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Geological issues relating to coal pillar design

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INTRODUCTION

The strength characteristics of coal pillars have been studied by many workers and the subject is well discussed in the literature (for example. Salamon and Monro, 1967; Wilson, 1972; Hustrulid, 1976). A range of strength relationships have been derived from four main sources:

- Laboratory strength measurements on different-sized coal block specimens;
- Empirical relationships from observations of failed and unfailed pillars;
- A theoretical fit of statistical data and observations; and
- 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. 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 within formed-up pillars.

Strata Control Technology (SCT) has 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 system geologies having a 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 the various elements is largely dependent on the confining stresses developed, as illustrated by 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 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 coal pillars were developed by Wilson (1972) and with the growing availability of measured 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

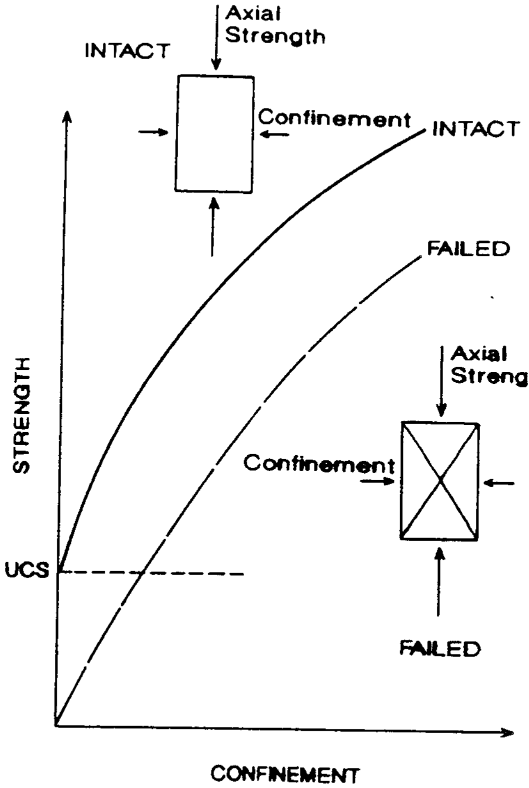


Figure 1 Effect of confining stress on compressive strengths of intact and fractured rocks (note that 'failed' should read 'fractured').

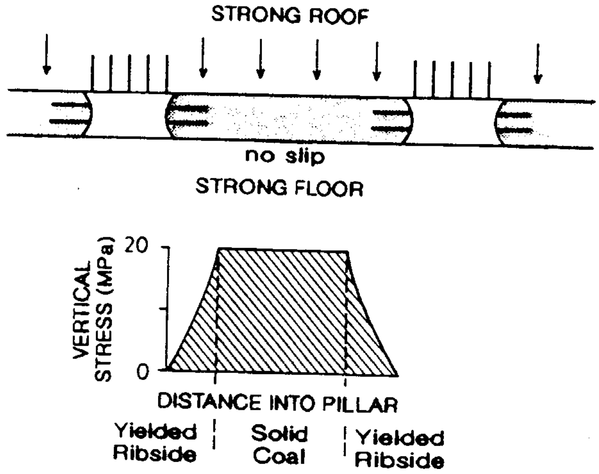


Figure 2 Rapid buildup of vertical stress bearing capacity within a well-confined coal pillar. Note that horizontal rib dowels provide extra confinement, additional to that generated by high coal / rock friction.

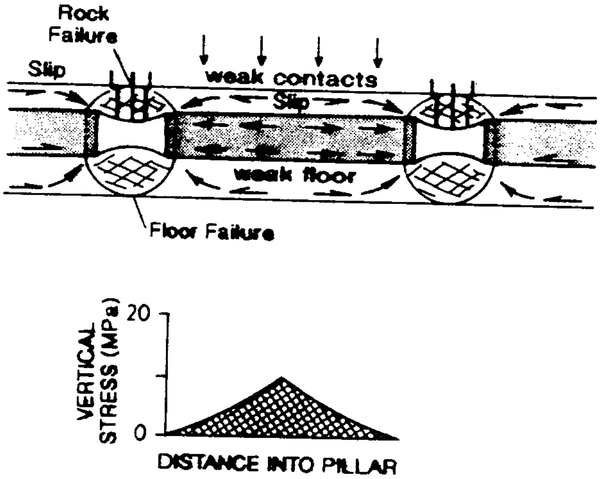


Figure 3 Low bearing capacity of coal pillar with weak (low shear strength) coal / rock interfaces. Note that horizontal slippage also causes roadway roof and floor failure, in addition to rib spall.

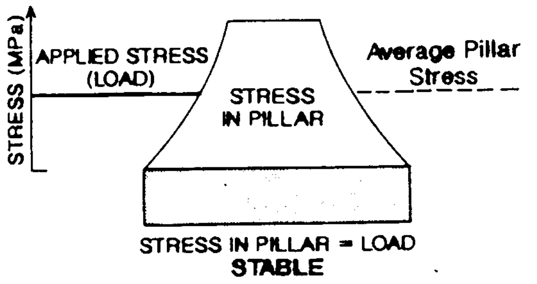
tendency for the coal and rock to move laterally and vertically into the roadway. In this situation, the horizontal stress acting across the pillar will form the confining stress within that pillar. If this lateral displacement is resisted by sufficient friction, cohesion and shear stiffness of the immediate 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. On the other hand, 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 drivage.

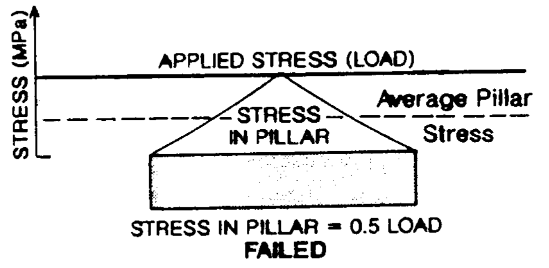
Pillar loading by abutment stresses

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 are predominantly vertical in orientation, but can generate additional horizontal (confining) stresses 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 strongly 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 (i.e., slippery) 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 failed due its inability to sustain the imposed vertical abutment stresses.



a) Strong System.



b) Weak System.

Figure 4 Pillar bearing capacities for strong and weak geologies. 'Geology' in this context means the immediate roof + coal pillar + immediate floor strata system. In this example the strong system is stable, but the weak system has failed.

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 (or 'thrown') onto nearby pillars.

One of the problems faced is that under certain stress conditions, the pillar can exhibit no failure of the coal or rock and display potentially high loading capabilities. However, at increased stress levels, certain rocks or structures in the system fail and allow lateral movement, which then reduces the confinement and subsequently the strength of the pillar. A similar situation arises if the roof or floor geology change along a panel. This could allow failure of certain rock types in one area and not in another, despite constant stress conditions.

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

- Lateral slip occurring totally unresisted, so that pillar strength is limited to its unconfined value; 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 in Figure 5. It is assumed that the rock mass

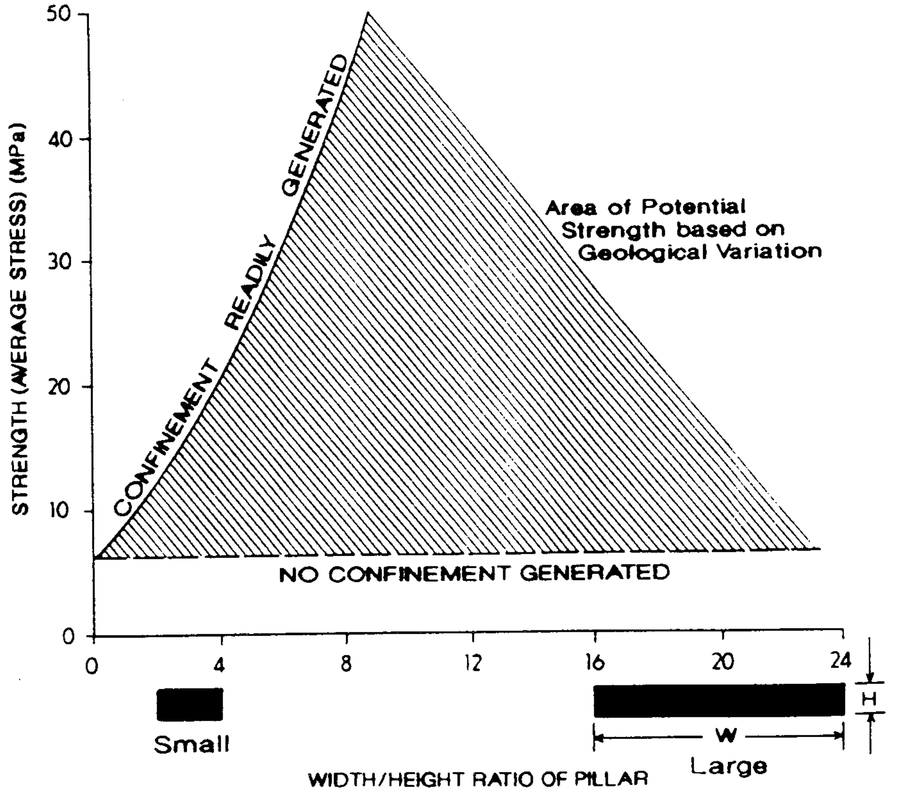


Figure 5 Range of potential pillar strengths relative to width-to-height (W / H) ratios and degree of lateral confinement.

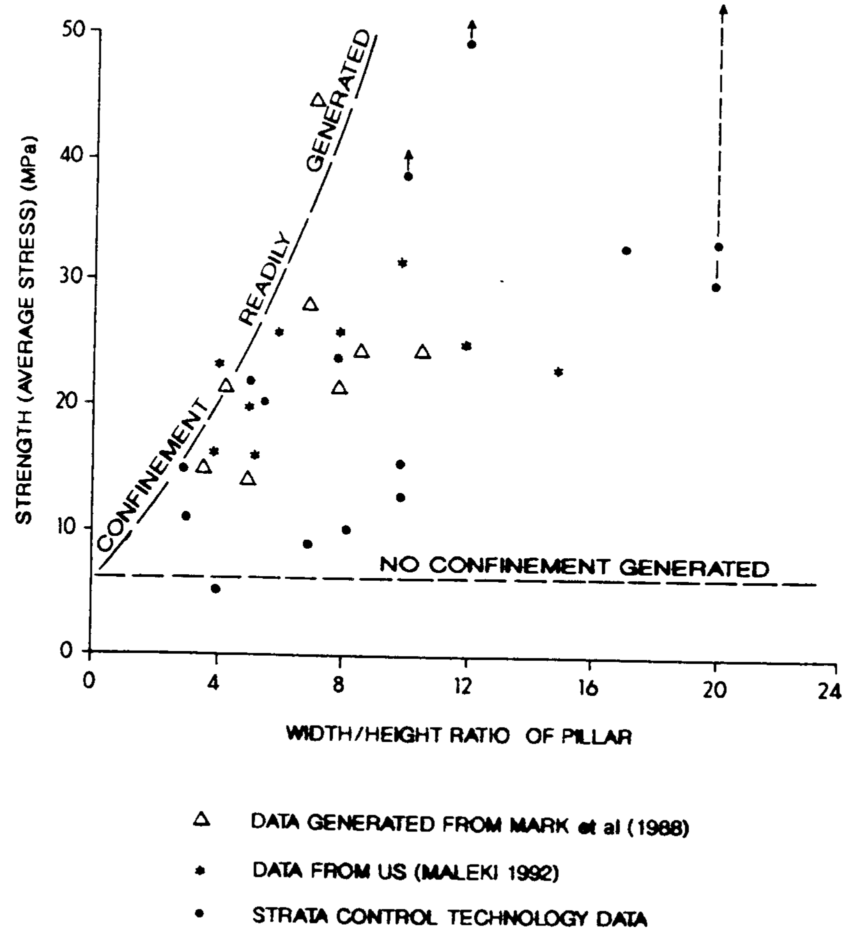


Figure 6 Measured pillar strengths in relation to W/H. This is the field data on which Figures 5 and 7 are based.

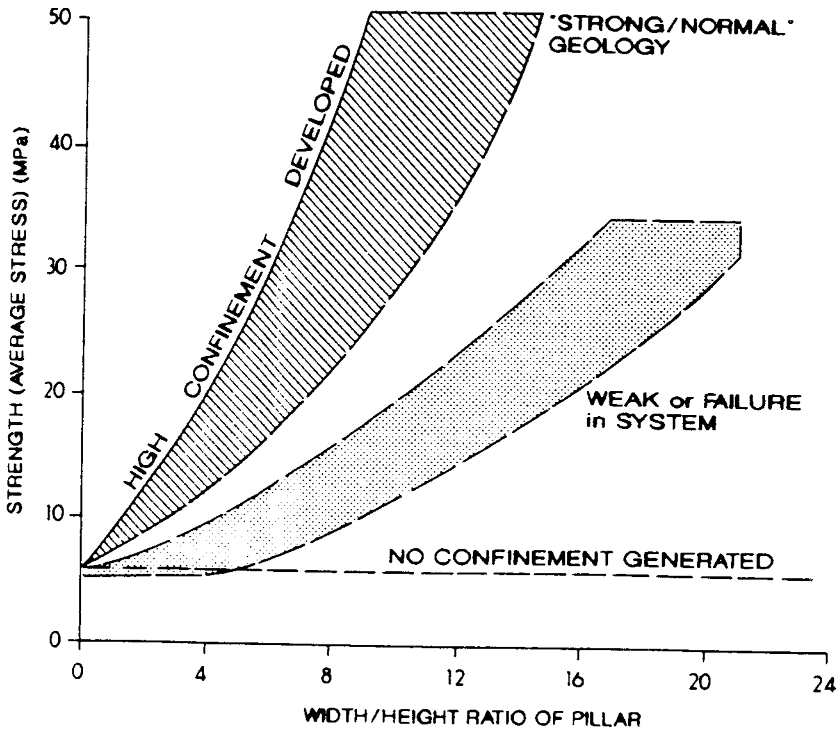


Figure 7 Generalised grouping of data points from Figure 6., indicating strong to normal weak geologies

or field strength of the coal is 6.5 MPa, or about one-quarter of the average UCS of intact NSW coal in 50 mm diameter core specimens, 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 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:

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

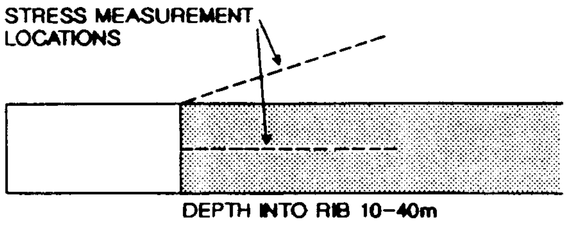
It should be noted that these two groupings are arbitrary and possibly due to a limitation of data. With more data points the grouping may become less obvious.

MEETHODS USED TO ASSESS STRENGTH CHARACTERISTICS

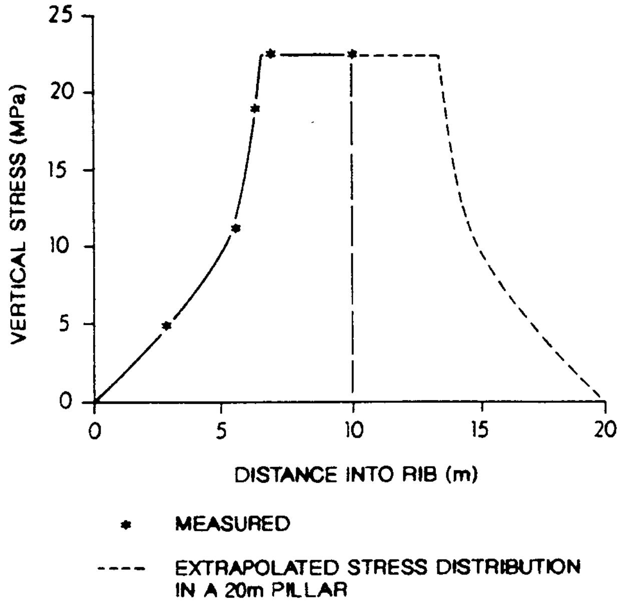
It should now be apparent that pillar design for long-term strength must take into account the geology of the immediate roof/coal pillar/immediate floor system, its failure geometry, its material strengths and the mining-induced stress changes. Methods to take such variables into account on a site-specific basis are limited, but exclude empirical and formula-based approaches. Back analysis of existing data is useful, but is often limited by the number of pillars having a suitable range of loading, and by the pillar geometries available.

The main approaches to assess the potential strength of a coal/rock sequence are are by field measurements of the stresses actually carried by pillars, and by computer simulations validated against field measurements. There are two approaches to field stress measurements:

- Monitoring stress and strain distributions above or within pillars during mining, using stress cells and rib extensometers. These measurements provide the vertical stress (load) distribution and the extent of failure into the pillar for various loads imposed during mining. Typically chain pillars are monitored, since these are heavily loaded.
- Measurement of the stress across a pillar or into a ribside, to determine the stress increase geometry. This technique utilises measurements to determine the vertical stress increase from the rib toward the pillar centre. The information is used to calculate the potential load distribution in different sized pillars and their ultimate strength under the geological conditions present. The general layout of measurements and the distribution measured is presented in Figure 8.



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



b) Stress Distribution in Pillar from Measurements.

Figure 8 Measurement of vertical stresses within and above a coal pillar, and stress profile through the pillar.

Computer simulation routines, together with detailed rock testing programs, can now be confidently applied to defining the potential strength characteristics of various strata systems. Field stress measurements have been used to confirm these results, or to assess the in-situ properties of certain units unable to be tested by normal laboratory methods.

EFFECT OF GEOLOGY

The impact of coal strength and width/height ratio on pillar strength is presented in Figure 9. This diagram shows the upper and lower bound average strengths from Figures 6 and 7, plus pillar strengths based on empirical formulae. It is clear that a wide range of pillar strengths are possible, and that these are not only related to coal rock mass strength and width/height ratio. Geological factors have a major impact on the strength achievable under the various pillar geometries.

Unfortunately, there is no simple formula which we can apply to various geological environments or mine geometries to get a satisfactory result. However some broad generalisations can be made:

- 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. Weak, clay-rich and sheared contacts adjacent to the mining section can reduce pillar strength.
- Soft strata in the immediate roof and floor, which fail under the mining-induced stresses, will weaken pillars.
- Cleat and other vertical defects may weaken smaller-sized pillars, but are unlikely to reduce the effective strength of larger pillars if adequate rib reinforcement is used.
- Tectonic deformation of coal in disturbed geological environments will reduce pillar strength, though the extent is dependent on geometry and shear strength of the discontinuities.
- The occurrence of water in failed ground often reduces strength.

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.

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 designs.

Two obvious problems with this approach are that:

- Estimates of pillar size can vary greatly, depending of the geological environment assumed.
- The pillar size versus strength data set used (Figure 6) is limited, and the groupings may be arbitrary rather than real.

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 measurements and computer simulation.

Design based on measurement requires that pillars be available for monitoring. It is most useful to measure the vertical stress rise into the pillar under a high

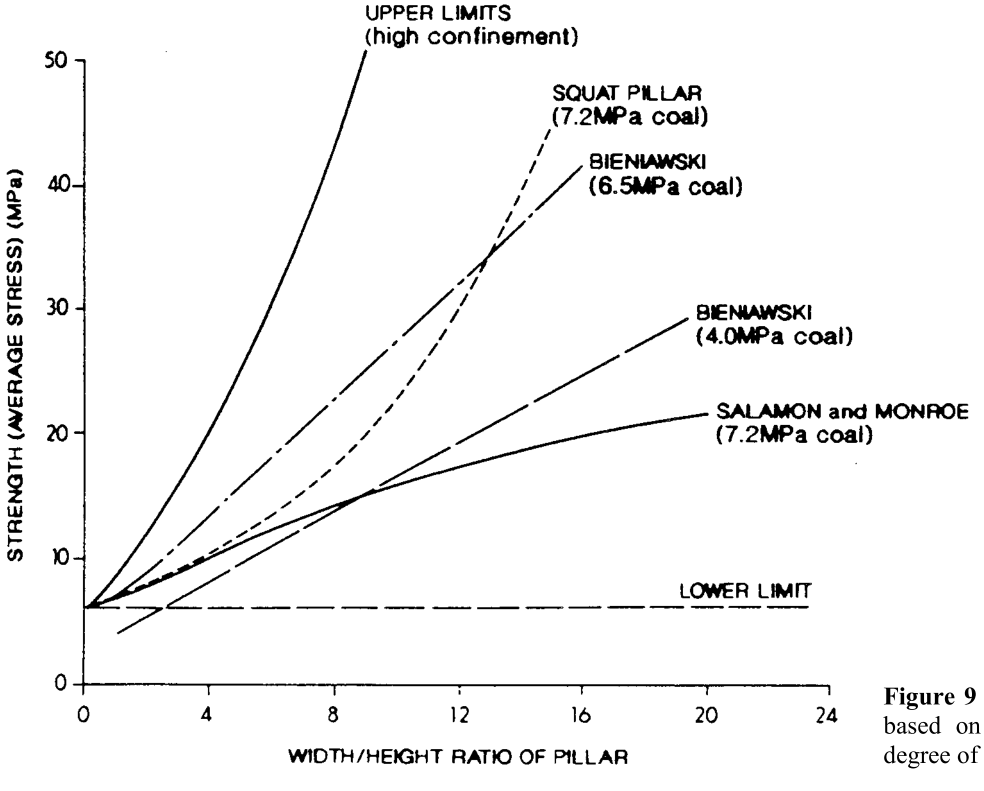


Figure 9 Range of pillar strengths, based on various formulae and on degree of confinement.

loading condition, or for the expected 'working loads' to include higher loading. The stress measurement profiles are used to determine the potential load distributions in pillars of varying dimensions, andhence to develop a pillar strength relationship suitable for that geological site.

Computer modeling methods have been developed to simulate the behaviour of the strata sections under various stress fields and mining geometries. Where possible, 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. Where computer modeling is used in association with validation measurements, the limitations noted in the measurement method are largely overcome.

One major benefit of computer modeling 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 many mining situations, the pillar geometry is influenced more by optimising roadway conditions and controlling ground movements than by the nominal pillar strength. Yield pillars and chain pillars are obvious examples of this application. Similarly, models also assess the geometry of other pillars and virgin coal areas in determining the impact of a particular load within a pillar, and the ability of the overburden to span over a yielded pillar and safely redistribute the excess stress to adjacent ground.

Computer simulation methods are used by SCT for the design of key layouts which require an assessment of geological variations, pillar size and stress field changes to optimise the mining operation. This approach also provides an expected roadway or pillar response, which can be monitored to determine if the ground is behaving as expected.

CONCLUSIONS

There are many factors which affect the strength of a coal pillar, some of which have been briefly discussed in this paper. There are a number of points to be made when considering a pillar size:

- The impact of geological factors, stress magnitude and rock failure mode on the load-carrying ability of mine pillars;
- Pillar strength formulae can only be used in a general sense. They are more relevant to large areas of standing pillars, as previously utilised in shallow bord and pillar operations, than to longwall operations.
- For pillar design, the effects of geological and geotechnical parameters together with the overall mining layout need to be addressed. In many cases, ground conditions and stress variations determine pillar size, not its nominal strength.
- Field measurements and computer simulations do address many of the design issues, if undertaken in a rigorous and validated manner.

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