, square inches,

e = unit deformation, inches per inch,

T_0 = tensile strength, bolts, pounds per square inch,

and $T_0 = C_0$; in a ductile material, ϕ approaches 0° .

The condition for comparable elastic restraint, or resistance to deformation, is fulfilled by e being numerically equal in the field and F/E model. Primed symbols represent the model bolt properties.

$$T_0' = \frac{30}{(0.147)} (4,800) = 11.76 \times 10^6 \text{ psi}$$

These properties cannot be obtained in a real material.

Where $E = \frac{P}{Ae}$, the ratio between model and field bolt modulus with strain (e) equal is--

$$\frac{E'}{E} = \frac{\frac{P'}{A'e}}{\frac{P}{Ae}} = \frac{P'A}{PA'} \quad (1)$$

Therefore,

$$E' = \frac{P'A}{PA'} E \quad (2)$$

Using the same reasoning, the model bolt tensile strength would be

$$T_o' = \frac{P'A}{PA'} T_o \quad (3)$$

Because a 1-inch "slice" in the F/E model corresponds to a 36-inch "slice" in the field, the bolt load ratio is

$$\frac{P}{P'} = 36 \quad ,$$

and because two 3- by 1-inch bolts in the F/E model (6 in^2) represent two 3/4-inch field bolts (0.88 in^2), the bolt area ratio is

$$\frac{A}{A'} = 0.147 \quad .$$

Hypothetically Strong Bolts

Initially, modeling a perfectly stiff nonyielding bolt was attempted, however, the F/E program is limited in its ability to handle extreme property variations in adjoining materials. The largest model bolt properties the program could consider (run F) were as follows: $E = 2.0 \times 10^6$ psi and $T_o' = 4,800$ psi. Corresponding field properties would be as follows:

From equation 2 $E = \frac{PA'}{P'A} E' \quad ,$

$$E = \frac{36}{0.147} (2.0 \times 10^6) = 49 \times 10^7 \text{ psi},$$

and from equation 3 $T_o = \frac{PA'}{P'A} T_o' \quad ,$

$$T_o = \frac{36}{(0.147)} (4,800) = 11.76 \times 10^5 \text{ psi}.$$

These properties cannot be obtained in a real material.

Normal Bolting

Of the runs made, run I most nearly simulates the support, or rock mass restraint, obtainable in normal field bolting. F/E representation of bolts still has approximately twice the restraining capacity of the actual Lucky Friday bolt pattern; however, this could be accomplished in the field if desired (double number of bolts). The analyses are not sufficiently discriminating to be of value in analyzing differences in support strength within this range at this level. This will be apparent in the subsequent discussion and illustrations. The model bolt properties were as follows: $E' = 2.44 \times 10^5$ psi, $T_o' = 370$ psi. Corresponding field bolt properties would be as follows:

$$\text{From equation 2, } E = \frac{PA'}{P'A} E' ,$$

$$E = \frac{36}{0.147} (2.44 \times 10^5) = 60 \times 10^6 .$$

$$\text{From equation 3, } T_o = \frac{PA'}{P'A} T_o' ,$$

$$T_o = \frac{36}{0.147} (370) = 90.6 \times 10^3 .$$

Analysis and Results

Five runs were made with various property inputs outlined in table 2. The table also shows the F/E deformations across each axis of the opening and corresponding field bolt properties in the two runs considering a bolt support.

TABLE 2. - Finite-element material properties and displacements
with corresponding field bolt properties

Run	Condi- tion	Materials	E, psi	C _o , psi	Deformation at 4 feet, inches		Corresponding field bolt	
					Short axis	Long axis	E, psi	C _o , psi
B	1	1, 2, 3	1.00×10^6	2,000.00	2.8	0.8	-	-
C	2	1, 2, 3	2.00×10^5	400.00	13.6	3.6	-	-
D-2	3	1, 2	2.00×10^5	.04	15.4	5.0	-	-
		3	2.00×10^5	400.00	-	-	-	-
F	3	1	2.00×10^6	4,800.00	15.2	4.8	24.5×10^7	5.9×10^5
		2	2.00×10^5	.04	-	-	-	-
		3	2.00×10^5	400.00	-	-	-	-
I	3	1	2.44×10^5	370.00	16.1	5.6	60.0×10^6	9.0×10^4
		2	2.00×10^5	.04	-	-	-	-
		3	2.00×10^5	400.00	-	-	-	-

NOTE.--In all materials, $\mu = 0.2$.
 In rock materials, $\phi = 52^\circ$.
 In "bolt" materials, $\phi = 0^\circ$.

Condition 1

Uniform rock mass properties were based on previous laboratory, field, and finite-element work in the Coeur d'Alene mining district. Rock mass property values were considered to be equal to approximately one-tenth the value of the corresponding laboratory specimen properties. This has been shown to be a reasonable assumption in similar work in the district (5). Figure 5A (run B) shows initial yield occurring at 90 pct of full load at the corner and center of the short dimension.

At full load (fig. 5B), the inner 2 feet of rock has yielded, with some yielding occurring up to 4 feet within the rock near the center portion of the long side of the opening.

Displacement at full (5,000 psi) field stress is 2.8 inches along the short axis and 0.8 inch along the long axis, showing that the rock properties assumed were too high to duplicate field conditions.

Condition 2

A homogeneous rock mass was considered (materials 1 through 3 the same), but the values further reduced by a factor of 5. This is a consistent procedure in determining field scale rock properties for comparison with field data (5).

Displacement at full load is 13.6 inches along the short axis and 3.6 inches along the long axis, more closely representing field conditions. Figure 6 (run C) shows that initial yield occurred at 80 pct load at the corner of the opening. At full load, general yield occurred within 2 feet of rock on the ends and 4 feet along the long side of the shaft.

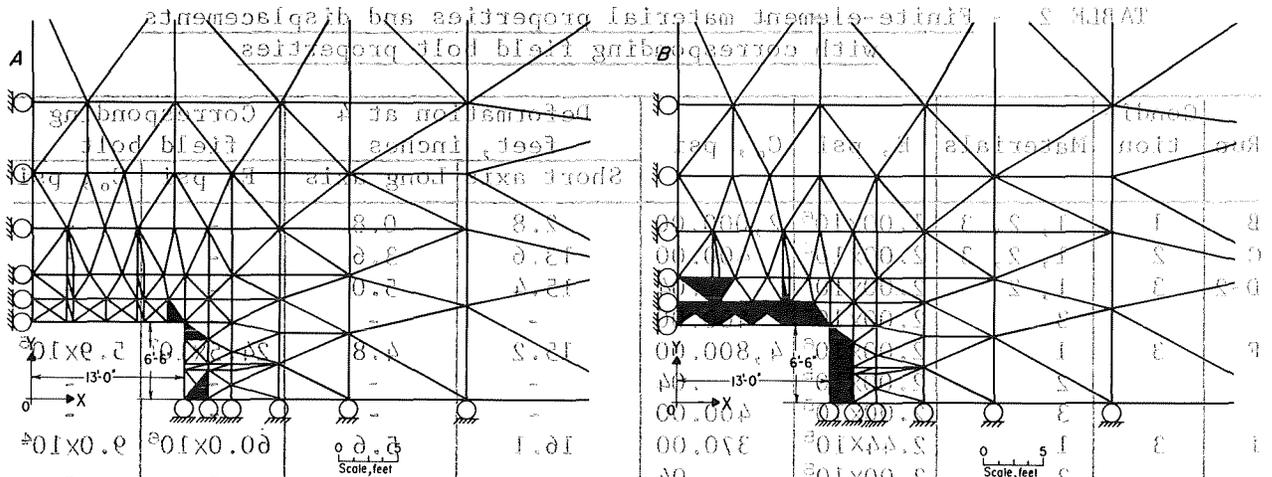


FIGURE 5. - Yield zones, model of strong rock mass condition 1. A, Run B-90-pct load; B, run B-100-pct load.

NOTE. - In all materials, $\mu = 0.2$.
In rock materials, $\phi = 32^\circ$.
In "bolt" materials, $\phi = 0^\circ$.

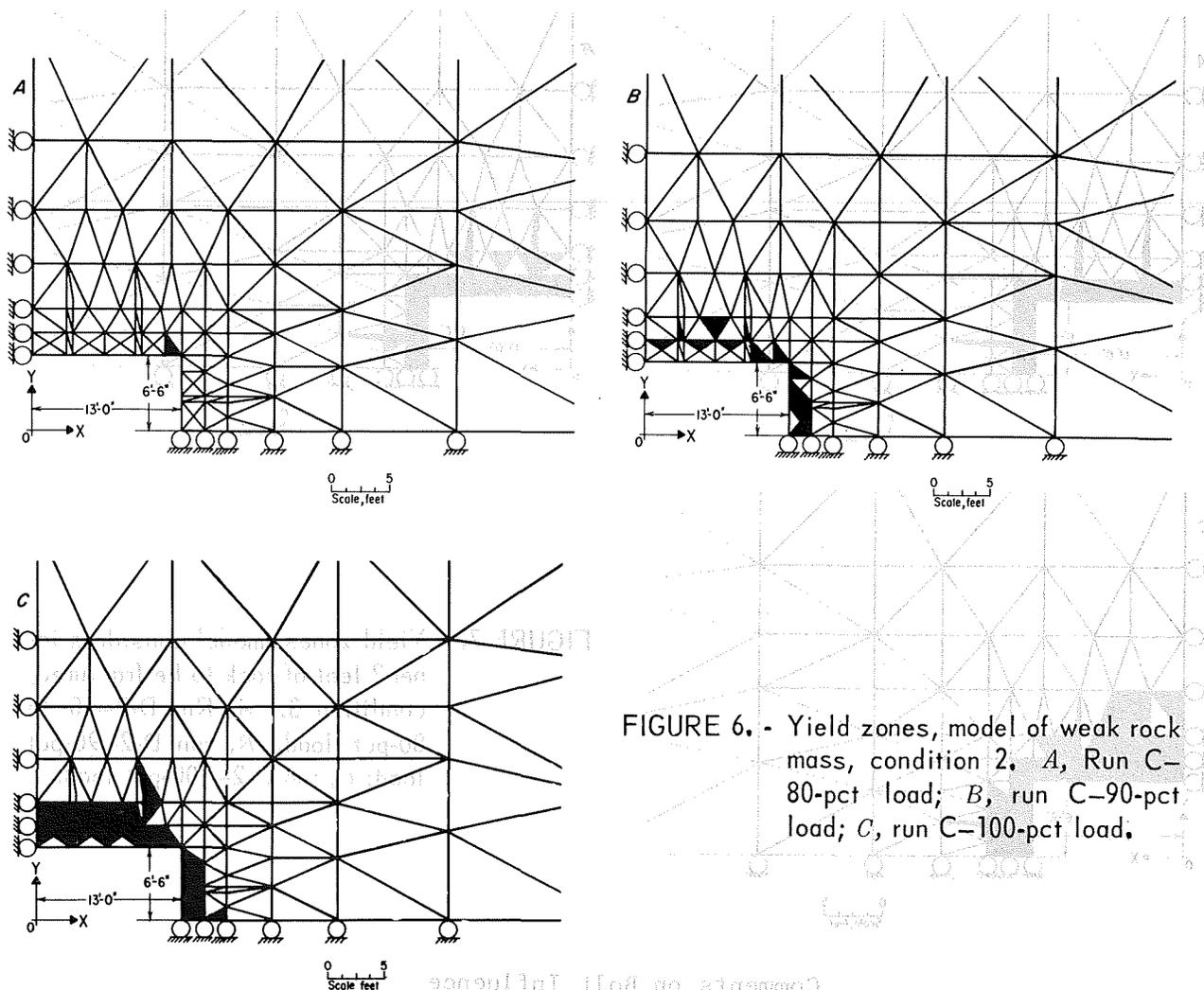


FIGURE 6. - Yield zones, model of weak rock mass, condition 2. A, Run C-80-pct load; B, run C-90-pct load; C, run C-100-pct load.

Condition 3

The true physical situation was more accurately portrayed by describing materials 1 and 2 with essentially no tensile strength. Figure 7 (run D-2) shows the yield zones, and the significant fact when comparing this to condition 2 is that at full load the general yield extends 8 feet into the rock along the long dimension. The "spikes" of yielded material in figure 7 at low load are from describing material 1 the same as material 2.

Deformation along the short axis is 15.4 inches and along the long axis 5 inches at full load, approximating field measurements.

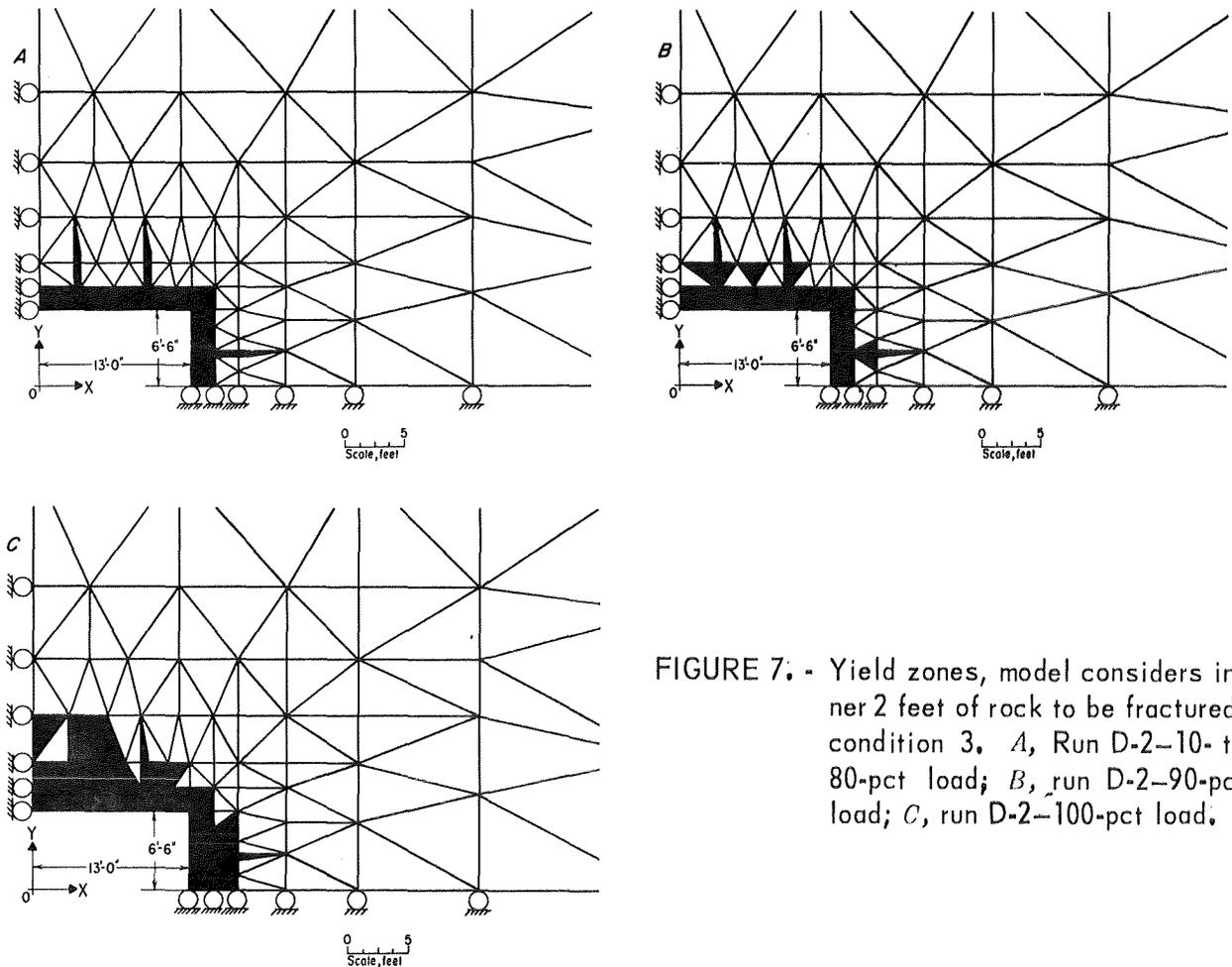


FIGURE 7. - Yield zones, model considers inner 2 feet of rock to be fractured, condition 3. A, Run D-2-10- to 80-pct load; B, run D-2-90-pct load; C, run D-2-100-pct load.

Comments on Bolt Influence

Tables 1 and 2 indicate that the F/E closures for conditions of no bolts (run D-2), hypothetically strong bolts (run F), and existing bolts (run I), approximate the closure measured in the mine shaft.

Figure 8 shows the yield zone for run F, the hypothetically strong bolts. The inner 2 feet yielded at a low load, and the bolt and rock elements near the bolts beyond 2 feet have yielded at full load. The bolts elements yielded at half load even though the elastic restraint is about 8 times greater than the F/E bolt model of the actual field bolts and their yield strength 15 times greater than the field simulation bolts (run I). Shaded bolt elements indicate yield; however, this does not necessarily indicate rupture in a ductile material. The amount of deformation is about the same as for the unbolted run D-2.

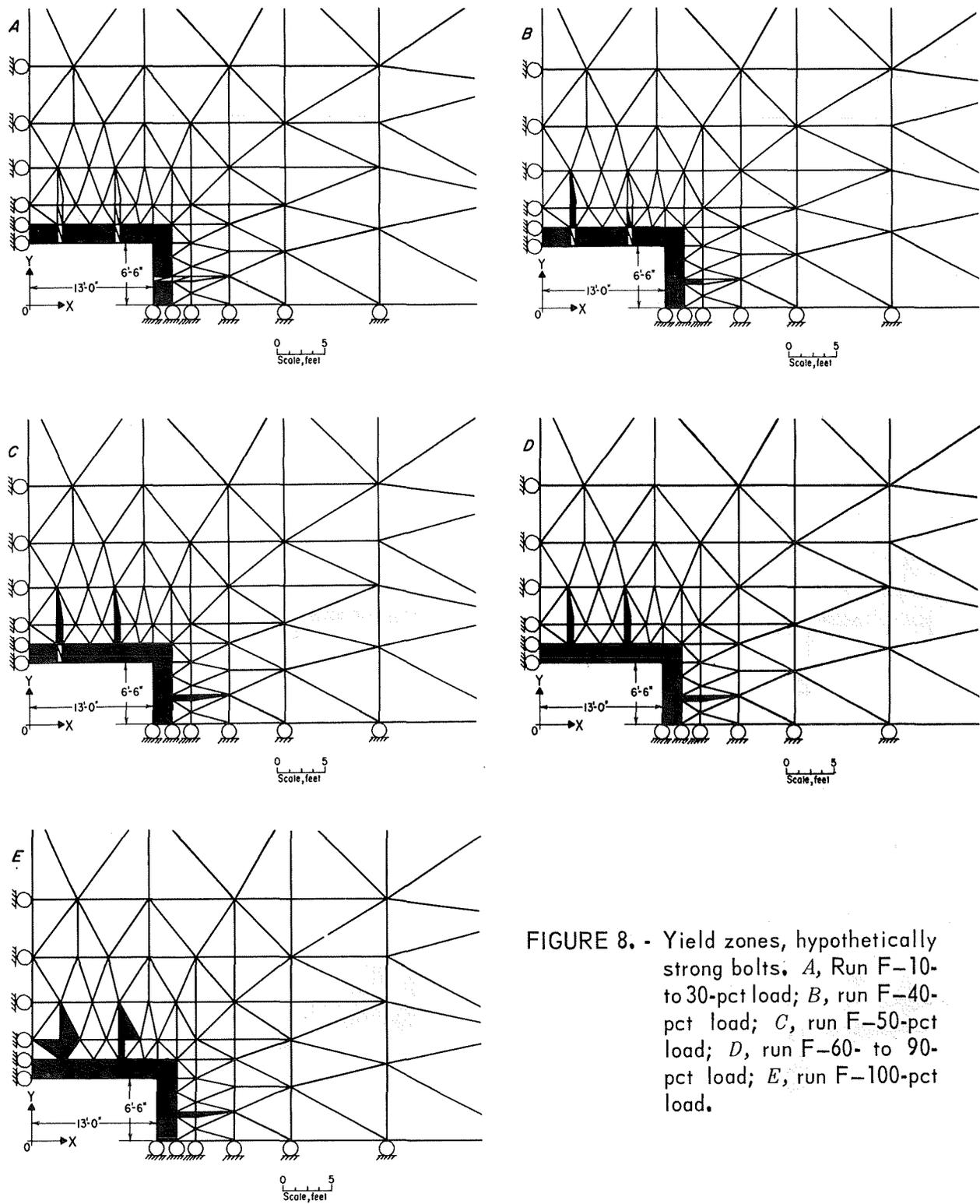


FIGURE 8. - Yield zones, hypothetically strong bolts. *A*, Run F-10- to 30-pct load; *B*, run F-40-pct load; *C*, run F-50-pct load; *D*, run F-60- to 90-pct load; *E*, run F-100-pct load.

In run I (fig. 9), materials are simulating actual bolting materials. At full load, yield extends 8 feet into the walls; rock-element failure is a little more extensive, and the deformations are slightly larger than in the unbolted model (run D-2).

Deformation

The F/E displacements in run I are illustrated in figure 10. The arrows represent vectorial displacement of each nodal point (fig. 4). Relative displacement vectors are multiplied by a factor of about three for clarity. Areas of simulated bolt elements are shaded. Of particular interest is the extent of rock-mass displacement well back in the material, at the base of the bolts and beyond. This is particularly pronounced behind the longest dimension side of the shaft (displacement parallel to the short axis).

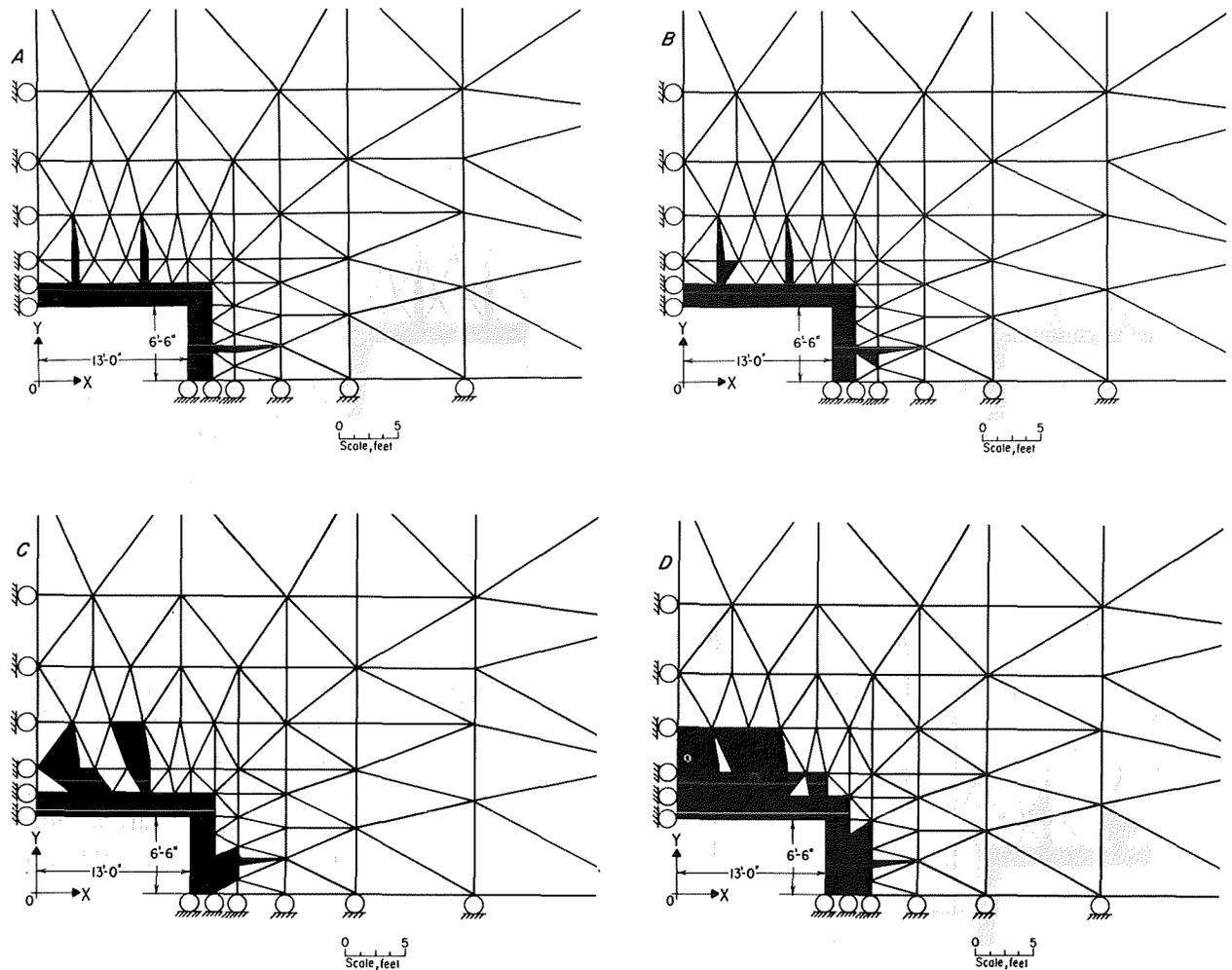


FIGURE 9. - Yield zones, normal bolts. *A*, Run I-10- to 70-pct load; *B*, run I-80-pct load; *C*, run I-90-pct load; *D*, run I-100-pct load.

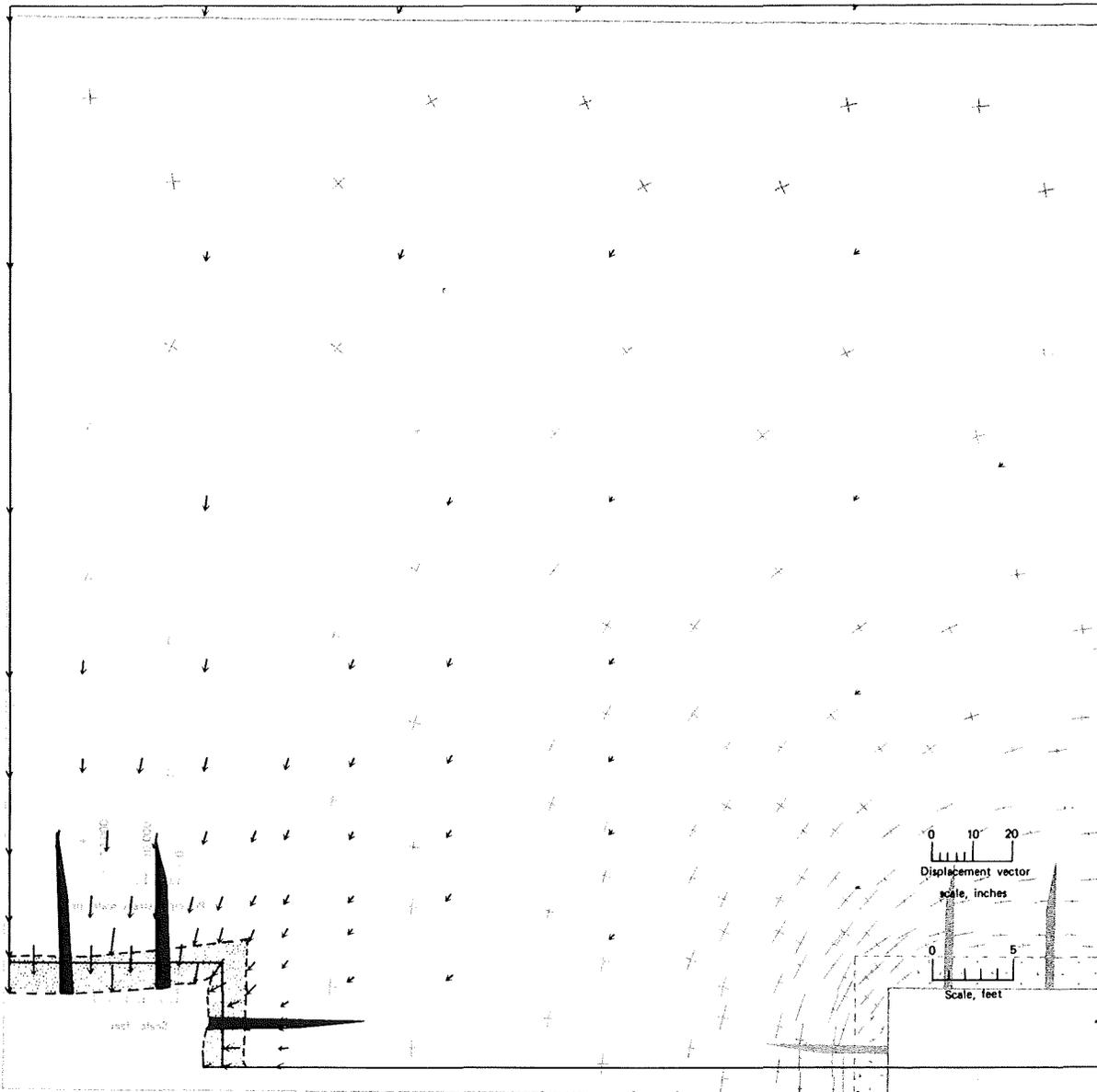


FIGURE 10. - Finite-element displacements, run 1.

FIGURE 11. - Principal stresses, run 1.

Stress Distribution

Comments on Elastic Analysis

Principal stresses of the F/E run 1 are illustrated in figure 11. This is a vector plot of principal stresses at the centroid of each element (fig. 4). All stress in the rock mass (excluding "bolts" and inner 2 feet of weak rock) is compressive. Stress distribution within the inner 2 feet of weak rock is inconclusive, because analytically, the material failed at 1/200 to 1/500 of the total load; however, high compressive stresses may be observed in the corners. The "bolt" material units (material 1), although a valid representation of a restraining "pin" effect on the adjacent rock, do not provide a basis for detailed analysis of the bolts alone.

High stresses in the bolt corners, as well as stresses in the rock mass, are apparent in the elastic analyses.

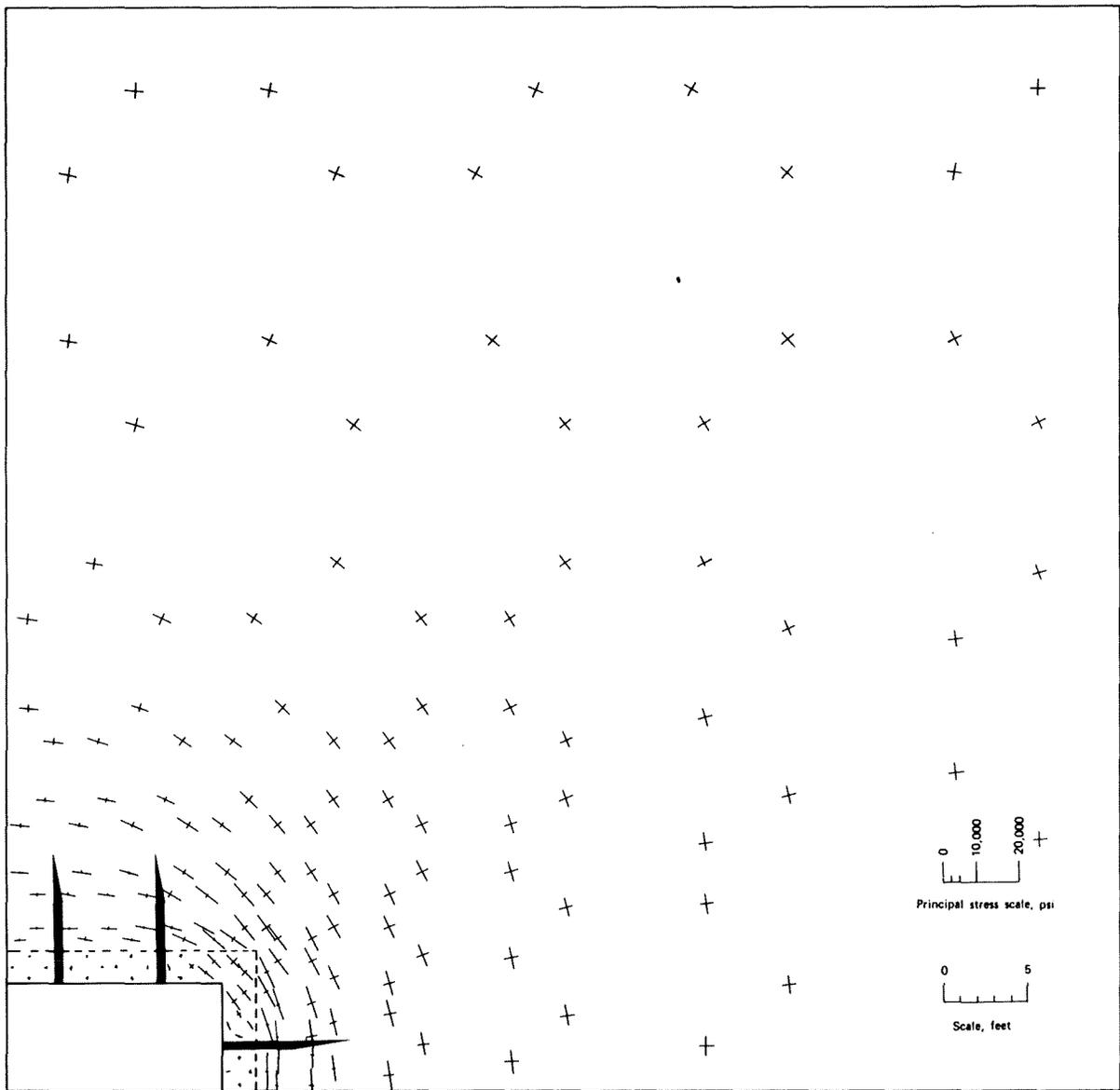


FIGURE 11. - Principal stresses, run 1.

Comments on Elastic Analysis

Elastic/plastic, F/E analyses determined the state of stress and deformation in a yielding material. In each run, however, an elastic-only analysis is developed. An involved discussion of the elastic-only analysis will not be attempted; however, two specific items observed are noteworthy:

1. About 80 pct of the deformation can be accounted for elastically.
2. High stresses in bolt elements, several times their yield strength, are apparent in the elastic analyses.

DISCUSSION

The analysis was not totally conclusive and was limited by the assumptions made. The major limiting assumptions were that the stress field was hydrostatic, material was acting elastic/perfectly plastic, the model is only two-dimensional, and a perfect bond between the grout, bolts, and rock exists. The bolt elements were considered as pins bonded to the rock. The authors' best assumption of a stress field without field measurement is a hydrostatic stress field of 5,000 psi. From experience with Coeur d'Alene rock-stress measurements, there is probably greater horizontal than vertical stress, but the authors feel that the stress field can more easily be estimated than rock properties. They preferred to vary the properties in this analysis. The assumption of plasticity would be reasonable. The rock quality of the shaft is poor and in addition to typical bedding, joint, and fracture planes, the shaft is making 160-gpm warm water and there is a nearby fault. These factors contribute to weakening of the rock mass, causing it to act plastically. Of interest is that in May 1975 the company experienced a rock fall in the shaft that approximated the failure zone shown by the finite-element model. This would tend to confirm that model assumptions were reasonable.

This study points up the following observations:

1. Bolts or timbers do not control the gross rock deformation. However, this does not imply that bolts and timbers do not perform a useful function in the shaft. As the operator knows, the bolts will keep the rock together and prevent spalling. Timbers are necessary for operation of the shaft and do provide some restraint to ground movement but at this depth and ground conditions it is small and therefore was not considered in the analysis. A comparison of closure in runs F, I, and D (table 2) shows that they are essentially the same even though run F considers bolt restraint in an order of magnitude greater than is possible in actual practice. Likewise, considering the rock mass as solid and intact in comparison to considering the outer 2 feet as fractured does not substantially reduce gross deformation (compare runs C and D-2, table 2).

2. The analysis raises many questions about bolting practice. The fieldwork and F/E analyses consider fully grouted bolts and their F/E counterpart. Noting figure 9, specifically the bolt elements, and the fact that all bolt material has yielded at some point below a 10-pct load (fig. 9A), the authors intuitively believe that the F/E analyses would show basically the same information whether it represented a grouted bolt, or a simply anchored prestressed bolt. There are, certainly, important effects attributable to the type of anchorage; however, consideration of these is beyond the scope of this investigation. A comparison of run D-2 (no bolts) to I (normal bolts) shows the failure zone and deformation are essentially the same. The bolts do not appear to contribute to the alleviation of rock yield in the 2- to 8-foot area along the long axis of the opening. This indicates that, to be more effective, the bolts should be anchored beyond the roughly 8-foot zone where major and minor principal stresses are nearly equal (less shearing stress) and ground movement is less (figs. 10-11). Ten- to twelve-foot grouted bolts or cables along the long side and six-foot bolts along the short side of the shaft

should be more effective by providing bolt anchorage outside of the yield zone. Of course, placing long bolts in these ground conditions is more easily said than done.

3. From a comparison of runs C and D in figure 7 (C is intact uniform rock, D-2 models the inner 2 feet as a fractured material), there is an indication that the nature of rock breaking may influence later support requirements.

4. The problem remains of accurately simulating field conditions; that is, in-place rock properties with an idealized mathematical model. However, the authors feel that the F/E mathematical model is a useful tool in mine-opening design if supplemented with good observations and experienced judgment.

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