

# Experience of Field Measurement and Computer Simulation

## Methods for Pillar Design

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This paper is developed for the 2<sup>nd</sup> International Workshop on Coal Pillar Mechanics and Design and is based on prior publications.

**Abstract:** Coal pillar design has been based on generalised formulae of the strength of the coal in a pillar and experience in localised situations. Stress measurements above and in coal pillars indicate that the actual strength and deformation of pillars varies much more than predicted by formulae. 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 UK, USA, South Africa, Australia, China, Japan and other countries are simply variations due to different strata-coal combinations and 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 presented.

*Key Words:* pillar strength, pillar design, pillar system, failure mechanics, computer simulation

## **Introduction**

The strength characteristics of coal pillars has been studied by many workers and the subject is well discussed in the literature (for example, Salamon and Monroe, 1967; Wilson, 1972; Hustrulid 1976; Mark and Iannacchione 1992; Gale 1996).

In general a range of strength relationships have been derived from four main sources:

- i) Laboratory strength measurements on different-sized coal block specimens;
- ii) Empirical relationships from observations of failed and unfailed pillars;
- iii) A theoretical fit of statistical data and observations; and
- iv) Theoretical extrapolation of the vertical stress buildup from the ribside toward the pillar centre, 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 formulae are favoured (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 formulae 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. Little of this 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, UK, Japan, USA, 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 formulae to assess the strength of a system which is controlled by

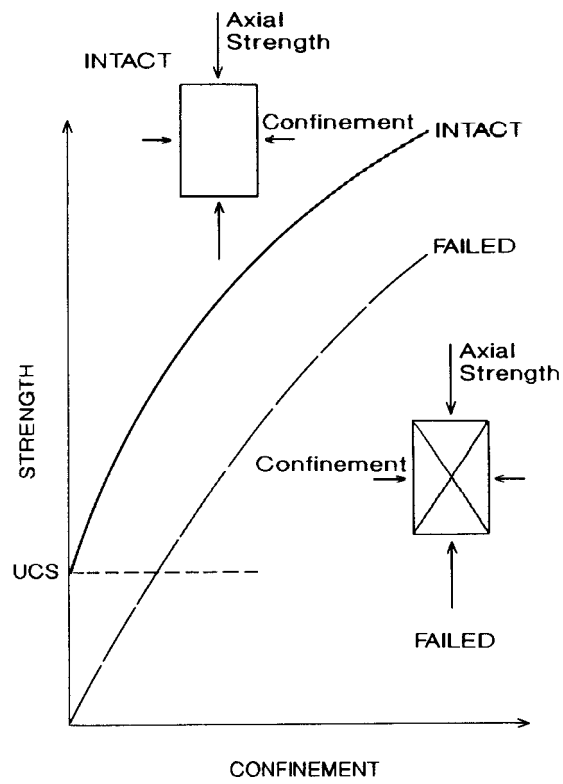
the interaction of geology, stress and associated rock failure is commonly an over simplification.

### **Mechanics of the Pillar-Coal System**

The strength of a pillar is basically determined by the magnitude of vertical stress which 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 which make up 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 having 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 and this will determine the pillar strength. The strength achievable in various elements is largely dependent 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 will increase 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 centre. This increased strength is often related to the width/height ratio, whereby the



**Fig. 1** Effect of confining stress on compressive strengths of intact and fractured rocks (note that “failed” rocks should read fractured).

larger this ratio the greater the confinement generated within the pillar. Hence squat pillars (high W/H) have greater strength potential than slender ones (of low W/H).

The basic concepts related to confinement within coal pillars was developed by Wilson (1972) and 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*

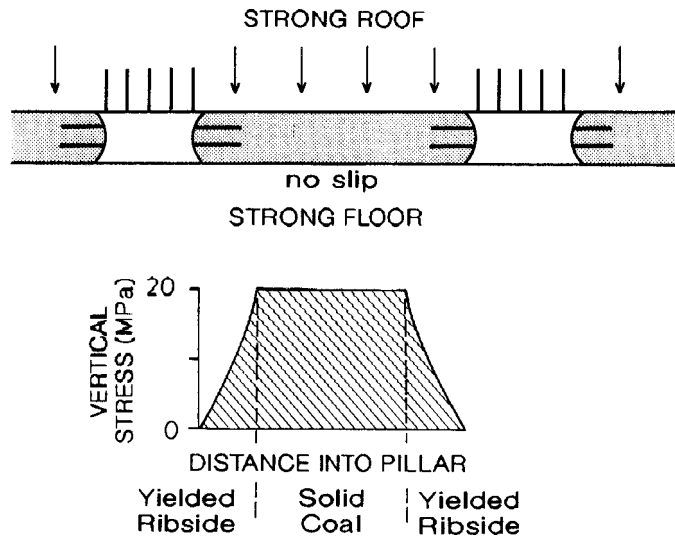
Prior to mining, the rock and coal units will have in situ horizontal and vertical stresses which form a balanced initial stress state in the ground. As an opening (roadway) is created in a coal seam, there is a natural tendency for the coal and rock to move laterally and vertically into the roadway. 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 by shear deformation of soft bands, then 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 that extending across the pillars. This mechanism determines the depth of failure into the pillar and the extent of ribside displacement during roadway driveage.

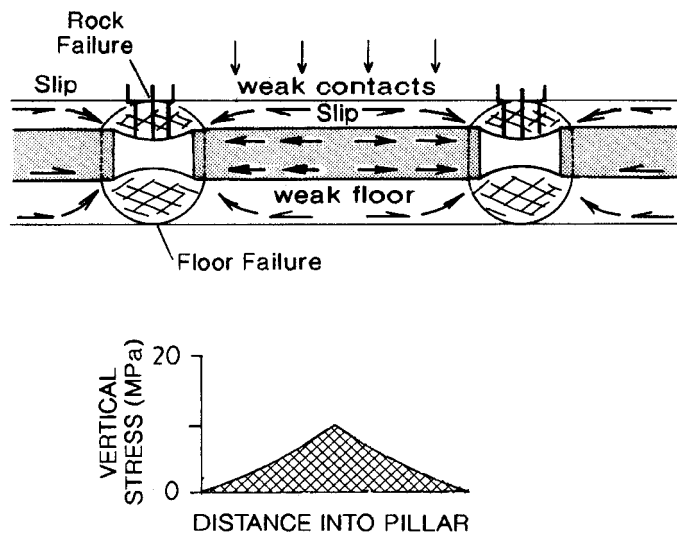
### *Pillar Loading by Abutment Stresses*

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 then this increased horizontal stress is not well developed, and increased rib squeeze is manifest instead.

This concept is presented in Figure 2, where with strong cohesive coal/rock interfaces, the confining stress in the pillar increases rapidly inwards 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 in Figure 2. The diagram shows that the pillar has



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



**Fig. 3** Slow building up of vertical stress in the pillar where slip occurs and confinement is reduced.



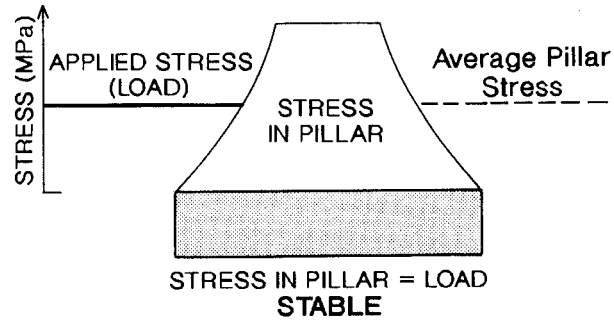
failed due to its inability to sustain the imposed vertical abutment stresses. In addition, lateral movement has caused floor heave and severe immediate roof shearing.

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 4a). If the applied load is greater, then the pillar is said to fail (Figure 4b) and the deficit stress must be redistributed onto nearby pillars.

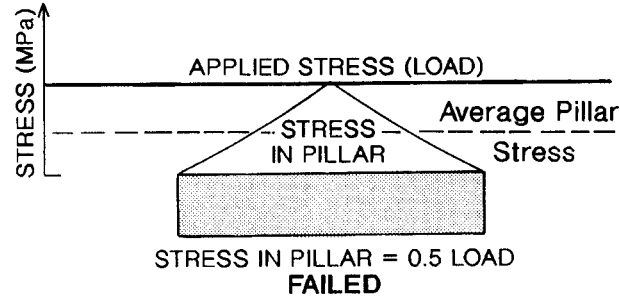
Conceptually, pillar strength behaviour should fall between the two end members of:

- (a) Lateral slip occurring totally unresisted, so that pillar strength is limited to the unconfined value of the coal; and
- (b) 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 W/H ratio, is presented after Gale 1996, in Figure 5. It is assumed that the rock mass strength of the coal is 6.5MPa, 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 UCS 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 width/height ratios.



a) Strong System.



b) Weak System.

Fig. 4 Pillar strength cases for strong and weak geologies.

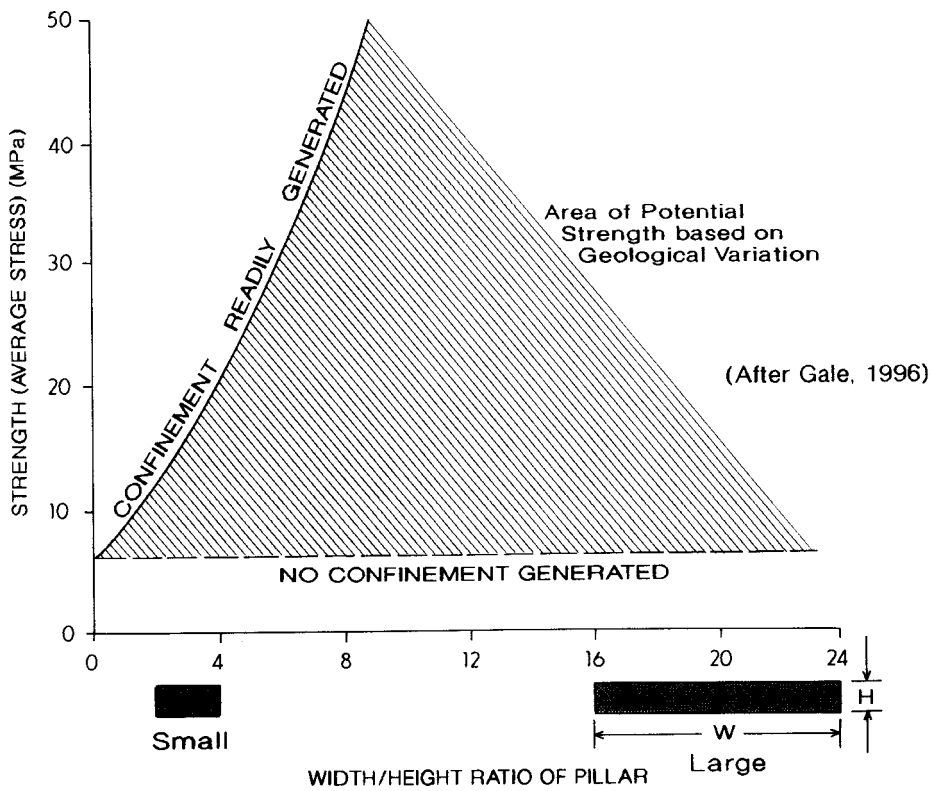


Fig. 5 Range of potential pillar strengths relative to width / height based on confinement variation.

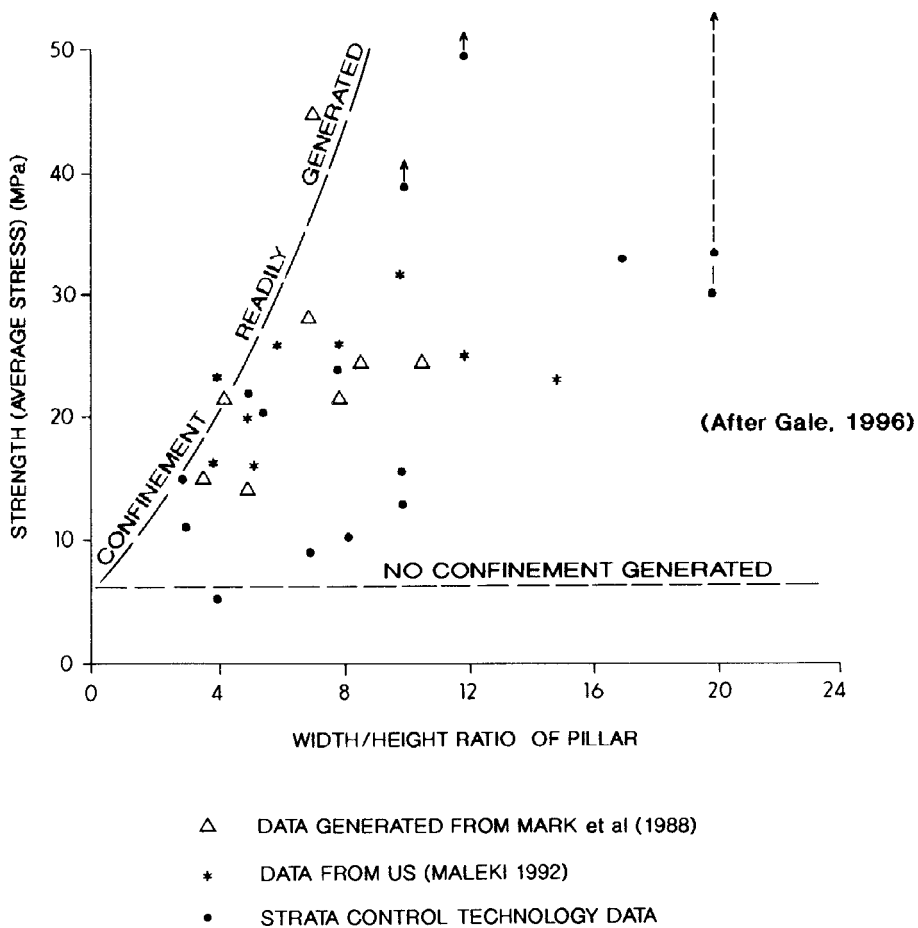
A comparison of these "end member" situations with a range of pillar strengths determined from actual measurement programs conducted in Australia and the UK by SCT and from USA (Mark et al, 1988) is presented in Figure 6. The comparison indicates that a wide range of pillar strengths have been measured 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.

- i) The "strong-normal" geologies, where pillar strength appears to be close to the upper bound.
- ii) The structured or weak geologies, where the strength is closer to the lower bound and where it is apparent that strength of the system is significantly limited.

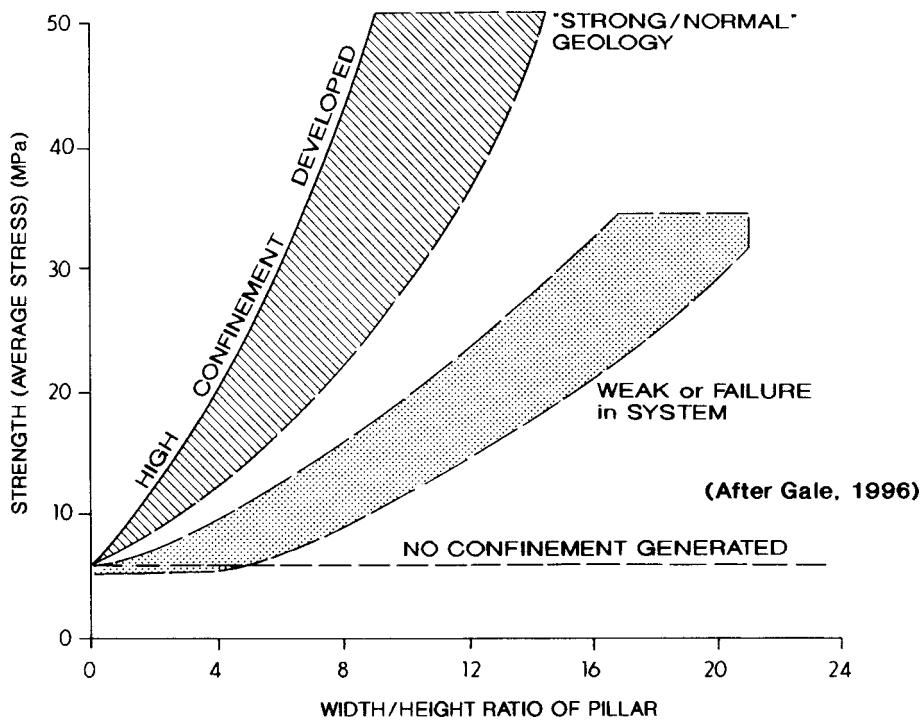
It should be noted that these two groupings are arbitrary and possibly due to a limitation of data. With more data points the grouping may become less obvious.

### **Effect of Geology**

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



**Fig 6** Pillar strength information relative to changes.



**Fig 7** Generalised groupings of strong / normal and weak geology.

### *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.

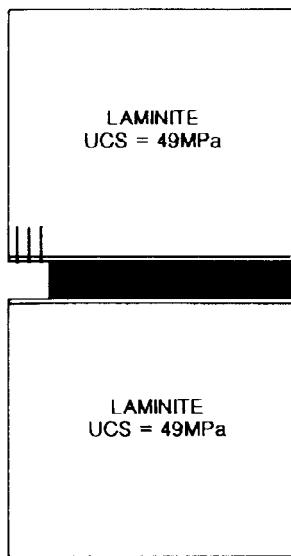
Computer models of four pillar systems were loaded to determine their strength characteristics.

The pillar systems are presented in Figure 8 and are;

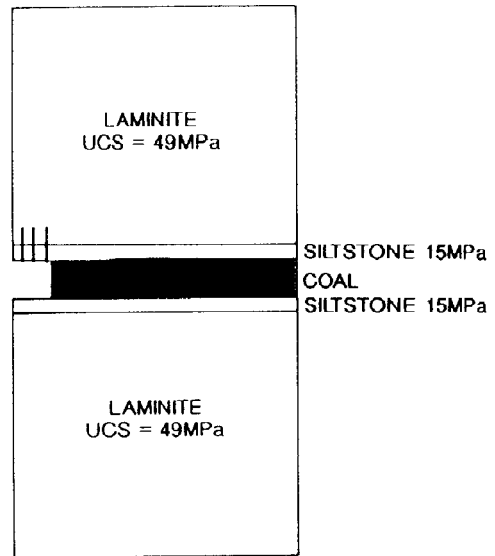
- i) massive sandstone – coal – massive sandstone
- ii) laminite – coal – sandstone
- iii) weak siltstone – coal – weak siltstone
- iv) laminite – clayband – coal – clayband – laminite

The results of the pillar strength characteristics relative to width/height 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 an insight into the geological factors affecting strength. The results indicate that:

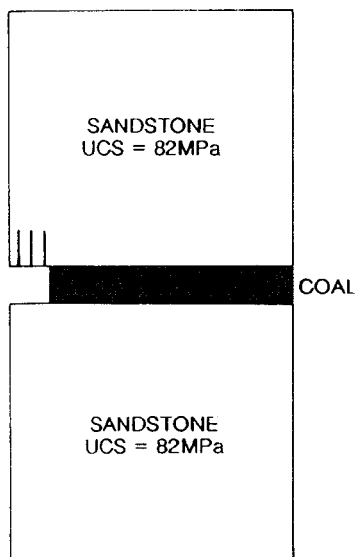
- (i) Strong immediate roof and floor layers and good coal to rock contacts provide a general relationship similar to the upper bound pillar strength in Figure 5.
- (ii) Weak, clay rich and sheared contacts adjacent to the mining section reduce pillar strength to the lower bound areas.



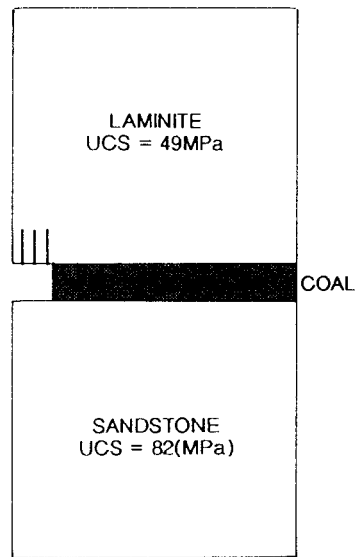
a) Coal / clay / laminite.



b) Coal / siltstone / laminite.

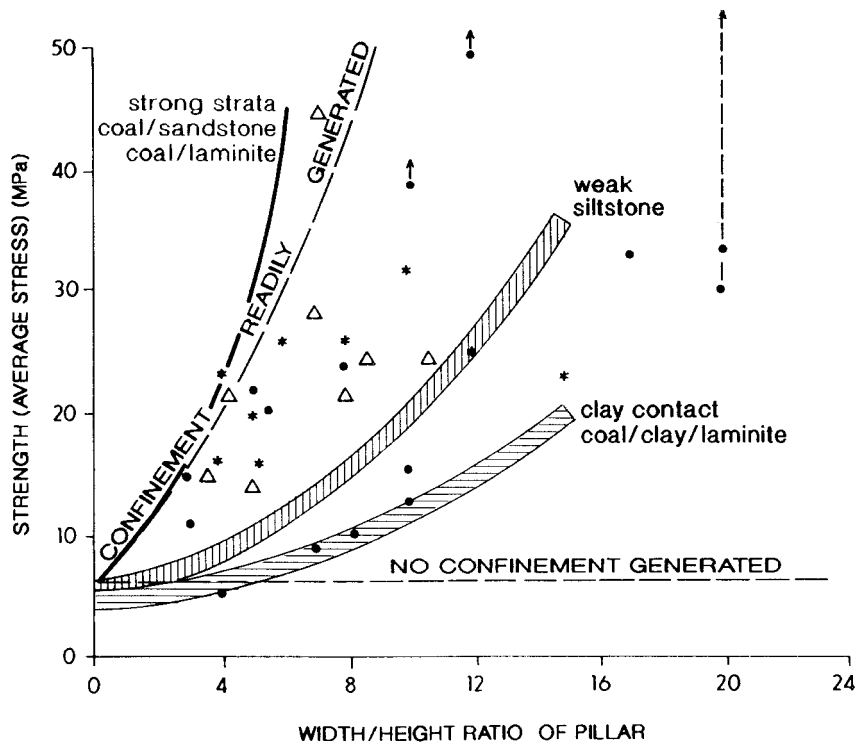


c) Coal / sandstone.



d) Coal / laminite / sandstone.

**Fig. 8 Geological sections modelled to assess load / deformation characteristics.**



- Δ DATA GENERATED FROM MARK et al (1988)
- \* DATA FROM US (MALEKI 1992)
- STRATA CONTROL TECHNOLOGY DATA

**Fig. 9** Strength / width height for models.

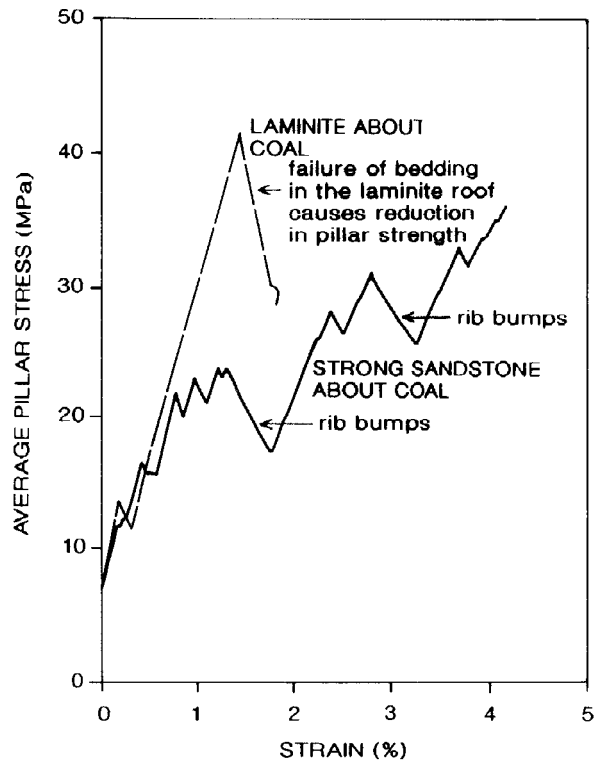
- (iii) Soft strata in the immediate roof and floor, which fail under the mining induced stresses, will weaken pillars to the lower bound areas.
- (iv) Tectonic deformation of coal in disturbed geological environments will reduce pillar strength, though the extent is dependent on geometry and strength 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.

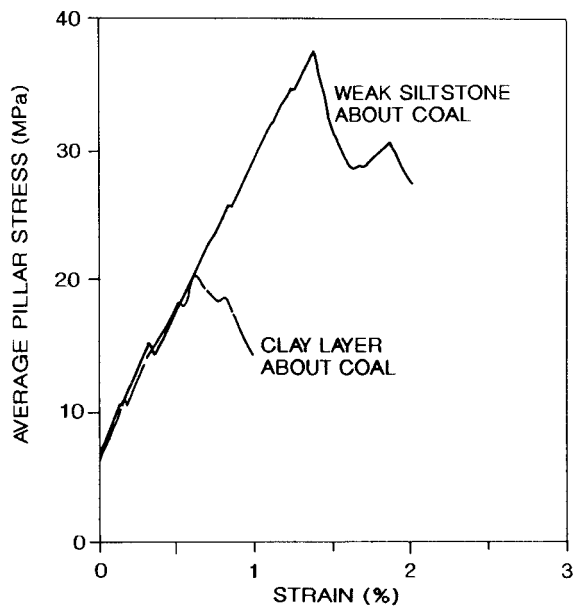
#### *Effect of Geology on Post Peak Pillar Strength*

The post peak pillar strength characteristics for some of the pillars modelled is presented in Figure 10. The pillar strength is presented as a stress/strain plot for various width/height pillars. The results presented in Figure 10a 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 modelled, “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 having a width/height less than  $4/5$  a loss in strength is expected at a high load due to failure of the coal.





a) Width / height = 5.



b) Width / height = 15.

Fig. 10 Post Peak strength of models.

In pillar systems having 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 modelled. Two examples are presented in Figure 10b where the post peak strength characteristics of pillars having weak mudstone or clay surrounding the coal. In these examples the strength loss is greatest in the situation of weak clay surrounding the coal.

The implications of this are significant for the design of barrier pillars 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 are possible ranging, 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 utilise the lower bound curve of the weak geology band in Figure 7. In good or normal geologies, the Bieniawski or squat pillar formulae may be suitable for initial estimates.

Two obvious problems with this approach are that:

- (i) Estimates of pillar size can vary greatly, depending on the geological environment assumed.
- (ii) The pillar size versus strength data set used (Figure 6) is limited.

This is why such formulae or relationships are considered as first pass estimates only, to be significantly improved later by more rigorous site specific design studies, utilising 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

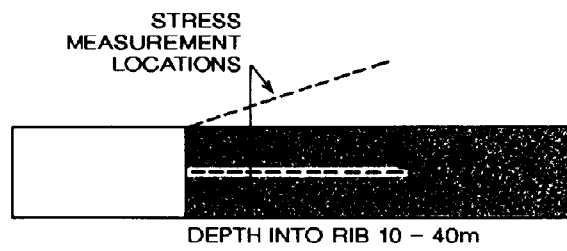
hence to develop a pillar strength relationship suitable for that geological site. An example of stress measurements over a pillar is presented in Figure 11(a) and (b), however the method is limited to determining the potential stress distribution in different pillar widths under the measured loading condition.

Extrapolation of increased loading is more problematical. In weak ground, an approach is to extrapolate the vertical stress build up from the rib toward the pillar centre. This may be possible where the vertical stress build up 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).

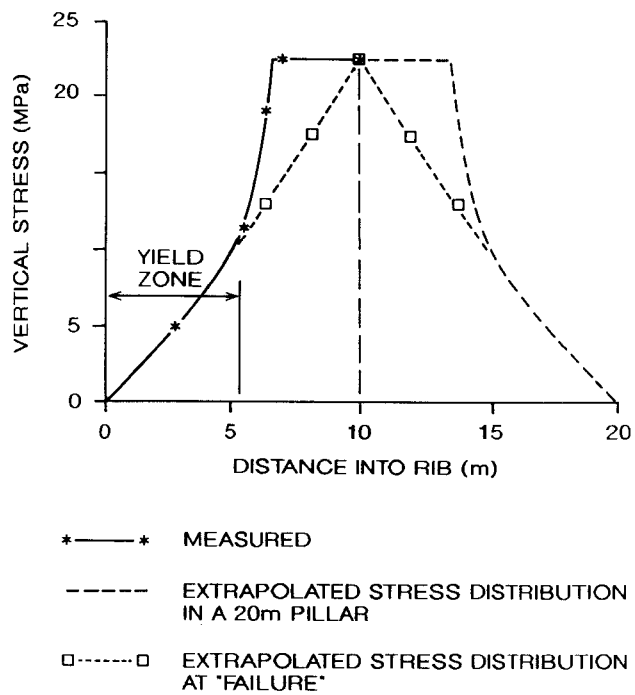
Experience suggests that this is more likely in weak ground, however in stronger ground the stress build up is often more exponential and as such, difficult to extrapolate.

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

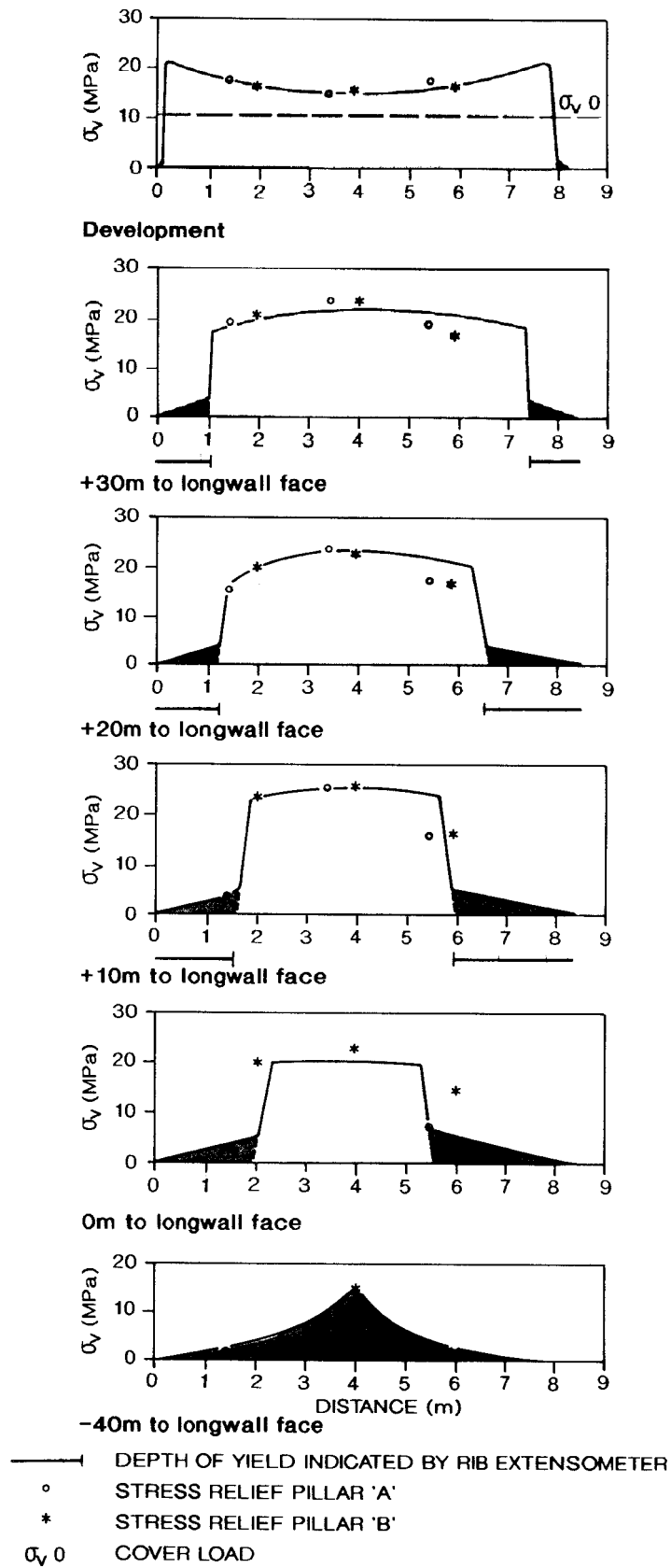


a) Typical Stress Measurement Locations.  
(Not to Scale)



b) Stress Distribution in Pillar from Measurements.

Fig. 11 Stress measurements over ribsides for strength assessment.

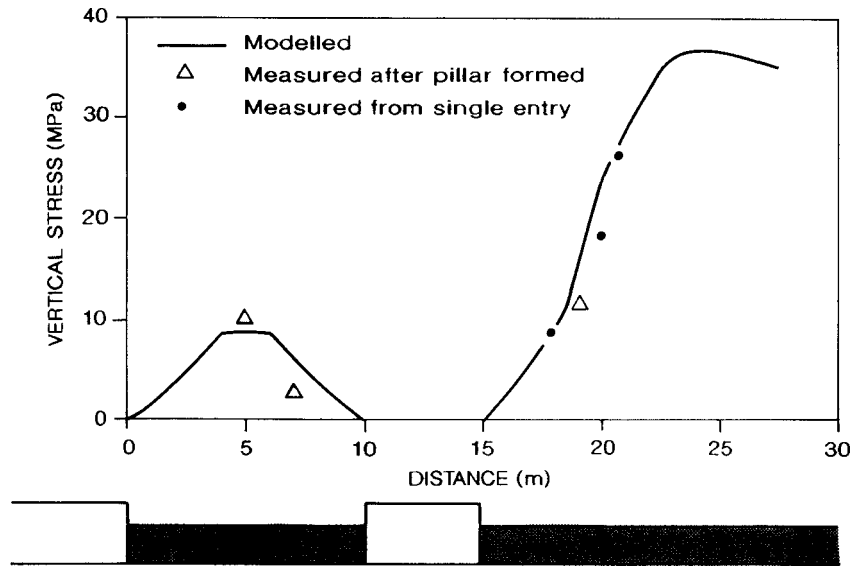


**Fig. 12** Example of small pillar monitoring studies indicating pillar stress history.

Detailed computer simulation, in association with field validation programs, is providing a method to extrapolate the stress redistributions associated with various loading conditions and rock failure modes. In this way, the strength of pillars having different size, or under various mine geometries, can be assessed.

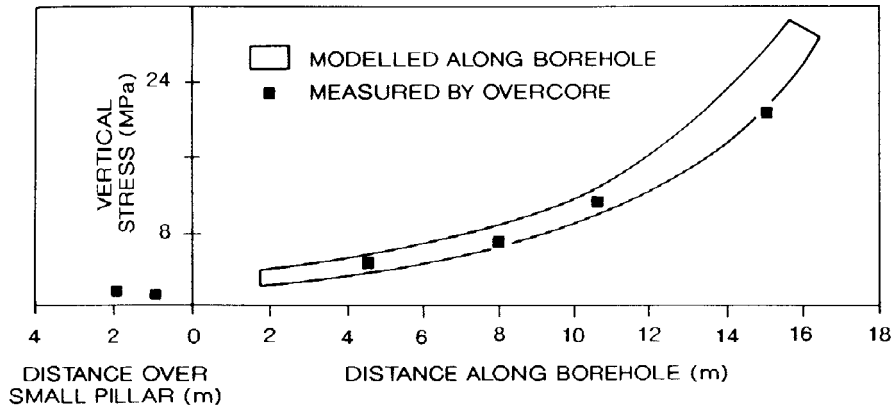
Computer modelling methods have been developed to simulate the behaviour of the strata sections under various stressfields and mining geometries. For mine design, such simulations need to be validated against actual ground behaviour and stress measurements. This provides confidence that sufficient geological investigation has been undertaken, and that the strength properties and deformation mechanisms are being simulated accurately.

Computer simulation methods are being developed which can be applied to determining the strength characteristics of various strata systems. The accuracy of the computer software developed by SCT 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 modelled stress distribution over a yield pillar and solid coal in a deep mine. Another example of computer modelling capabilities is presented in Figure 14 for weak ground adjacent to a longwall panel. A series of stress measurements were 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. The comparisons indicate that rigorous computer simulation methods can provide a good estimation of the actual stresses and ground failure zones.

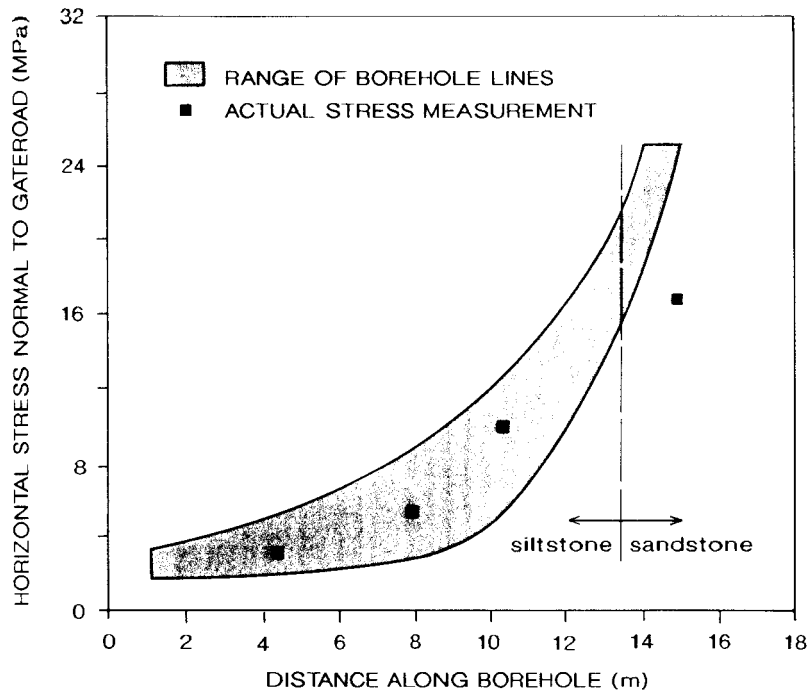


**Fig. 13** Stress over yield pillar and adjacent to longwall.





a) Comparison of Modelled and Measured Vertical Stress.



b) Comparison of Modelled and Measured Horizontal Stress.

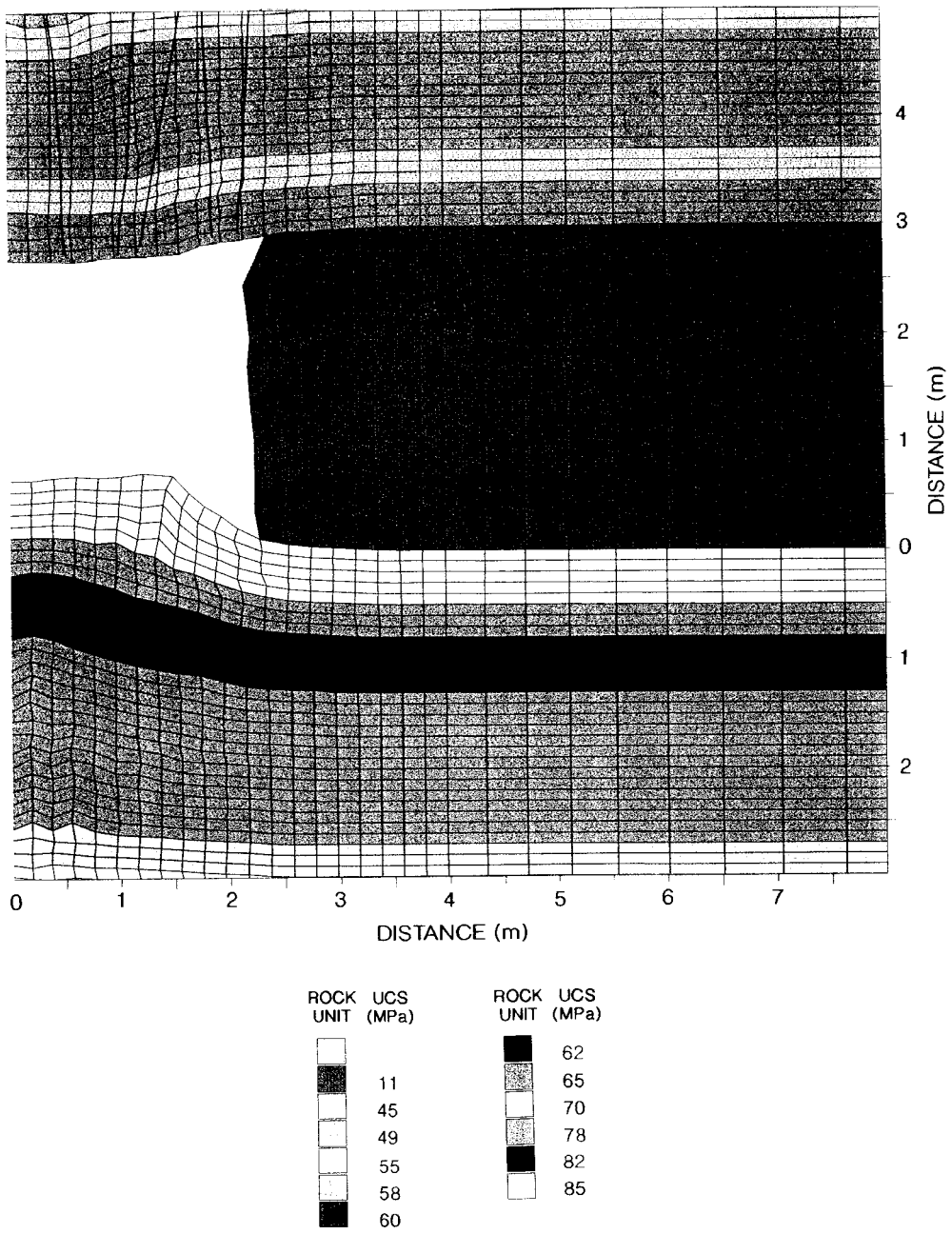
**Fig. 14** Comparison of modelled and measured vertical and horizontal stress over a longwall side abutment. Stress measurements were made in borehole drilled from an adjacent roadway.

One major benefit of computer modelling is that the behaviour of roadways adjacent to the pillars can be simulated. In this way the design of a pillar will not only reflect 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.

In mining situations where there are large areas of solid ground about the working area the potential for regional collapse of pillars are typically low. Design in these areas usually relates to optimising roadway conditions and controlling ground movements rather than by 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 behaviour rather than “small scale” pillar strength criteria.



**Fig. 15** Simulation of roadway conditions under abutment stress.

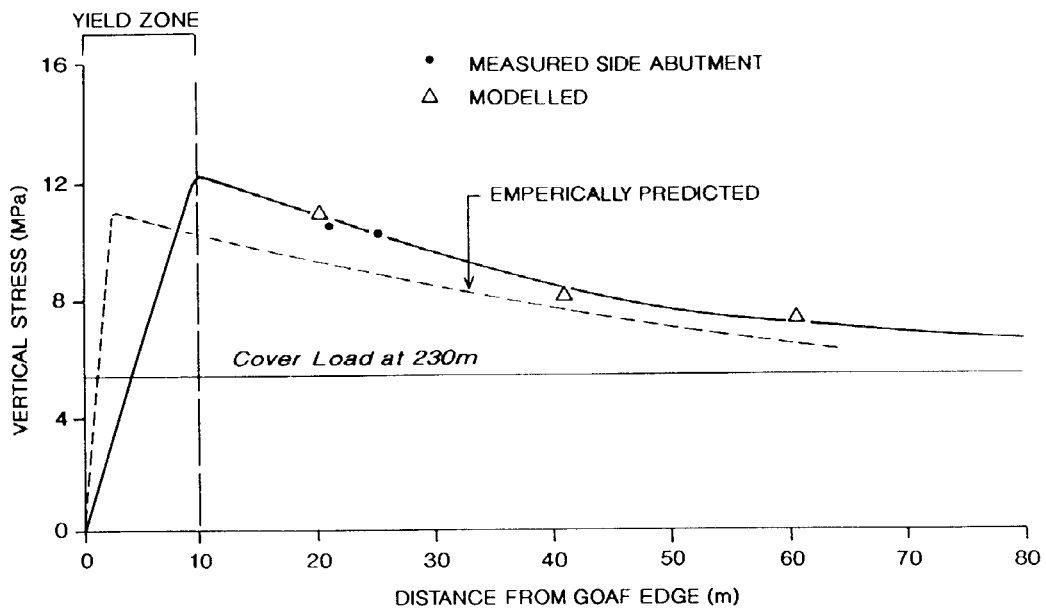
Microseismic monitoring (Kelly et al 1998) has demonstrated significant rock fracture above and below chain pillars. Computer modelling of caving (Gale 1998) has also demonstrated rock fracture above and below pillars. Rock failure above and below chain pillars occurs as a result of gross scale stress changes and fluid pressure redistributions.

The strength and loading conditions of chain pillars can reflect the larger scale fracture geometries which may develop. An example of an abutment stress within a pillar at shallow depth (250m) is presented in Figure 16.

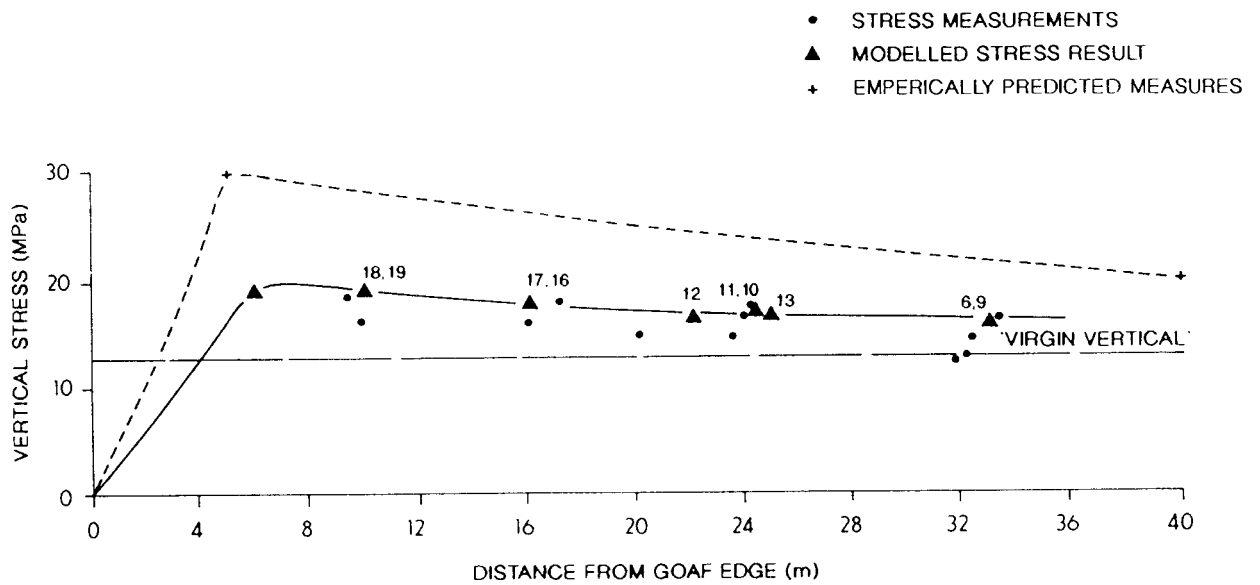
In this case, rock failure extends over the ribside and shifts the abutment distribution within the pillar.

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 spread over a longer lateral extent. An example is present in Figure 17.

In both these examples computer modelling of the caving process within the geological section has given a very close correlation with the measured data. The use of generalised empirical methods to determine the abutment profile is also presented and indicates that their application is best utilised as initial estimates to be reassessed by site specific investigations for key design areas.



**Fig. 18** Longwall side abutment profiles for modelled, measured and empirical approaches. In this example rock failure occurred about the pillar forming a more extensive yield zone.



**Fig. 17** Longwall side abutment profiles for modelled, measured and empirical approaches in a high stress mining area.

Rock failure above and below chain pillars does not necessarily occur at all sites, however experience suggests that it 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 modelling and microseismic investigations play a key role in defining the key 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 it would be applied to.

## **Conclusions**

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

The post failure strength of pillars is an important issue to consider in design particularly in areas of weak strata, where a post failure strength loss in moderate to large width/height pillars is possible.

Field stress measurements and computer modelling provide methods to assess the strength of pillars and the areas of ground fracture.

Computer simulation methods in association with site measurements are recommended for the design of key layouts which require an assessment of geological variations, pillar size and stressfield changes to optimise the mining operation. This approach also assesses the expected roadway conditions or pillar response for various mine layouts and which 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 be based on a ground control criteria rather than a pillar strength criteria alone.

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