Coal Pillar Design Issues in Longwall Mining

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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.

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:

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 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. Such relationships have usually been developed for relatively small pillars having width to height (W/H) ratios less than 5, and can only be used with confidence in these situations. 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 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.

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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 Fig. 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 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).

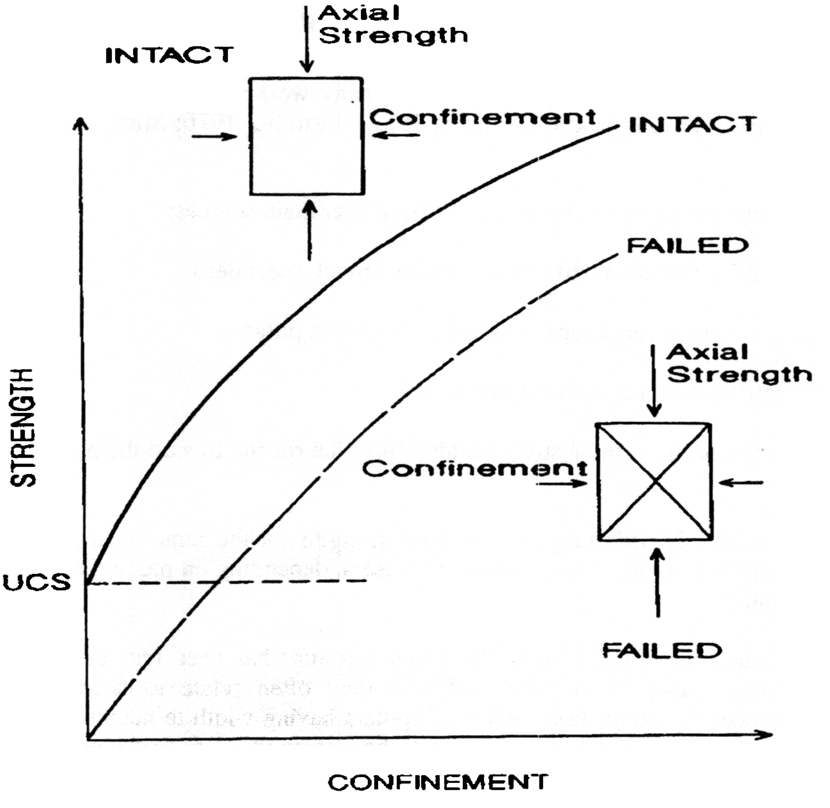


Fig. 1 - Effect of confining stress on compressive strengths of intact and fractured rocks (Note that "failed" rocks should read fractured)

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 Fig. 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 Fig. 3. In this situation confinement cannot be maintained sufficiently, hence the allowable vertical stress would be significantly less than in Fig. 2. The diagram shows that the pillar has 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 Fig. 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 (Fig. 4a). If the applied load is greater, then the pillar is said to fail (Fig. 4b) and the deficit stress must be redistributed onto nearby pillars.

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

- Lateral slip occurring totally unresisted, so that pillar strength is limited to the unconfined value of the coal; and
- 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 Fig. 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.

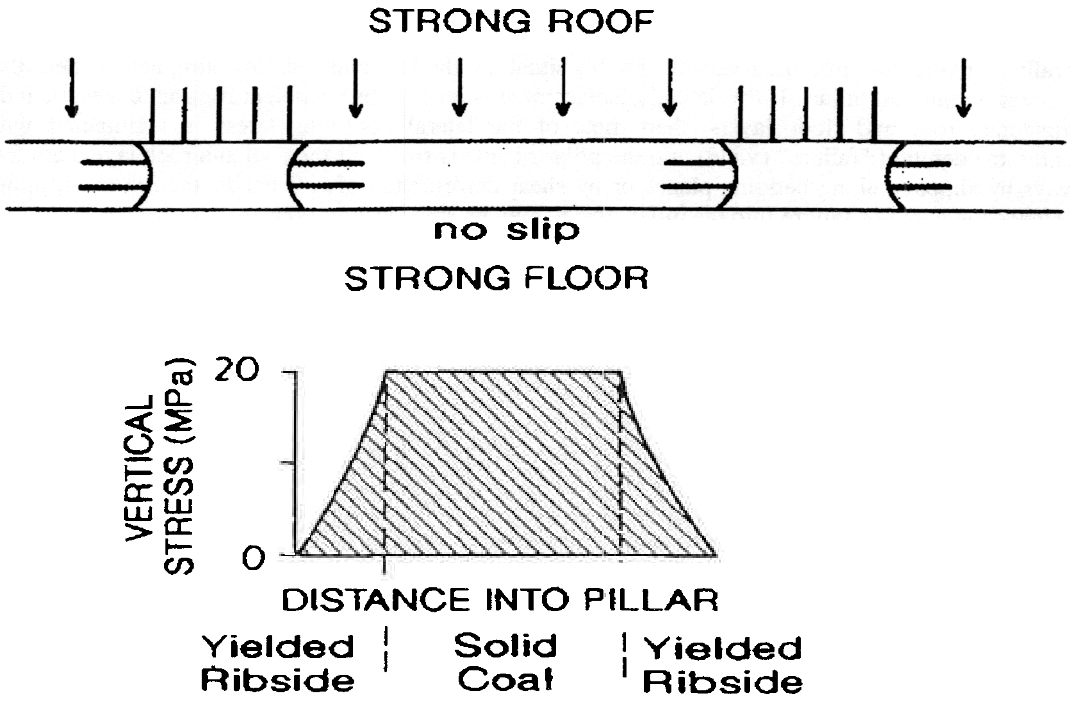


Fig. 2 - Rapid build up of vertical stress into the pillar where high confining stresses are maintained

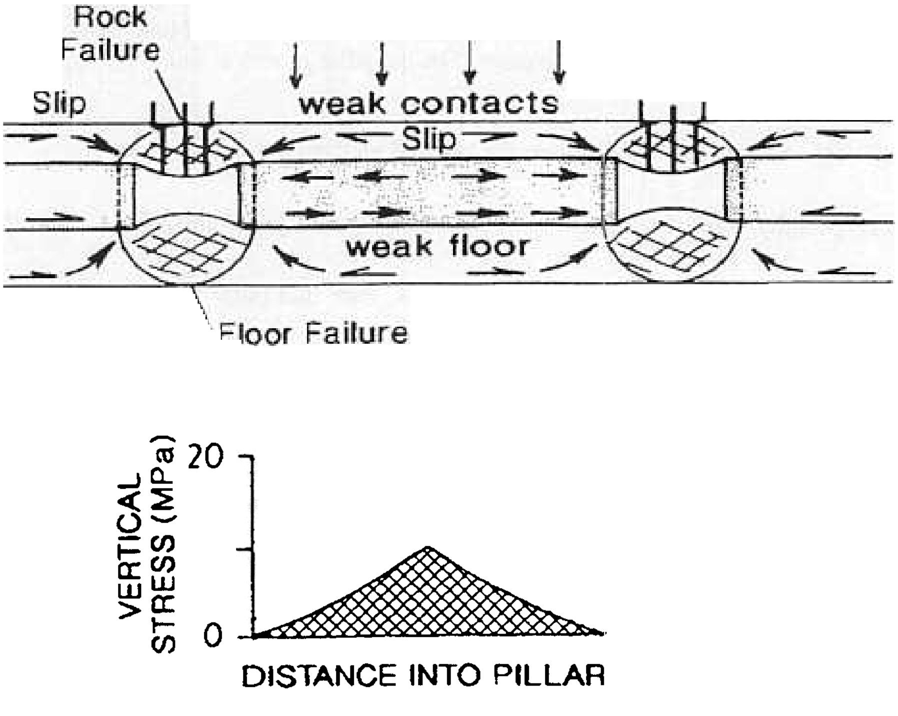


Fig. 3 - Slow build up of vertical stress in the pillar where slip occurs and confinement is reduced

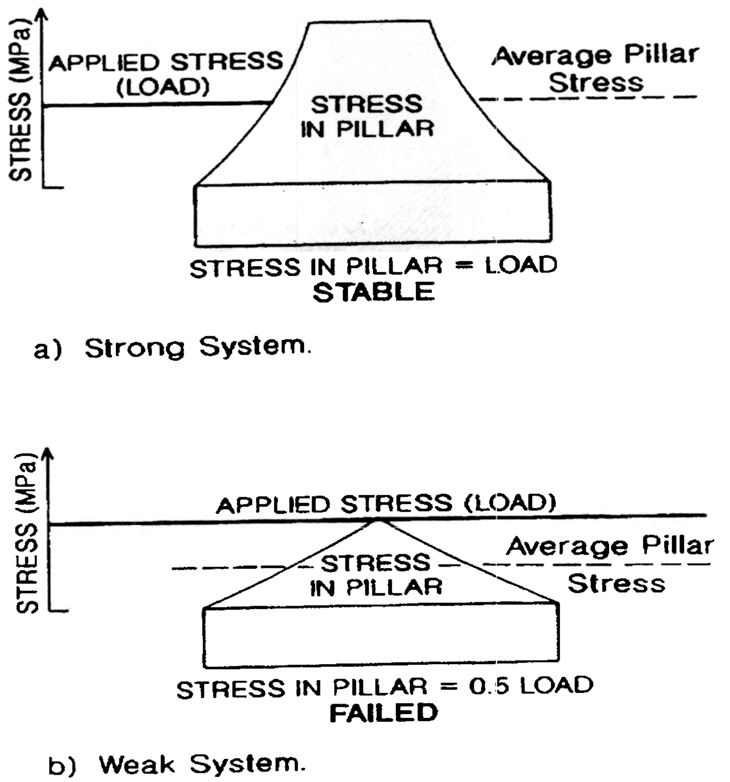


Fig. 4 - Pillar strength cases for strong and weak geologies

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 Fig 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 Fig. 7:

- The "strong-normal" geologies, where pillar strength appears to be close to the upper bound; and
- 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.

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.

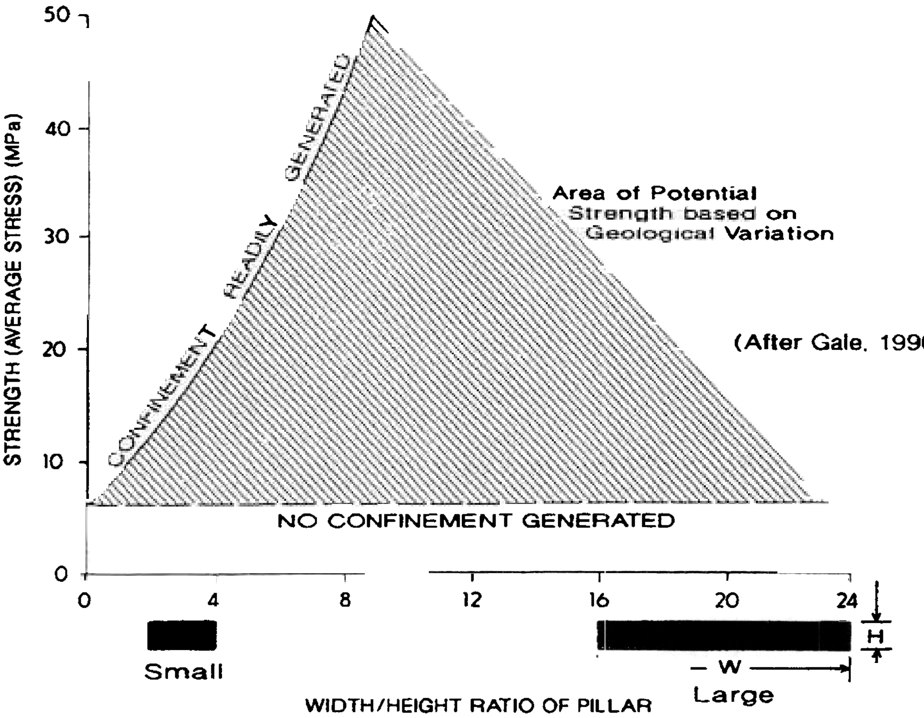


Fig. 5 - Range of potential pillar strengths relative to width / height based on confinement variation

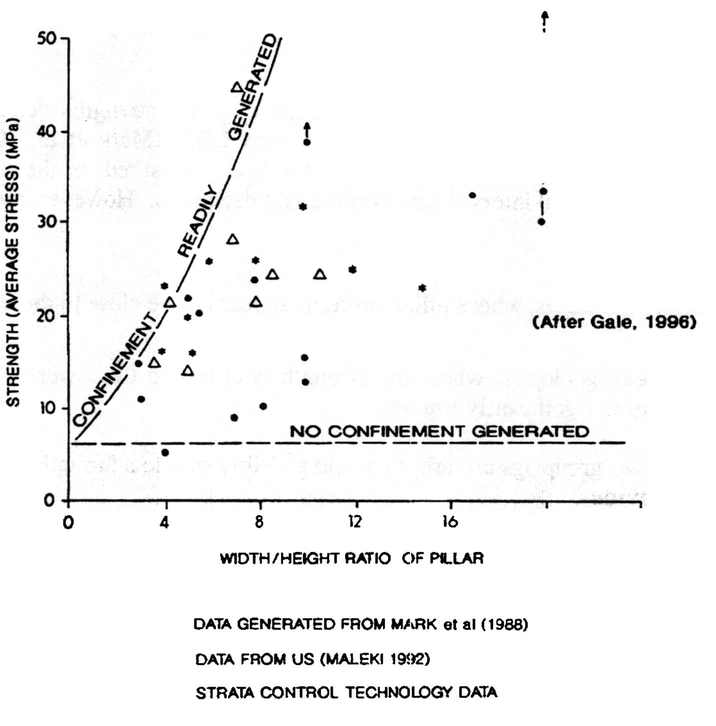


Fig. 6 - Pillar strength information relative to changes

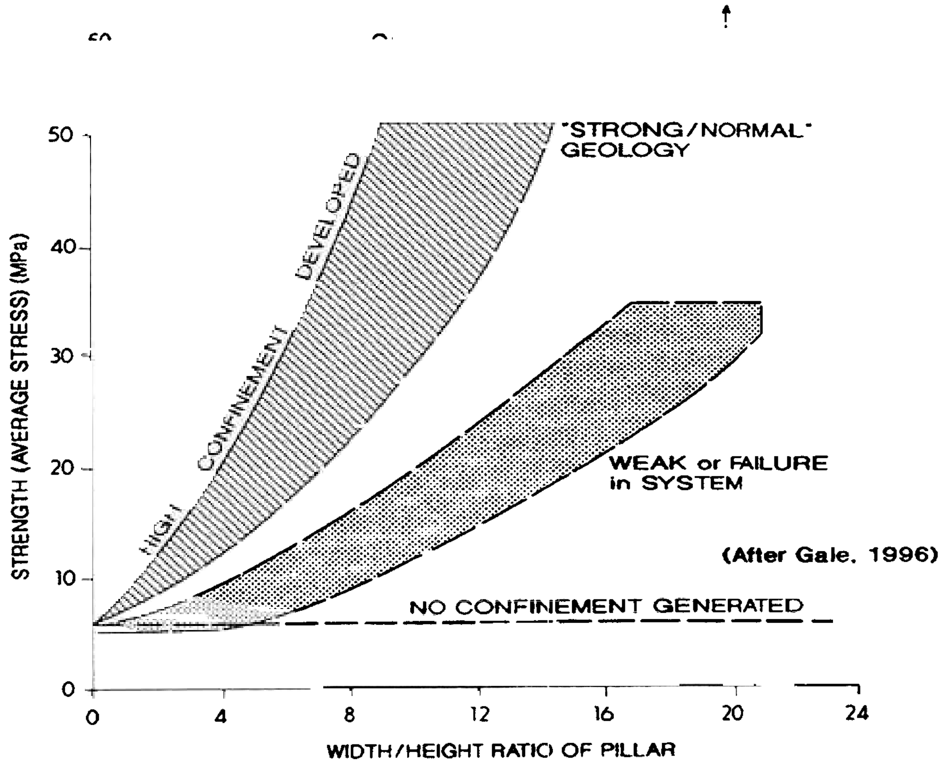


Fig. 7 - Generalised groupings of strong / normal and weak geology

The pillar systems are presented in Fig. 8 and are;

a) laminite – clayband – coal – clayband – laminite.

b) weak siltstone – coal – weak siltstone;

c) massive sandstone – coal – massive sandstone; and

d) laminite – coal – sandstone;

The results of the pillar strength characteristics relative to width/height are presented in Fig. 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:

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

- Weak, clay rich and sheared contacts adjacent to the mining section reduce pillar strength to the lower bound areas;

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

- Tectonic deformation of coal in disturbed geological environments will reduce pillar strength, though the extent is dependent on geometry and strength of the discontinuities.

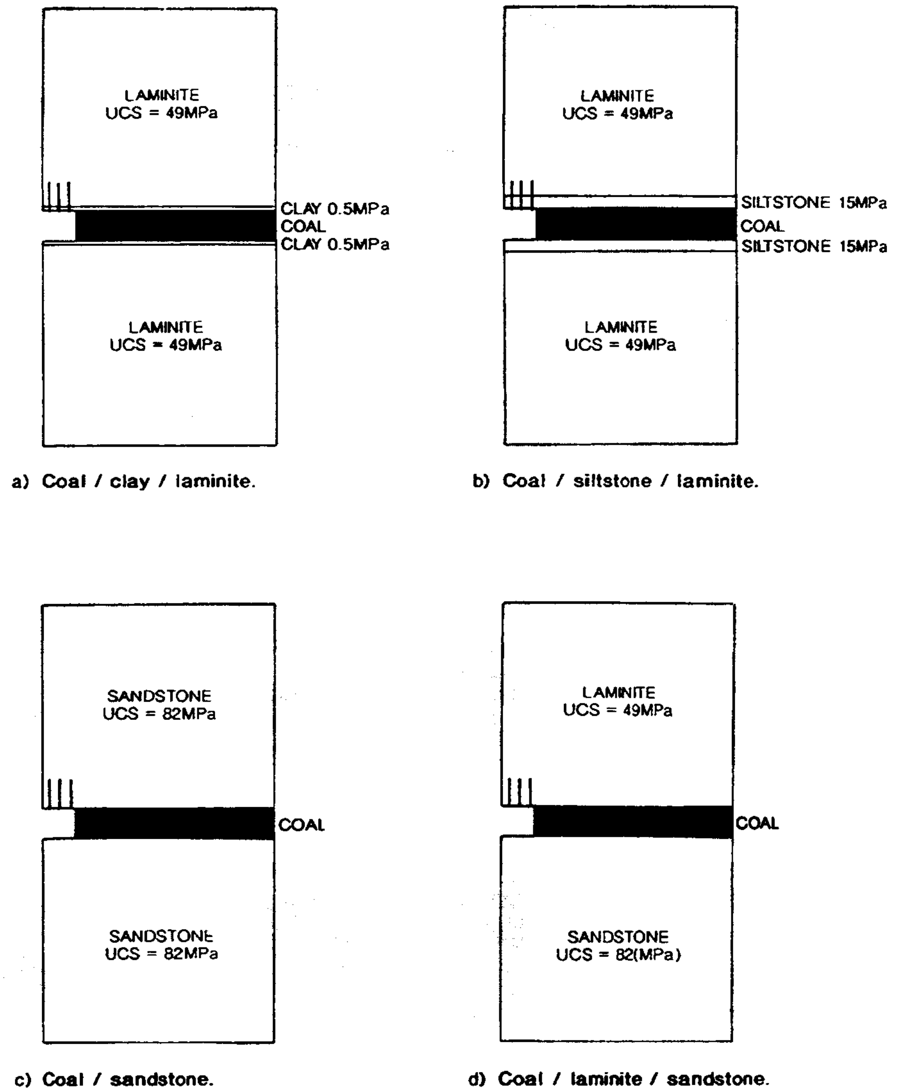


Fig. 8 - Geological sections modelled to assess load / deformation characteristics

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 Fig. 10. The pillar strength is presented as a stress/strain plot for various width/height pillars. The results presented in Fig. 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 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.

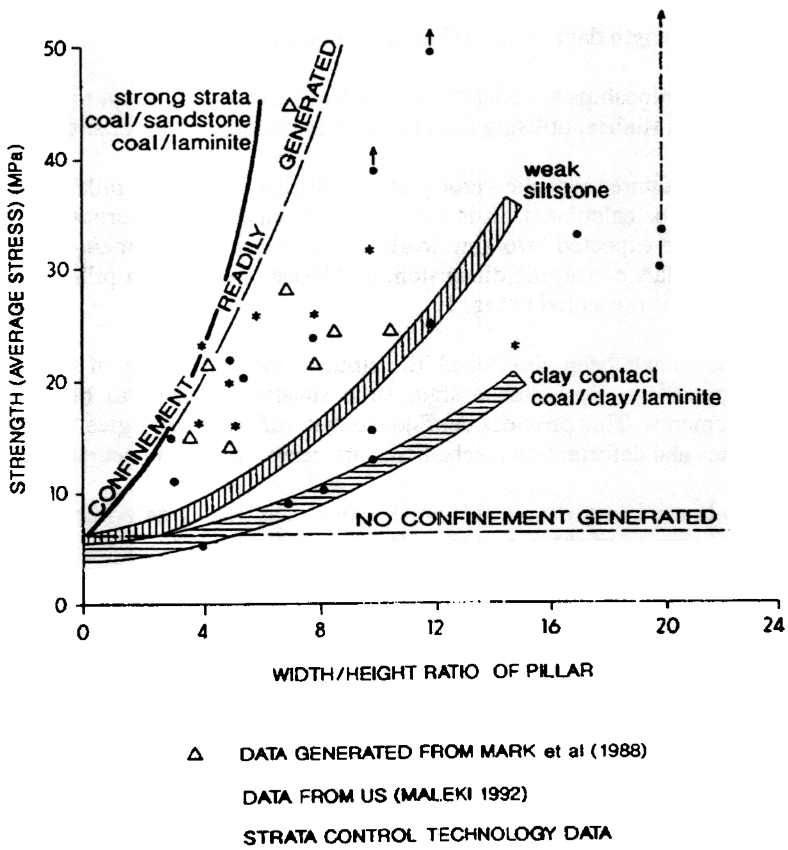


Fig. 9 - Strength / width height for models

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 Fig. 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

Pillar strength

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 Fig. 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:

- Estimates of pillar size can vary greatly, depending on the geological environment assumed; and
- The pillar size versus strength data set used (Fig. 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 is presented in Fig. 11.

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.

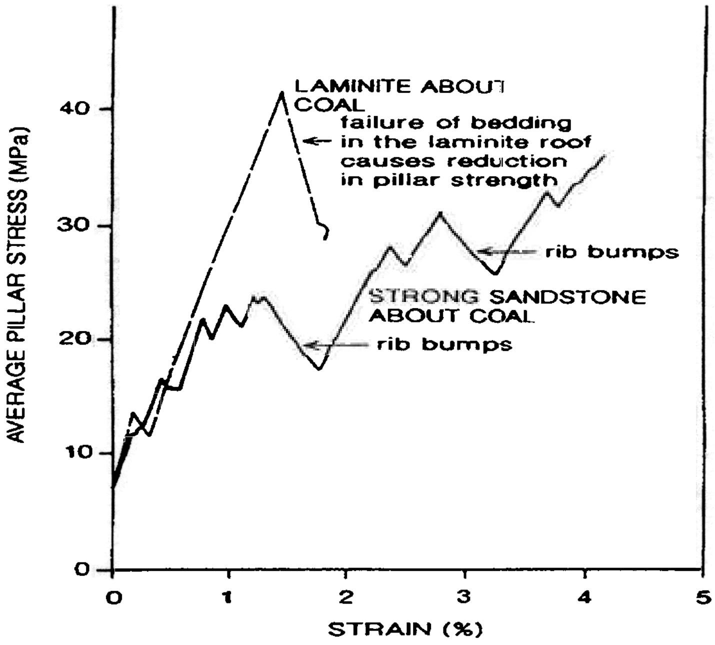
Computer simulation methods are being developed which can be applied to determining the strength characteristics of various strata systems. The accuracy of the computer software developed by SCT has been verified in a number of field investigations where computer predictions of stress distributions and rock failure zones have been compared. An example is presented in Fig. 12 which compares the measured and modelled stress distribution over a yield pillar and solid coal in a deep mine. The comparisons indicate that rigorous computer simulation methods can provide a good estimation of the actual stresses and ground failure zones.

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.

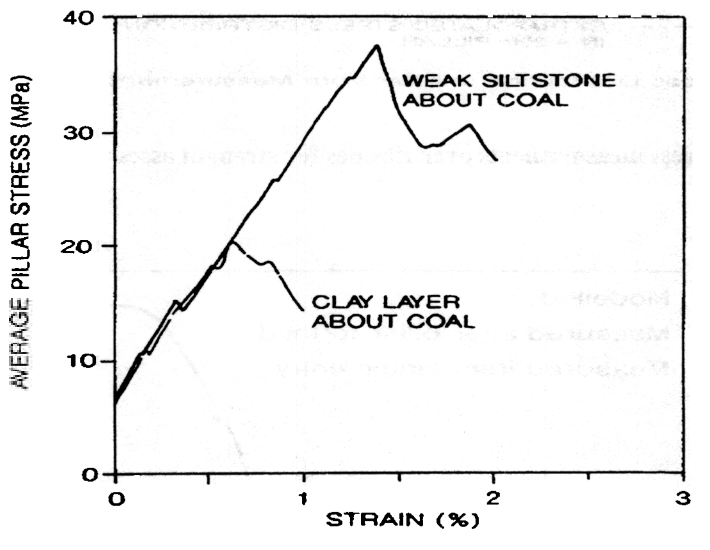
In mining situations where there are large areas of solid ground about the working area the potential for regional collapse of pillars are typically low. Design in these areas usually relates to optimising roadway conditions and controlling ground movements rather than by the nominal pillar strength. 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. Fig. 12 shows an example of this process for a failed ("yield") pillar adjacent to solid ground for which vertical stress above the yield pillar has been "shed" to the solid coal abutment area.

Abutment load estimates

In virgin conditions, the tributary method is widely used for an approximation to the average stress across a pillar, however for other conditions mining abutment loads should be determined on the basis of monitoring data bases or computer modelling of the actual mine geometry. Estimation of the abutment geometry is often done on the basis of empirical formulae (eg Wilson, 1972; Mark, 1992) or a range of stresses possible depending on various assumptions of goaf loading and post peak pillar strengths. Measurement programs may be required to validate the load distributions in certain geometries to ensure that further prediction of loading in inaccessible areas (eg in the goaf) are justified. The goaf load capacity is a function of extraction width and the bridging capacity of the ground. Monitoring and modelling has demonstrated a significant variation in abutment stress distributions resulting from differing geological sequences and virgin stress systems.



a) Width / height = 5.



b) Width / height = 15.

Fig. 10 - Post peak strength of models

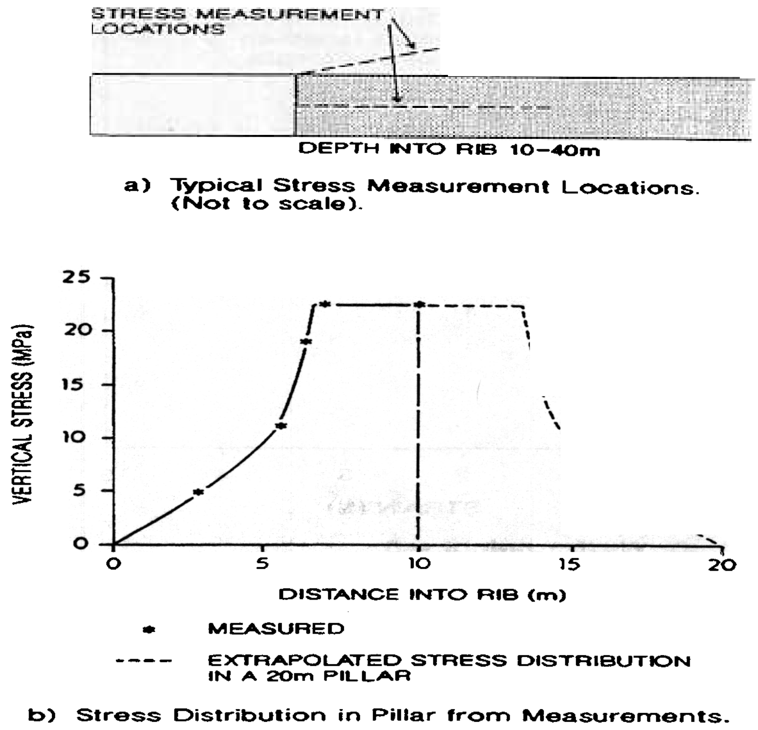


Fig. 11 - Stress measurements over ribsides for strength assessment

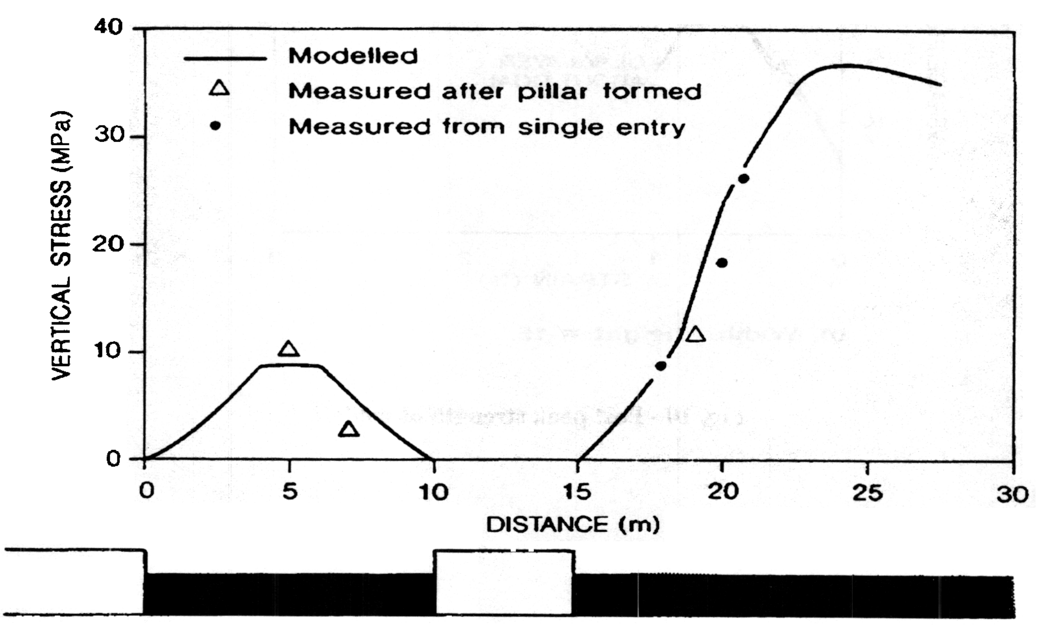


Fig. 12 - Stress over yield pillar adjacent to longwall

In certain situations failure may extend above and/or below the coal pillar which modifies the vertical stress abutment geometry. These failure modes are predicted by computer modelling and microseismic monitoring currently undertaken by CSIRO/SCT (Kelly et al, 1997). Lateral stress relief into the goaf in high stress environments can reduce the abutment magnitude but extend the zone of influence. Two examples are presented in Fig. 13 for a ribside for which rock failure extends over the ribside and a situation of stronger roof in a high lateral stressfield. In 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.

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.

Failure of strata above and below chain pillars is possible and has been confirmed by microseismic investigations.

Field measurement (stress measurement, microseismic monitoring, rock displacement) 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.

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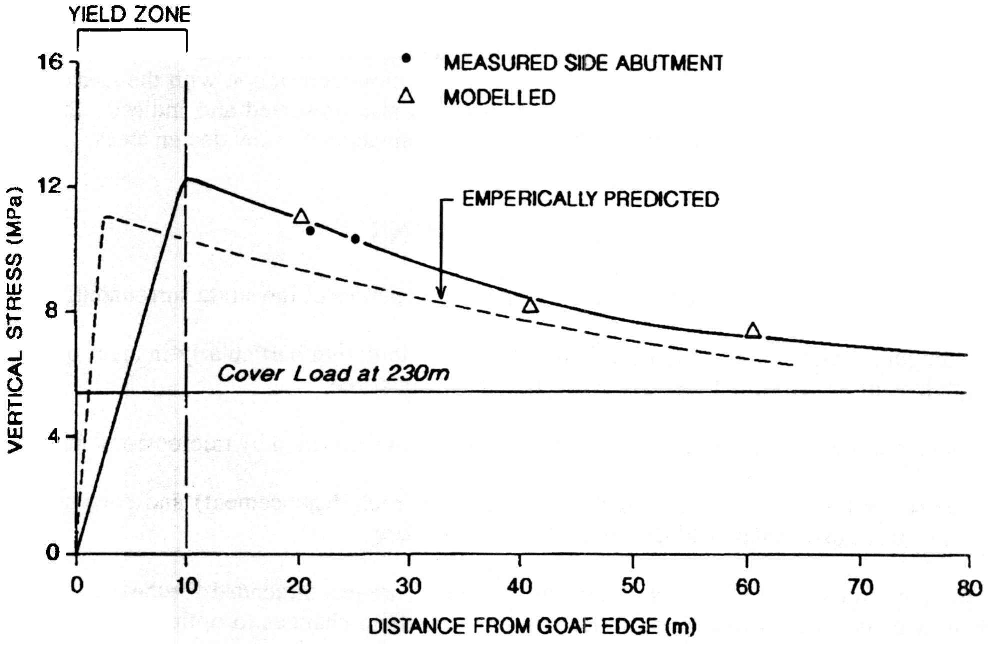

Fig.. 13(a) Longwall side abutment profiles for modelled, measured and empierical apporaches. In this example rock failure occurred the pillar forming a more extensive yield zone

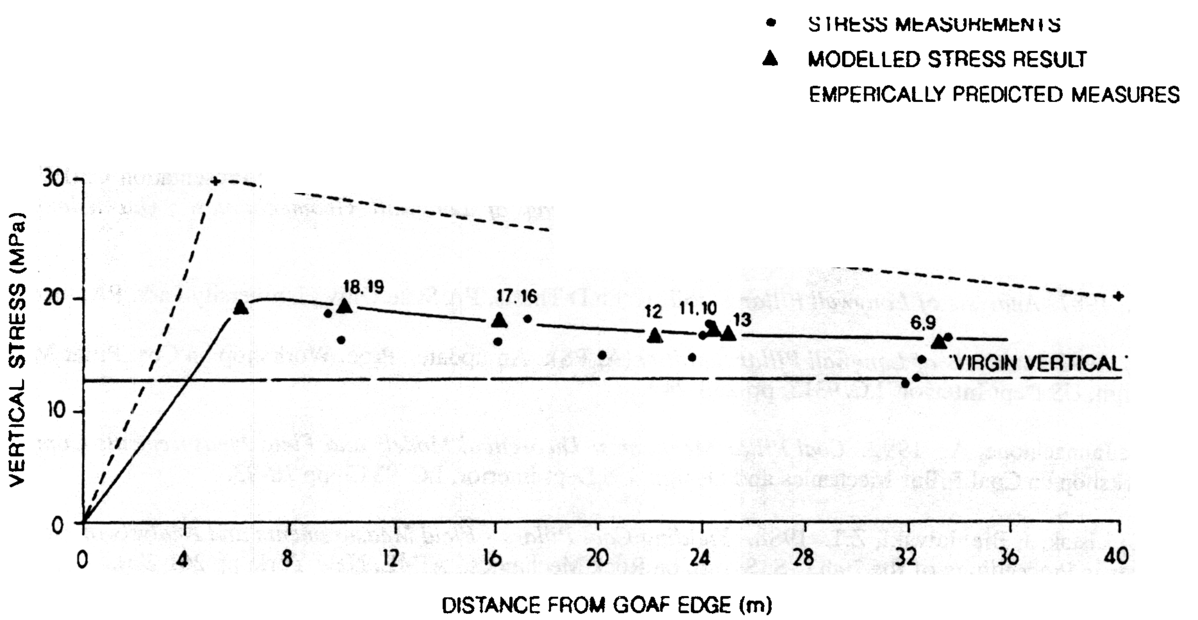

Fig. 13(b) - Longwall side abutment profiles for modelled, measured and empierical apporaches in a high stress mining area