EXPERIENCE OF FIELD MEASUREMENT AND COMPUTER SIMULATION METHODS FOR PILLAR DESIGN

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ABSTRACT

Coal pillar design has been based on generalized formulas of the strength of the coal in a pillar and experience in localized situations. Stress measurements above and in coal pillars indicate that the actual strength and deformation of pillars vary much more than predicted by formulas. This variation is due to failure of strata surrounding coal. The pillar strength and deformation of the adjacent roadways is a function of failure in the coal and the strata about the coal. When the pillar is viewed as a system in which failure also occurs in the strata rather than the coal only, the wide range of pillar strength characteristics found in the United Kingdom, United States, Republic of South Africa, Australia, People's Republic of China, Japan, and other countries are simply variations due to different strata-coal combinations, not different coal strengths.

This paper presents the measured range of pillar strength characteristics and explains the reasons. Methods to design pillar layouts with regard to the potential strength variations due to the strata strength characteristics surrounding the seam are also presented.

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INTRODUCTION

The strength characteristics of coal pillars have been studied by many, and the subject is well discussed in the literature (Salamon and Munro [1967]; Wilson [1972]; Hustrulid [1976]; Mark and Iannacchione [1992]; Gale [1996]). In general, a range of strength relationships has been derived from four main sources:

(1) Laboratory strength measurements on different-sized coal block specimens;

(2) Empirical relationships from observations of failed and unfailed pillars;

(3) A theoretical fit of statistical data and observations; and

(4) Theoretical extrapolation of the vertical stress buildup from the ribside toward the pillar center to define the load capacity of a pillar.

These relationships provide a relatively wide range of potential strengths for the same pillar geometry. In practice, it has been found that various formulas are favored (or modified) by users, depending on past experience in their application to certain mining districts or countries.

In general, the application of empirically and statistically based formulas has been restricted to the mining method and geological environment for which they were developed, and they often relate to specific pillar geometries. In general, these methods were developed for shallow, extensive bord-and-pillar operations for which the pillar was designed to hold the weight of overburden. The wider application of longwall mining methods and increasing depth has required a greater understanding of factors influencing pillar strength and their role in the control of ground deformation about the mining operations. The development of stress measurement and detailed rock deformation recording tools over the last 10-15 years has allowed much more quantification of actual pillar stresses and deformations. Few data were available when many of the pillar strength relationships were originally defined. Similarly, the development of computer simulation methods has allowed detailed back-analysis of the mechanics of strata-coal interaction in formed-up pillars.

The author and his colleagues have conducted numerous monitoring and stress measurement programs to assess roadway stability and pillar design requirements in Australia, the United Kingdom, Japan, the United States, Indonesia, and Mexico. The results of these investigations and others reported in the literature have demonstrated that the mechanical response of the coal and surrounding strata defines the pillar strength, which can vary widely depending on geology and stress environment. The application of a pillar strength formula to assess the strength of a system that is controlled by the interaction of geology, stress, and associated rock failure is commonly an oversimplification.

MECHANICS OF THE PILLAR-COAL SYSTEM

The strength of a pillar is determined by the magnitude of vertical stress that can be sustained within the strata-coal sequence forming and bounding it. The vertical stress developed through this sequence can be limited by failure of one or more of the units that comprise the pillar system. This failure may occur in the coal, roof, or floor strata forming the system, but usually involves the coal in some manner. The failure modes include shear fracture of intact material, lateral shear along bedding or tectonic structures, and buckling of cleat-bounded ribsides.

In pillar systems with strong roof and floor, the pillar coal is the limiting factor. In coal seams surrounded by weak beds, a complex interaction of strata and coal failure will occur; this will determine the pillar strength. The strength achievable in various elements largely depends on the confining stresses developed, as illustrated in figure 1. This indicates that as confinement is developed in a pillar, the axial strength of the material increases significantly, thereby increasing the actual strength of the pillar well above its unconfined value.

The strength of the coal is enhanced as confining stress increases toward the pillar center. This increased strength is often related to the width-to-height (w/h) ratio; the larger the ratio, the greater the confinement generated within the pillar. Hence, squat pillars (high w/h) have greater strength potential than slender ones (low w/h).

The basic concepts related to confinement within coal pillars were developed by Wilson [1972]; with the growing availability of measurement data, these general mechanics are widely accepted. However, confining stress can be reduced by roadway deformations such as floor heave, bedding plane slip, and other failure mechanisms. These mechanisms are described below.

ROADWAY DEVELOPMENT PHASE

Prior to mining, the rock and coal units will have in situ horizontal and vertical stresses that form a balanced initial stress state in the ground. As an opening (roadway) is created in a coal seam, there is a natural tendency for the coal and rock to move laterally and vertically into the roadway. In this situation, the horizontal stress acting across the pillar will form the confining stress within that pillar. If this lateral displacement is resisted by sufficient friction, cohesion, and shear stiffness of the immediate roof and floor layers, then most of the lateral confining stress is maintained within the pillar. Consequently, the depth of "failure" (yield) into the pillar ribside is small. If the coal and rock layers are free to move into the roadways by slippage along bedding planes or shear deformation of soft bands, this confining stress will be reduced.

Hence, the depth of failure into the pillar ribside may be significantly greater.

The geometry of failure in the system and the residual strength properties of the failure planes will therefore determine the nature of confining stress adjacent to the ribsides and extending across the pillars. This mechanism determines the depth of failure into the pillar and the extent of ribside displacement during roadway drivage.

PILLAR LOADING BY ABUTMENT STRESSES

Roadways are subjected to an additional phase of loading during longwall panel extraction, as front and then side abutment pressures are added to the previous (and generally much smaller) stress changes induced by roadway excavation. These abutment stresses typically considered are predominantly vertical in orientation, but can generate additional horizontal (confining) stresses (by the Poisson's ratio effect) if there is sufficient lateral restraint from the surrounding roof and floor. Conversely, if the ground is free to move into the roadway, this increased horizontal stress is not well developed and increased rib squeeze is manifest instead.

This concept is presented in figure 2; with strong cohesive coal-rock interfaces the confining stress in the pillar increases rapidly inward from the ribsides, allowing high vertical stresses to be sustained by the pillar. The opposite case of low shear strength coal-rock contact surfaces is presented in figure 3. In this situation, confinement cannot be maintained sufficiently; hence, the allowable vertical stress would be significantly less than that in figure 2. The diagram shows that the pillar has failed because of its inability to sustain the imposed vertical abutment stresses. In addition, lateral movement has caused floor heave and severe immediate roof shearing.

The implications of this for the strength of an isolated pillar are presented in figure 4, where the load carried by the pillar is the mean of the vertical stress across it. If this mean stress is equal to the average "applied load" to be carried by the pillar, then the pillar is stable (figure 4*A*). If the applied load is greater, then the pillar is said to fail (figure 4*B*) and the deficit stress must be redistributed onto nearby pillars.

Conceptually, pillar strength behavior should fall between the two end members of:

(1) Lateral slip occurring totally unresisted, so that pillar strength is limited to the unconfined value of the coal; and

(2) Lateral slip being resisted by system cohesion and stiffness, such that pillar strength is significantly above its unconfined value due to confinement.

A range of potential pillar strengths associated with these two end members relative to the w/h ratio is presented after Gale [1996] in figure 5. It is assumed that the rock mass strength of the coal is 6.5 MPa and that the coal is significantly involved in the failure process. This range of pillar strengths is representative of most rock failure combinations, except in rare cases where small stiff pillars may punch into soft clay-rich strata at loading levels below the field uniaxial compressive strength of the coal. In the punching situations, pillar strength may be lower than that depicted, but the variation would generally be confined to pillars having small w/h ratios.

A comparison of these "end member" situations with a range of pillar strengths determined from actual measurement programs conducted in Australia and the United Kingdom by Strata Control Technology and from the United States [Mark

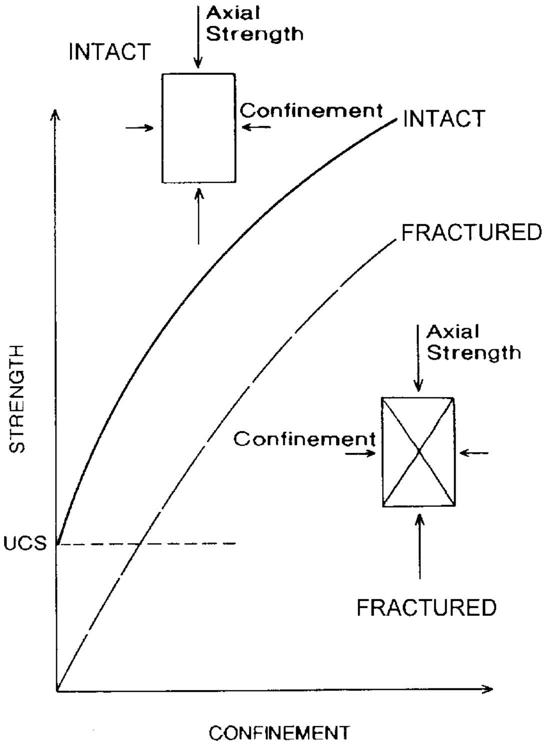

Figure 1.—Effect of confining stress on compressive strengths of intact and fractured rocks.

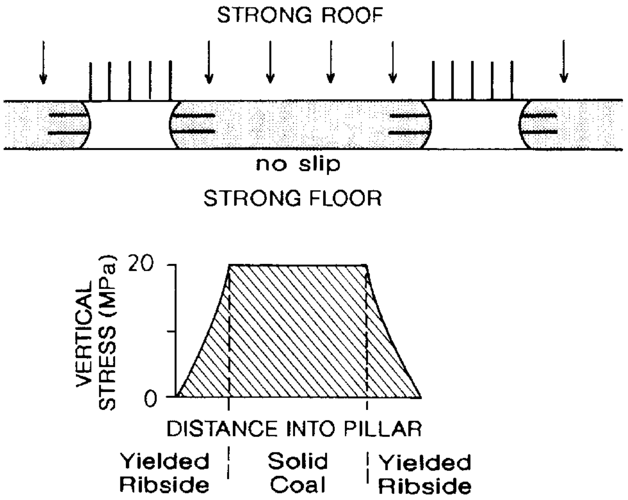

Figure 2.—Rapid buildup of vertical stress into the pillar where high confining stresses are maintained.

et al. 1988] is presented in figure 6. The comparison indicates that a wide range of pillar strengths have been measured for the same geometry (in terms of w/h) and that the data appear to span the full interval between the end members. However, two groupings can be discerned and are shaded in figure 7:

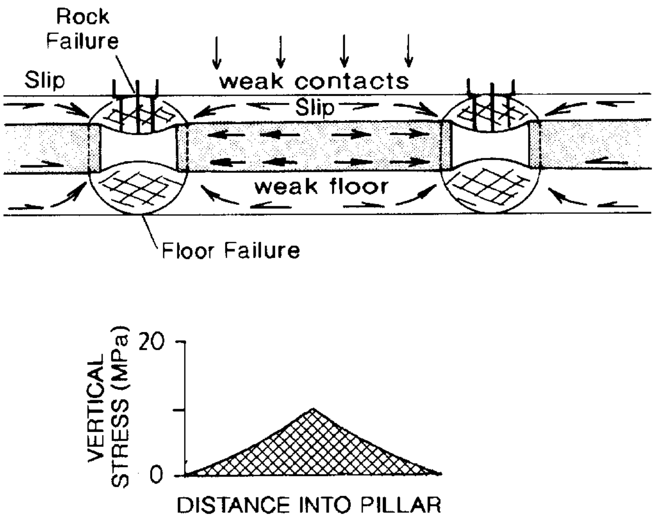

Figure 3.—Slow buildup of vertical stress in the pillar where slip occurs and confinement is reduced.

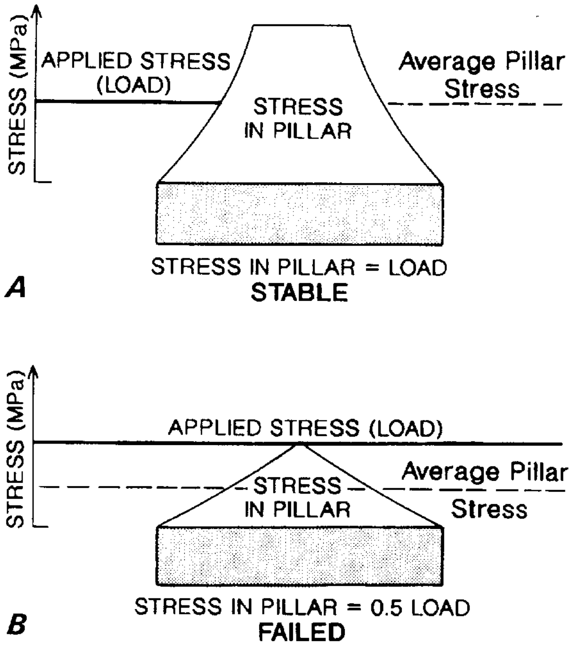

Figure 4.—Pillar strength cases for strong and weak geologies. *A*, strong system; *B*, weak system.

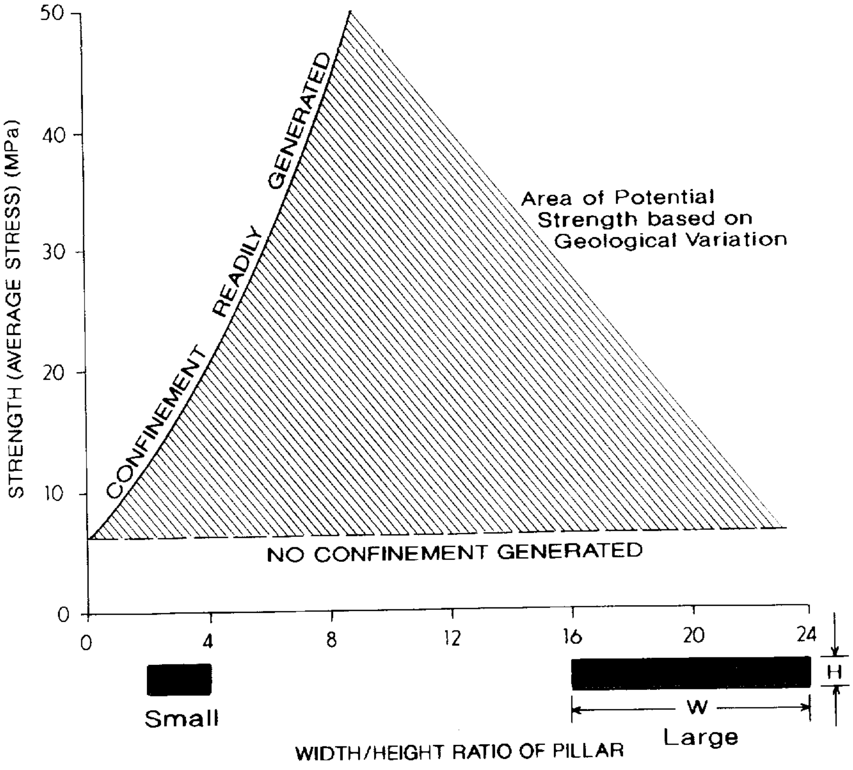

Figure 5.—Range of potential pillar strengths relative to w/h based on confinement variation (after Gale [1996]).

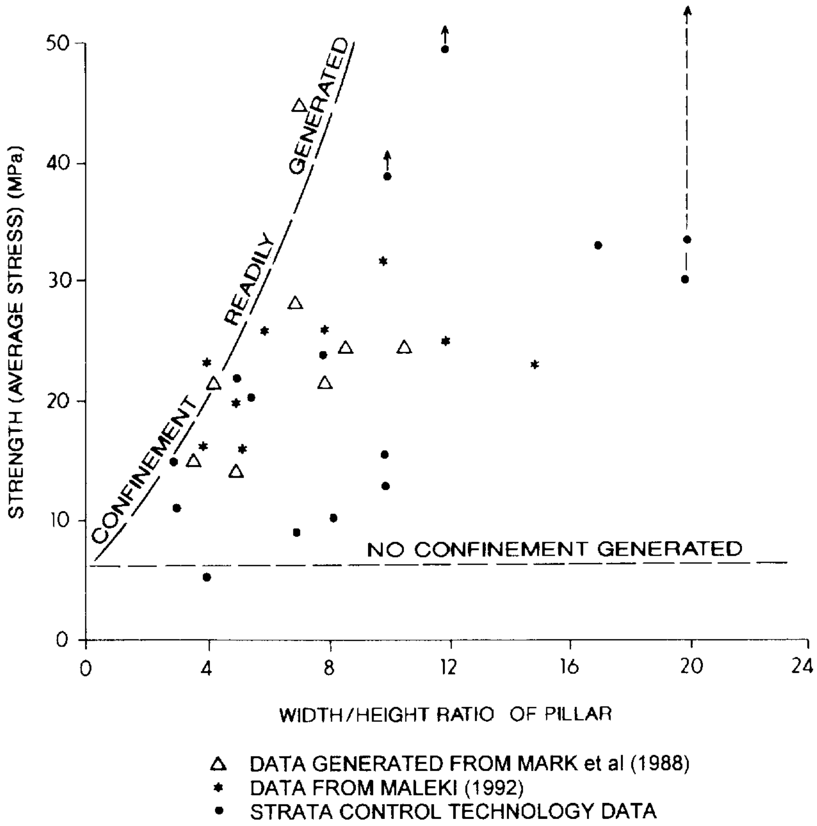

Figure 6.—Pillar strength information relative to changes (after Gale [1996]).

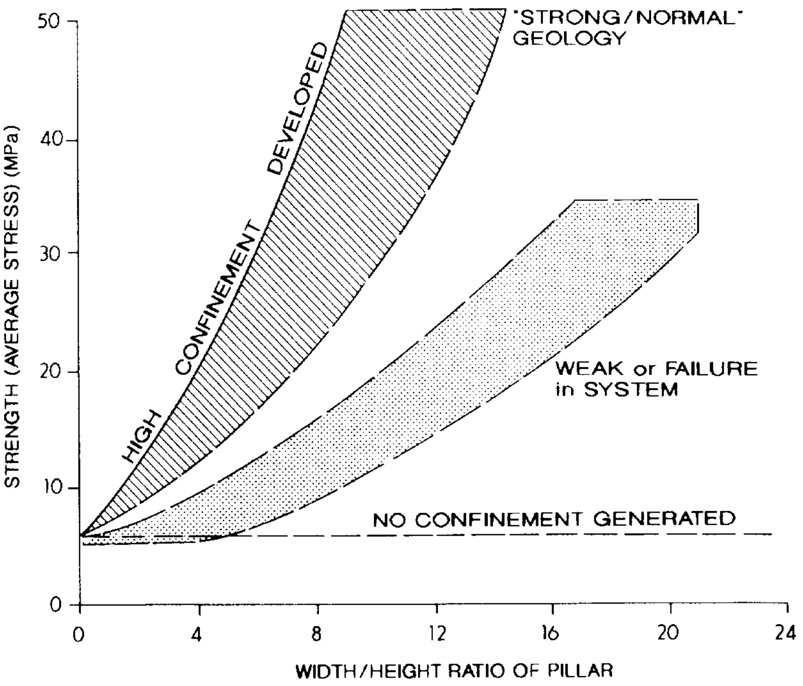

Figure 7.—Generalized groupings of strong/normal and weak geology (after Gale [1996]).

(1) The "strong/normal" geologies, where pillar strength appears to be close to the upper bound.

(2) The structured or weak geologies, where the strength is closer to the lower bound and it is apparent that the strength of the system is significantly limited.

It should be noted that these two groupings are arbitrary and are possibly due to limited data. With more data points, the grouping may become less obvious.

EFFECT OF GEOLOGY

It is clear that a wide range of pillar strengths is possible and that these are not only related to coal strength and w/h ratio. Geological factors have a major impact on the strength achievable under the various pillar geometries.

EFFECT OF GEOLOGY ON PILLAR STRENGTH

The effect of various strata types in the roof-coal-floor pillar systems has been investigated further by computational methods. Computer models of four pillar systems were loaded to determine their strength characteristics (figure 8). These are—

- Massive sandstone-coal-massive sandstone
- Laminite-coal-sandstone
- Weak siltstone-coal-weak siltstone
- Laminite-clayband-coal-clayband-laminite

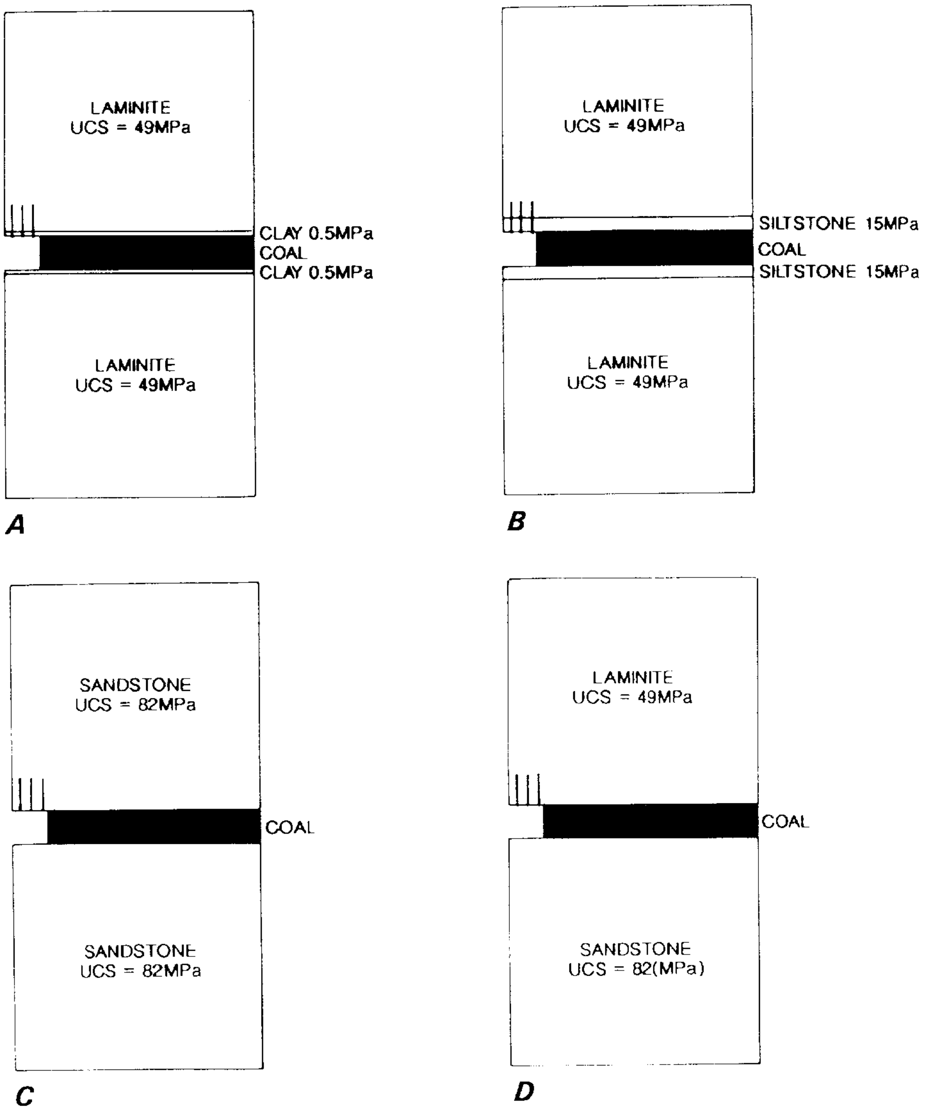

Figure 8.—Geological sections modeled to assess load deformation characteristics. *A*, coal-clay-laminite; *B*, coal-siltstone-laminite; *C*, coal-sandstone; *D*, coal-laminite-sandstone.

The results of the pillar strength characteristics relative to w/h are presented in figure 9. The results closely relate to the field measurement data and confirm that the strata types surrounding the coal have a major impact on strength and also provide insight into the geological factors affecting strength. The results indicate that—

(1) Strong immediate roof and floor layers and good coal-to-rock contacts provide a general relationship similar to the upper bound pillar strength in figure 5.

(2) Weak, clay-rich, and sheared contacts adjacent to the mining section reduce pillar strength to the lower bound areas.

(3) Soft strata in the immediate roof and floor, which fail under the mining-induced stresses, will weaken pillars to the lower bound areas.

(4) Tectonic deformation of coal in disturbed geological environments will reduce pillar strength, although the extent depends on geometry and strength of the discontinuities.

Obviously, combinations of these various factors will have a compounding effect. For example, structurally disturbed, weak, and wet roof strata may greatly reduce pillar confinement and, consequently, pillar-bearing capacity.

EFFECT OF GEOLOGY ON POSTPEAK PILLAR STRENGTH

The postpeak pillar strength characteristics for some of the pillars modeled are presented in figure 10. The pillar strength is presented as a stress/strain plot for various width/height pillars. The results presented in figure 10*A* show that in strong sandstone geology, high strengths are achievable in small pillars (w/h ' 5) and the pillar maintains a high load-carrying capability. In the example modeled, "short-term" load losses were noted to occur in association with sudden rib failure. These instances are present in figure 10*A* as "rib bumps." In sections of laminite roof, these pillars may lose strength if the laminite fails at a very high load above the pillar. For pillars with a w/h less than 4/5, a loss in strength is expected at a high load due to failure of the coal.

In pillar systems with weak strata surrounding the coal, the pillars typically exhibit a strength loss after peak load is achieved. Large width/height pillars are required to develop a high load-carrying capacity after failure in the weak pillar systems modeled. Two examples are presented in figure 10*B*, which shows the postpeak strength characteristics of pillars with weak mudstone or clay surrounding the coal. In these

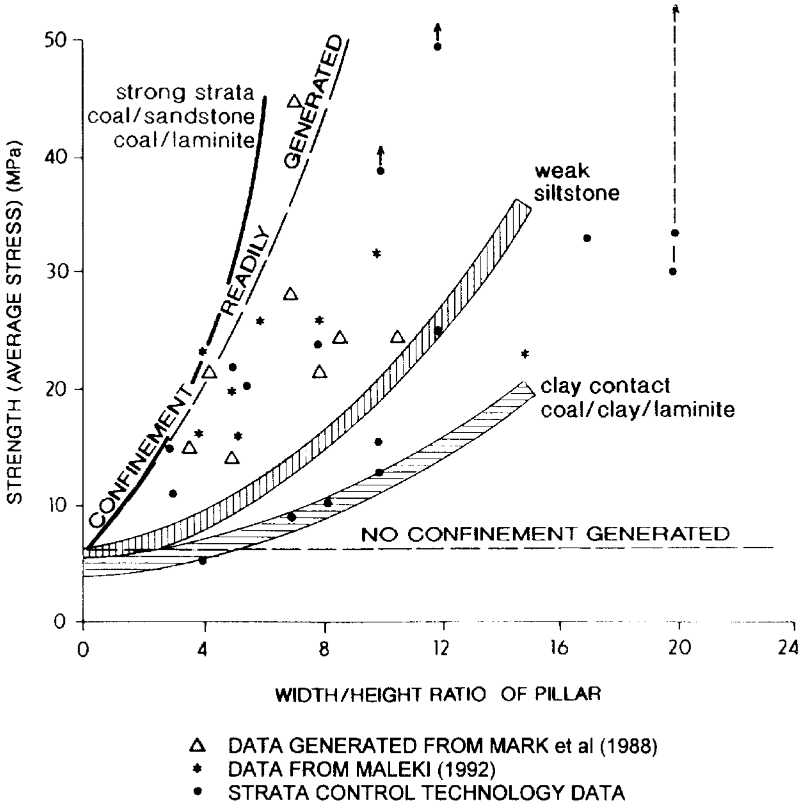

Figure 9.—Strength and w/h for models.

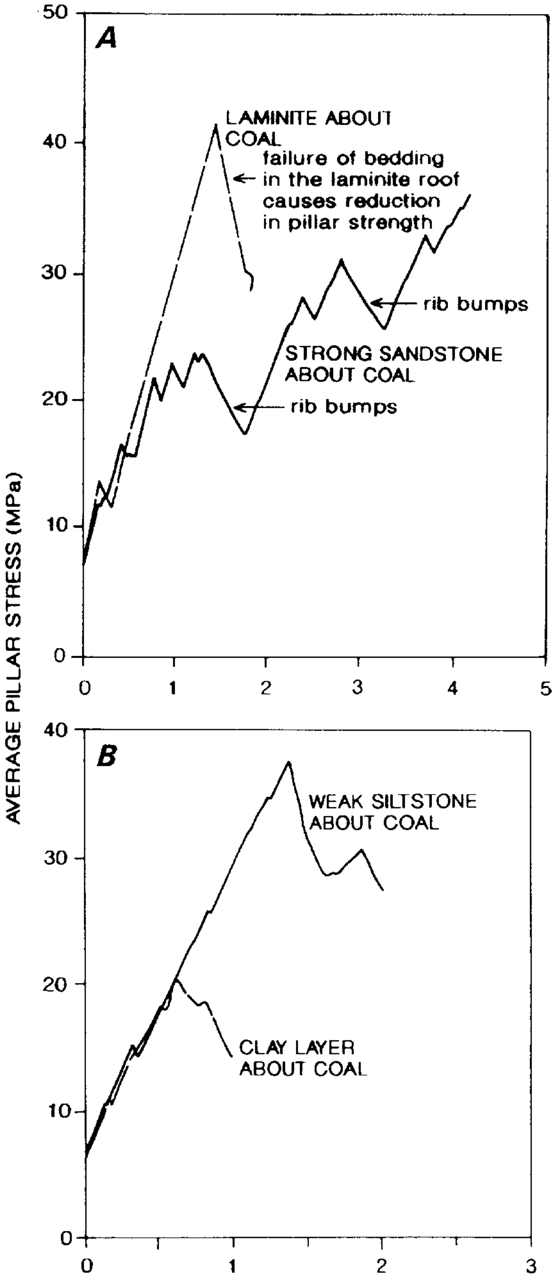

Figure 10.—Postpeak strength of models. ***A*****, w/h ' 5;** ***B*****, w/h ' 15.**

examples, the strength loss is greater in the situation of weak clay surrounding the coal.

The implications of this are significant for the design of barrier and chain pillars where high loads are anticipated. If excessive loads are placed on development pillars in this environment, pillar creep phenomena are possible due to the load shedding of failed pillars sequentially overloading adjacent pillars. The effect of load shedding in chain pillars when isolated in the goaf is to redistribute load onto the tailgate area and to potentially display increased subsidence over the pillar area. The typical result is to have major tailgate deformation, requiring significant secondary support to maintain access and ventilation.

AN APPROACH TO PILLAR DESIGN

Field studies suggest that a range of strengths is possible extending within upper and lower bounds. If we make use of these relationships as "first-pass estimates" to be reviewed by more detailed analysis later, then a number of options are available. In known or suspected weak geologies, the initial design may utilize the lower bound curve of the weak geology band in figure 7. In good or normal geologies, the Bieniawski or squat pillar formulas may be suitable for initial estimates. Two obvious problems with this approach are:

(1) Estimates of pillar size can vary greatly, depending on the geological environment assumed; and

(2) The pillar size versus strength data set used (figure 6) is limited.

This is why such formulas or relationships are considered as first-pass estimates only, to be significantly improved later by more rigorous site-specific design studies utilizing field measurements and computer simulation.

Design based on measurement requires that the vertical stress distribution within pillars be determined and the potential strength for various sized pillars be calculated. It is most useful to measure the vertical stress rise into the pillar under a high loading condition or for the expected "working loads." The stress measurement profiles are used to determine the potential load distributions in pillars of varying dimension and hence to develop a pillar strength relationship suitable for that geological site. An example of stress measurements over a pillar is presented in figure 11; however, the method is limited to determining the potential stress distribution in different pillar widths under the measured loading condition.

Extrapolation of increased loading is more problematic. In weak ground, an approach is to extrapolate the vertical stress buildup from the rib toward the pillar center. This may be possible where the vertical stress buildup approximates a line in the yield zone. This often provides a low estimate of the peak pillar strength and should be considered a working estimate only. An example of this is presented in figure 11*B*. Experience suggests that this is more likely in weak ground; however, in stronger ground the stress buildup is often more exponential and, as such, difficult to extrapolate.

To assess the potential strength under higher loading conditions, a method to redistribute the stress within the pillar associated with an increased average load, or the ability to monitor the effect of additional loading, is required.

Monitoring of stress distributions within pillars during mining can provide elevated loading conditions for analysis. An example is presented in figure 12, whereby small pillars were

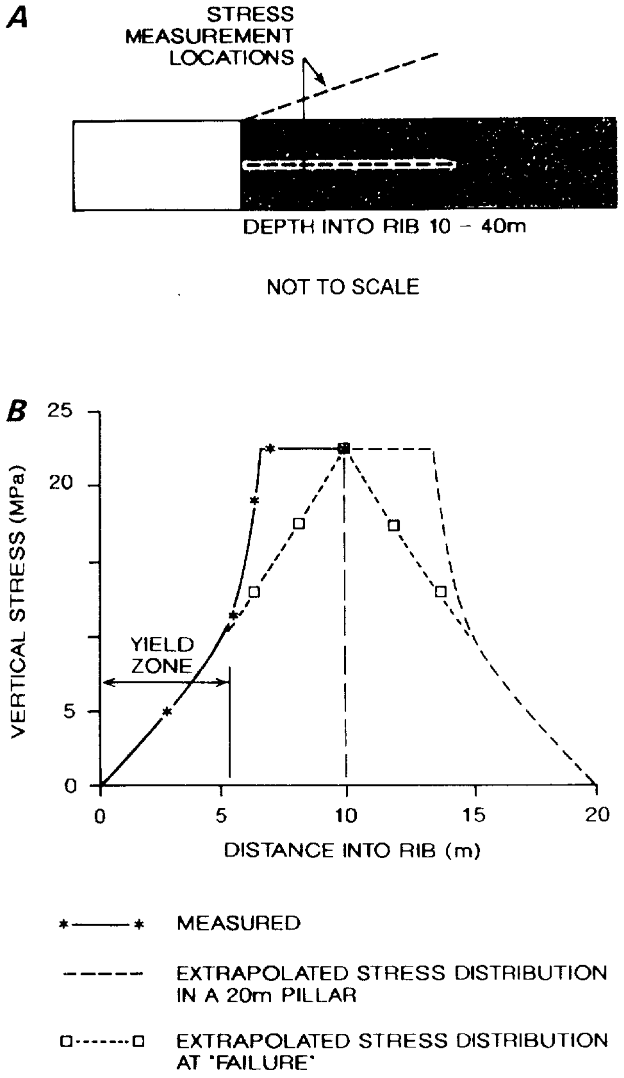

Figure 11.—Stress measurements over ribsides for strength assessment. ***A*****, typical stress measurement locations;** ***B*****, stress distribution in pillar from measurements.**

instrumented with CSIRO HI Cells and monitored until well isolated in the goaf after the passage of a longwall panel.

Computer modeling methods have been developed to simulate the behavior of the strata sections under various stress fields and mining geometries. For mine design, such simulations must be validated against actual ground behavior and stress measurements. This provides confidence that sufficient geological investigation has been undertaken and that the strength properties and deformation mechanisms are being simulated accurately. The computer software developed by Strata Control Technology has been verified in a number of field investigations where computer predictions of stress distributions and rock failure zones have been compared. An example is presented in figure 13, which compares the measured and modeled stress distribution over a yield pillar and solid coal in a deep mine. Another example of computer

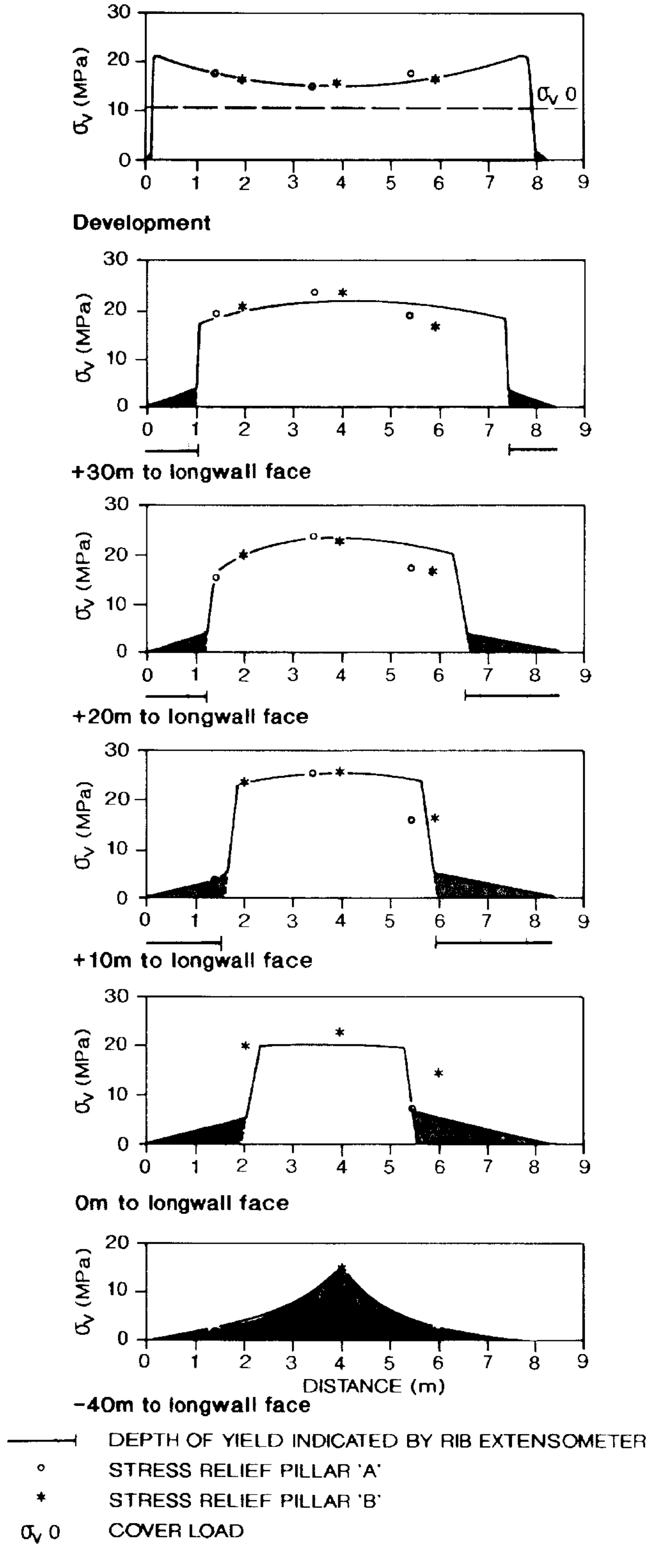

Figure 12.—Example of small pillar monitoring studies indicating pillar stress history.

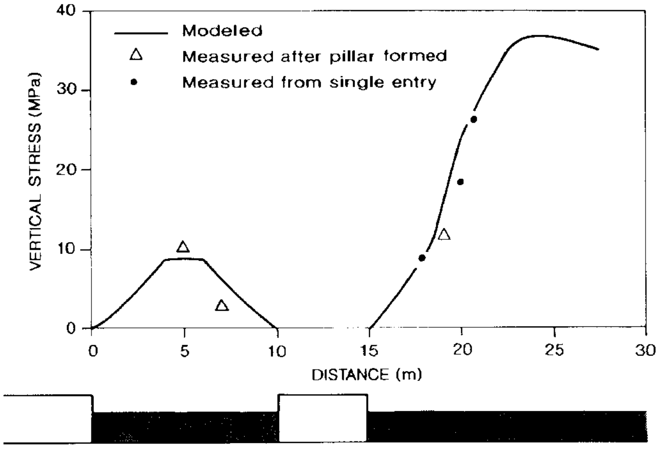

Figure 13.—Stress over yield pillar and adjacent to longwall.

modeling capabilities is presented in figure 14 for weak ground adjacent to a longwall panel. A series of stress measurements was conducted to define the abutment geometry and compared to computer simulations based on the geological section and goaf geometry. The results indicate a very close correlation and that rigorous computer simulation methods can provide a good estimation of the actual stresses and ground failure zones.

One major benefit of computer modeling is that the behavior of roadways adjacent to the pillars can be simulated. In this way, the design of a pillar will reflect not only the stress distribution within it, but also its impact on roadway stability. An example is presented in figure 15 in which the anticipated deformation of a roadway adjacent to a longwall panel under elevated abutment loading was evaluated. The effect of various reinforcement, support, and mining sections was simulated to determine the appropriate mining approach.

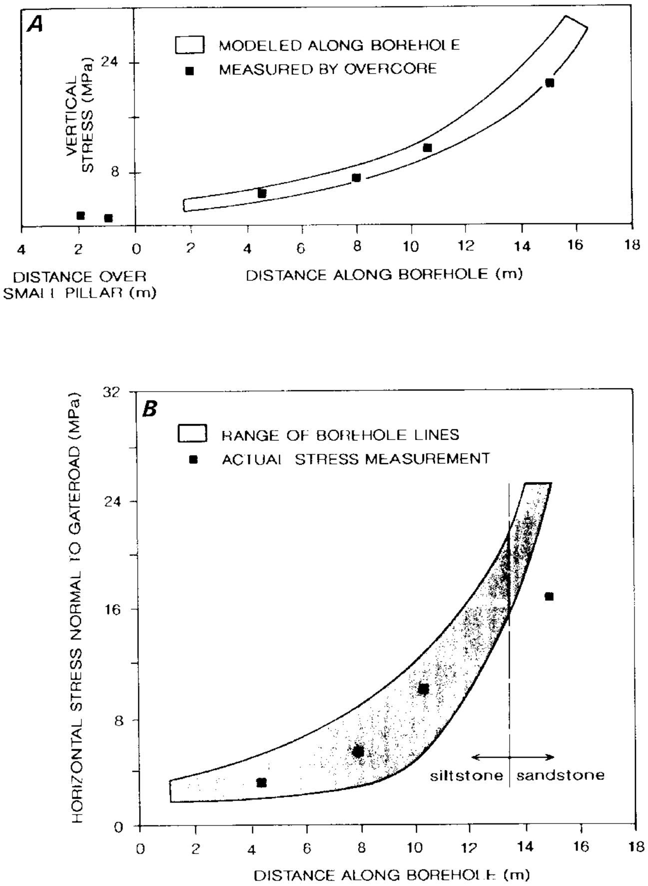

Figure 14.—Comparison of modeled and measured (*A*) vertical and (*B*) horizontal stress over a longwall side abutment. Stress measurements were made in a borehole drilled from an adjacent roadway.

In mining situations where there are large areas of solid ground about the working area, the potential for regional collapse of pillars is typically low. Design in these areas usually relates to optimizing roadway conditions and controlling ground movements rather than the nominal pillar strength. Yield pillars and chain pillars are obvious examples of this application. Design must assess the geometry of other pillars and virgin coal areas in determining the impact of a particular stress distribution within a pillar and the ability of the overburden to span over a yielded pillar and safely redistribute the excess stress to adjacent ground. Figure 13 shows an example of this process for a failed ("yield") pillar adjacent to solid ground.

CHAIN PILLAR DESIGN ISSUES

It has become increasingly apparent from field monitoring and computer simulations of longwall caving that the design of chain pillars requires a larger scale review of ground behavior rather than "small-scale" pillar strength criteria. Microseismic monitoring [Kelly et al. 1998] has demonstrated significant rock fracture above and below chain pillars. Computer modeling of caving [Gale 1998] has also demonstrated rock fracture above and below pillars. Rock failure above and below chain pillars occurs as a result of gross scale stress changes and fluid pressure redistributions.

The strength and loading conditions of chain pillars can reflect the larger scale fracture geometries that may develop. An example of an abutment stress within a pillar at shallow depth (250 m) is presented in figure 16. In this case, rock failure extends over the ribside and shifts the abutment distribution within the pillar.

Modification of the vertical abutment stress distribution has been noted in field monitoring and computer simulations under conditions of high lateral stress. It has been found that the abutment distribution tends to have a lower peak stress, but it spreads over a longer lateral extent. An example is presented in figure 17.

In both of these examples, computer modeling of the caving process within the geological section closely correlates with the measured data. The use of generalized empirical methods to determine the abutment profile is also presented and indicates that their application is best utilized as initial estimates to be reassessed by site-specific investigations for key design areas.

Rock failure above and below chain pillars does not necessarily occur at all sites; however, experience suggests that this is common. The gross scale rock failure about longwall panels, therefore, requires design for ground control issues rather than pillar design, as traditionally conceived. Field measurement, computer modeling, and microseismic investigations play a key role in defining the design criteria. Empirical databases are also useful; however, the user should be aware of the ground deformation mechanics in order to assess the applicability of the data being used relative to the site conditions to which it would be applied.

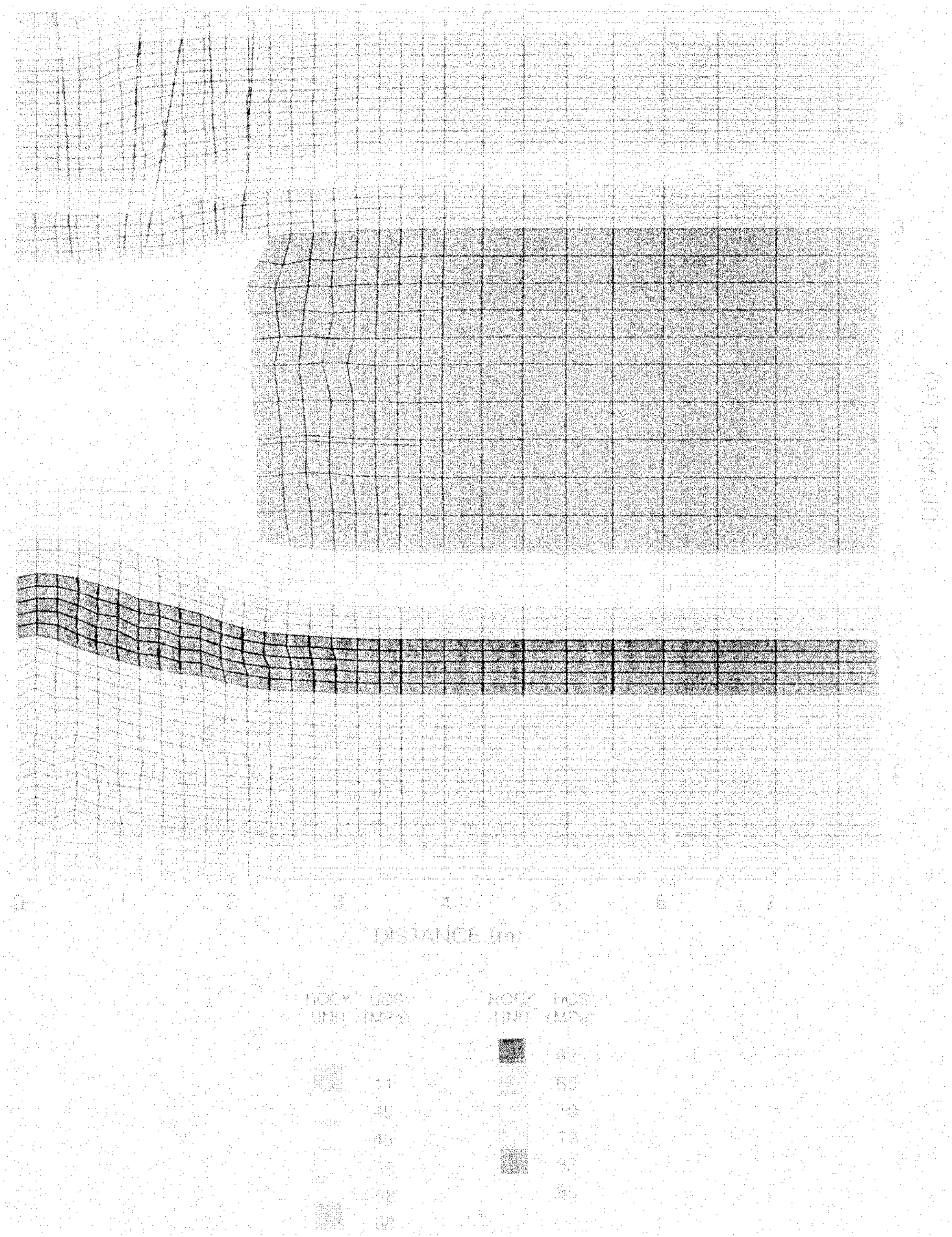

Figure 15.—Simulation of roadway conditions under abutment stress.

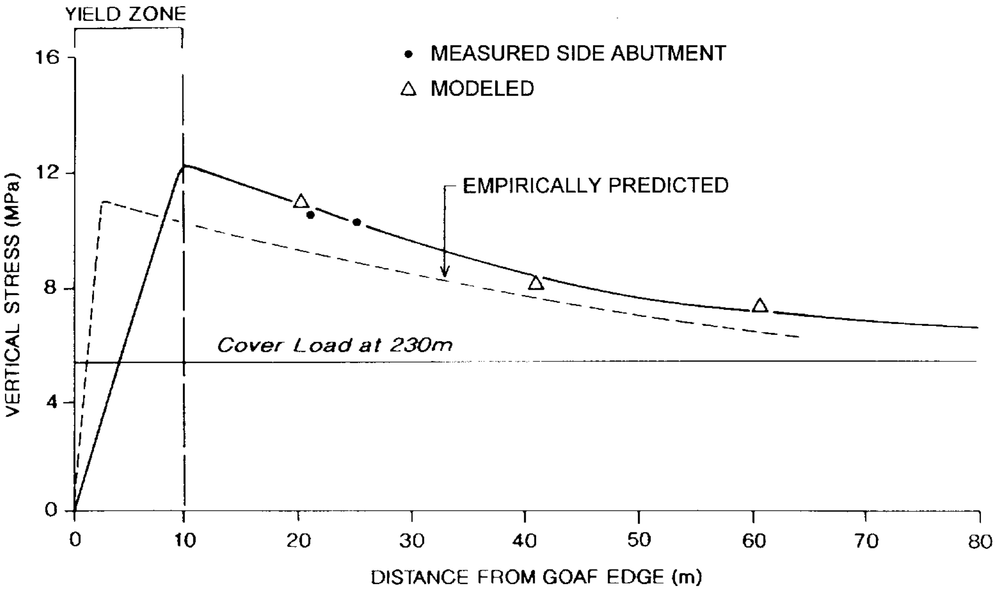

Figure 16.—Longwall side abutment profiles for modeled, measured, and empirical approaches. In this example, rock failure occurred about the pillar, forming a more extensive yield zone.

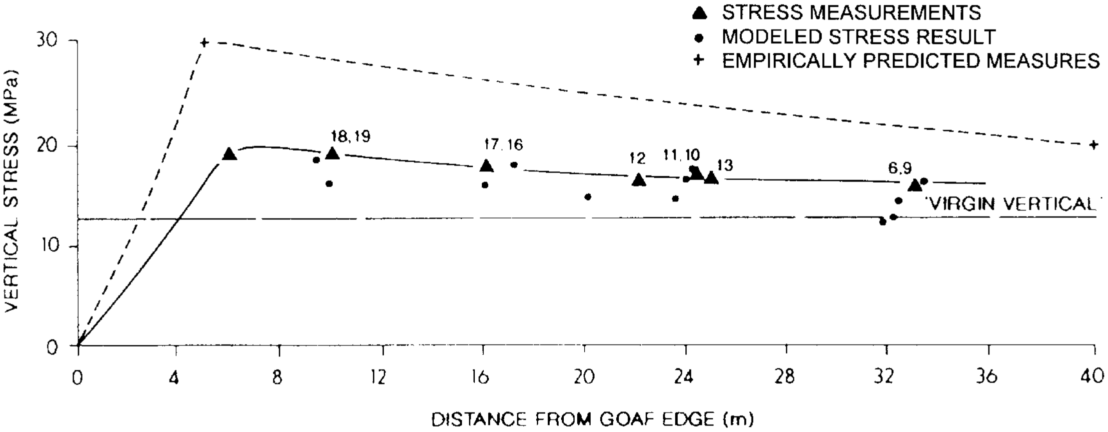

Figure 17.—Longwall side abutment profiles for modeled, measured, and empirical approaches in a high stress mining area.

CONCLUSIONS

The strength characteristics of pillars depend on the strength properties of the strata surrounding the coal.

It is important to consider the postfailure strength of pillars in design, particularly in areas of weak strata where a postfailure strength loss in moderate to large width/height pillars is possible.

Computer simulation methods in association with site measurements are recommended for the design of key layouts that require an assessment of geological variations, pillar size, and stress field changes to optimize the mining operation. This approach also assesses the expected roadway conditions or pillar response for various mine layouts; these can be monitored to determine if the ground is behaving as expected.

Design of pillars adjacent to large extraction areas needs to include the large-scale fracture distributions and, in general, needs to be based on a ground control criterion rather than on a pillar strength criterion only.

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