A Review of the Mechanics of Pillar Behaviour

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ABSTRACT: In recent years, the drive to reduce the impacts of surface subsidence has led to mine layout designs that rely for their effectiveness on the long-term stability of pillar systems. This paper reviews the mechanics of coal strength behaviour inferred from laboratory testing of coal specimens as a context to better understand the appropriateness of different pillar design strategies.

Laboratory testing of coal specimens to very high confining pressures (163 MPa) illustrates the independence of the two fundamental components of coal strength: cohesive strength and frictional strength. Testing of numerous coal samples from the same coal seam and coal samples from different coal seams illustrate the variability of cohesive strength. The significant influence of frictional strength when confining pressure is available is also apparent. These two fundamental components of coal strength combine to influence the range of pillar behaviours observed in practice. This paper explores the characteristics of these two components and their implications for the application of various pillar design approaches.

INTRODUCTION

In recent years, the drive to reduce the impacts of surface subsidence has led to mine layout designs in New South Wales and Queensland that rely for their effectiveness on the long-term stability of pillar systems. The University of New South Wales (UNSW) pillar design methodology has become a benchmark for assessing long-term stability of pillars in Australia. The method is being applied in a wide range of geological settings and for a broad range of pillar geometries. Galvin, *et al.* (1999) warn that the UNSW methodology approach is empirical and only suitable for the conditions in which the methodology was developed; a warning that tends to be ignored.

The UNSW approach and most other empirical approaches do not specifically consider the changing characteristics of coal strength or the influence of roof and floor strata on the ability of pillars to develop confinement. This paper describes how two independent components of coal strength combine to give the strength characteristics of coal pillars observed in practice and the implications for pillar design.

The results presented in this paper draw upon a significant body of work that was completed in the 1990's as part of a collaborative AMIRA project (Gale and Mills 1994) and during a study of pillar behaviour in claystone strata in the Southern Lake Macquarie area (Mills and Edwards 1997). As part of the AMIRA project, a program of testing coal, including at very high confining pressures, showed that coal strength can be characterised as comprising two components, a cohesive component and a frictional component.

The in situ cohesive strength component of Australian coals is estimated to be about 6 MPa (equivalent to the background vertical stress at overburden depths of approximately 240 m) based on observations of the onset of rib spall as overburden depth increases. Mobilisation of the in situ

frictional strength component of coal is found to be highly dependent on factors external to the coal seam such as geological conditions and the strength of strata units surrounding the coal seam.

COAL STRENGTH CHARACTERISTICS

Figure 1 illustrates the load-deformation characteristics of specimens of Pittsburgh Coal loaded over a range of confining pressures. The diagram is reproduced from Kripakov (1981) with original work by Sture (1974) and modified to include metric units.

There are four stages in the deformation history evident at each confining pressure:

- 1. a linear increase in load in the initial pre-failure stage
- 2. a peak load when the intact strength is reached
- 3. a gradual loss of strength with post-peak deformation
- 4. a steady load or residual strength that is maintained largely independent of deformation.

These four stages of strength development are typical of coal and many other types of rock.



Figure 1: Stress / Strain behaviour - Pittsburgh Coal (After Kripakov 1981)

The stress-strain (or load-deformation) characteristics of these Pittsburgh Coal specimens show that:

- when the coal fails, it loses strength, a process referred to as brittle failure
- at zero confining pressure, initial intact strength is lost when the coal is loaded beyond its peak strength and failure occurs
- both the peak strength and the residual strength after failure increase significantly with confining pressure

Figure 2 shows the relationship between intact strength and confining pressure and residual strength and confining pressure for Bulli Seam coal with both axes plotted at the same scale. The significant characteristics of these envelopes are:

- the intact and residual strength envelopes are slightly curved, but approximately parallel to each other
- both intact and residual coal strength are very sensitive to applied confining pressure increasing at a rate approximately four times the applied confining pressure
- intact strength is relatively modest by comparison with the strength able to be developed by applying confining pressure.

To investigate coal strength behaviour at high confining pressures, five specimens of Bulli coal were tested in triaxial compression at confining pressures up to 163 MPa. The results, shown in Figure 3, indicate that coal strength behaviour at high confining pressures is consistent with the strength behaviour at lower confining pressures.

- The strength of coal continues to increase with confining pressure at a similar rate for confining pressures up to at least 163 MPa (the maximum tested).
- Coal continues to deform in a brittle fashion (i.e. loses strength after failure) even at high confining pressures.
- The residual strength envelope remains parallel with the intact strength envelope indicating that the strength loss that occurs with failure is constant and independent of confining pressure.
- Stress-strain characteristics are similar at each confining pressure. In each test, there is a well-defined residual strength plateau and a similar level of post-failure deformation required to reach this plateau.

The behaviour observed for Bulli coal in this series of tests is significantly different to the behaviour reported at high confining pressures for coal (Barron and Penn 1992) and some other rock types (Hoek and Brown 1980 and Mogi 1966).

The observation that the intact and residual strength envelopes for coal remain parallel even to very high confining pressures suggests a model of coal strength behaviour involving two independent components. One component that is lost when the coal fails and a second component that is dependent only on confining pressure and is present both before and after coal failure.



MODEL OF COAL STRENGTH BEHAVIOUR

If the failure envelopes were linear, these two components would be represented by a Mohr-Coulomb type strength relationship:

 $\sigma_1 = \sigma_c + \sigma_3 \tan\beta$ $\sigma_{1r} = \sigma_3 \tan\beta$

where σ_1 is the intact strength, σ_{1r} is the residual strength, σ_c is a measure of the internal cohesion within the coal fabric, σ_3 is the confining pressure, and tan β a scalar of the confining pressure representing the internal frictional forces generated by the confining pressure, whether the coal is broken or unbroken.

When the confining pressure is zero, the internal frictional forces are zero and the unconfined strength of the coal is then equal to σ_{C} .







Although the failure envelopes determined for coal are slightly curved, the concept of the strength relationship based on two components is nevertheless still valid.

This two component model of coal strength behaviour is helpful for understanding the behaviour of coal pillars in the field, the relationships between the behaviour of small and large pillars, and the potential for geological settings to significantly influence coal pillar behaviour.

For convenience, the cohesive component of strength is referred to as cohesive strength and the frictional component of strength is referred to as frictional strength. The characteristics of these two components are described below.

Characteristics of Cohesive Strength

Cohesive strength can be envisaged as being associated with the natural bonds that hold the intact coal fabric together. Cohesive strength is the strength that exists when a sample of coal is unconfined. The sample has shape and holds together as an intact material that has strength. When this sample is overloaded though, the sample loses its original form and becomes a collection of smaller disconnected pieces. In effect, the cohesive strength has gone.

The cohesive component of coal strength is recognised to be:

- associated with the intactness of the coal
- lost when the coal becomes overloaded and fails
- effectively independent of confining pressure
- variable depending on the nature of the coal and factors such as jointing
- a function of test specimen size
- significant to pillar behaviour at low confining pressures
- suitable to be characterised using statistical methods.

The results of laboratory tests shown in Figures 1-3 indicate that cohesive strength is available only until the coal reaches its peak strength. Once it has been overloaded, the cohesive component of strength is lost and cannot be recovered.

The parallel intact and residual strength envelopes shown in Figures 2 and 3 confirm that cohesive strength is independent of confining pressure. Cohesive strength can be thought of as a separate component of material strength that is independent of confining pressure.

Characteristics of Frictional Strength

Frictional strength in coal can be envisaged as being a function of confining pressure and the frictional properties of coal. Frictional strength is effectively zero at zero confining pressure but increases with confining pressure at a rate approximately four times the confining pressure.

As described in this section, the frictional component of coal strength is recognised to be:

- independent of cohesive strength
- unaffected by failure or loss of cohesive strength i.e. the same before and after failure because the frictional properties of coal do not change with failure
- insensitive to factors such as deformation, specimen size and coal seam
- significant for larger coal pillar behaviour.

The parallel intact and residual strength envelopes shown in Figures 2 and 3 indicate that frictional strength does not change when cohesive strength is lost i.e. intact frictional strength is effectively the same as residual frictional strength and frictional strength and cohesive strength are independent of each other.

The load deformation plots shown in Figures 1 and 3 indicate a plateau in the residual strength at large deformations indicating that the frictional strength is largely independent of deformation. Frictional strength is present before the coal fails, after it has failed and continues to be present even after large amounts of subsequent deformation. The material has not changed and so the frictional strength has not changed.

Laboratory testing of different coal types, presented in the following section, indicates that the frictional strength of coal varies only slightly between coal seams and this variation is much less than the variation in cohesive strength.

There is limited data available to confirm the relationship between frictional strength and specimen size. Further work is required to confirm the absence of a size effect. The nature of frictional strength suggests there is unlikely to be any size effect so as a first approximation no size effect is assumed.

VARIABILITY OF COAL STRENGTH PROPERTIES

The variability in coal seam strength properties are investigated in this section. Comparison of the strength behaviour of different coal seams indicates that most of the coal strength variability between and within seams comes from the cohesive component. The frictional component varies somewhat between seams but is much more consistent especially within any given coal seam or region and much more dependent on the geological setting in which coal pillars are located.

Specimen Size

The size of coal and rock specimens are widely recognised to have a significant effect on unconfined strength. Small laboratory sized specimens tend to be stronger than larger field sized specimens. There are two commonly held explanations for this phenomenon:

- Jointing and other weaknesses reflected in large samples tend to be absent in smaller laboratory sized samples, especially samples selected for testing, because of sampling bias.
- Larger specimens store greater amounts of energy when loaded and this energy promotes the propagation of the unstable microcracks leading to failure at lower loading levels.

Both these factors play a role in the coal strength observed in the field being significantly lower than coal strengths measured on laboratory sized specimens. Hustrulid (1976) summarises empirical techniques that have been used to infer the field strength of coal specimens from laboratory size specimens. In general, he concludes that these relationships can be well represented by a relationship of the form:

$\sigma_{\rm C}$ = k / $\sqrt{\rm D}$	for D < 1 m
σ_{c} = k	for $D > 1 m$

where σ_c is the field strength, k is a constant for each coal that relates to its unconfined laboratory strength and D is the height of an equivalent cubic specimen. The 1m specimen size represents a critical size above which strength is not thought to be reduced any further.

The natural variability of cohesive strength is expected given the association of cohesive strength with the natural cement binding the coal fabric together. Imperfections in the coal structure from one sample to the next inevitably lead to variations in cohesive strength.

Laboratory testing of different coals indicates that cohesive strength varies between and within coal seams. Variations in cleat spacing, the proportion of brighter coal fractions and the natural processes of coalification have potential to lead to variations in the cohesive strength of coal.

Strength Property Variation for Different Coal Seams

The confined strength properties of coals from multiple sites were tested as part of the AMIRA Project (Gale and Mills 1994). The results are shown in Figure 4, together with a selection of coal strength data available from the USA and UK. To allow ready comparison between groups, the lower bound of the intact strength envelope developed for Bulli Seam coal is shown on each of the plots of intact strength and the residual strength for Bulli Seam coal is shown on each of the plots of residual strength.

The strength data presented in Figure 4 is derived primarily from multi-stage triaxial compression tests. The axial strength of the cylindrical test specimens is plotted on the vertical axis. The confining pressure is plotted on the horizontal axis. Unconfined tests on coal show a high degree of variability. Triaxial compression testing shows less variability and is considered a better estimate of cohesive strength. The variability in cohesive strength observed from triaxial testing is similar to the variability in cohesive strength of in situ coal inferred from the failure of small pillars.

The variability of the intact strength is an indication of the variability of the cohesive strength of the coal samples tested. The plots of residual strength provide an indication of the frictional strength of the various coal samples tested.

In Figure 4, the coal strength envelopes from different sites have been grouped together by region and in groups that show similar behaviour.

Bulli Seam coal and Wongawilli Seam coal from the Southern Coalfield, Katoomba Seam coal from the Western Coalfield, and Kupakupa Seam coal from Huntly West Mine, New Zealand, show confined strength properties that are similar (Figure 4a). These coals have generally lower intact confined strength than coals from other regions. The residual strength is less variable than the intact strength.

Coals from the Newcastle Coalfield - Greta, Great Northern, Wallarah - and from Ulan at the northern end of the Western Coalfield show intact confined strength properties that are significantly stronger than Bulli coal (Figure 4b). Greta Seam coal is the strongest coal from this region. The others group into a narrower band that is stronger than Bulli Seam coal, and towards the bottom end of the Greta Seam coal strength envelope.

The residual strength of all the coals in this group are stronger than the residual strength of Bulli Seam coal. The spread of residual strengths is slightly greater than the Bulli group, but much less than the spread of the intact strengths. The residual strength of Greta Seam coal is within the residual strength envelope of the other coals, despite Greta Seam coal having significantly higher intact strength.



Figure 4: Strenth properties of various coal types

Coals from Central Queensland – Castor Seam, German Creek Seam, Harrow Creek Seam - have confined intact strength properties that are greater than Bulli Seam coal but less than the cohesive strength of coal from the Newcastle region. Their frictional strengths residual strength shows a similar relationship to the residual strengths of coals from the other regions.

The strength properties of selected coals from elsewhere in the world are shown in Figure 4d. Coal from Pittsburgh and from the United Kingdom show intact and residual strength properties that are stronger and increase more quickly with confining pressure than the residual strength of Bulli Seam coal. Coal from the Barnsley Hard Seam appears to be an exception which, although significantly stronger than Bulli Seam coal in its intact state, has similar residual strength properties.

Unconfined Strength Variability from a Single Seam

Unconfined laboratory tests provide a direct measure of the cohesive strength of coal. Laboratory measurements indicate that unconfined strength of coal is highly variable, not only between different coal types but also between different specimens of the same coal. As an example, Figure 5 shows a summary of 58 laboratory measurements of the unconfined strength of coal samples from the Wongawilli Seam in New South Wales. The strengths measured range from 3 MPa to 22 MPa.

This variability is thought to be at least partly associated with the high proportion of bright bands present in Wongawilli Seam coal in the lower part of the seam and the duller coal with a higher mudstone fraction in the upper parts of the seam. With such large variability, it is difficult to be confident from laboratory testing of the unconfined field strength that would be available for pillar design purposes. Some of this variability may be a result of the variation of sample location within the coal seam. The upper part of the Wongawilli Seam has a higher proportion of dull coal and a higher ash content. The cohesive strength from this section of the seam is typically higher.



Figure 5: Variation in Wongawilli Seam coal UCS

Variability of Cohesive Strength Under Confinement

The variability in cohesive strength is evident in the triaxial strength results presented in Figure 2 and 4 for a range of coal seams. The variability in cohesive strength evident in these tests is much less than the variability shown in Figure 5 for unconfined tests in the Wongawilli Seam.

The cohesive strength indicated by triaxial testing varies from approximately 10MPa to approximately 40 MPa. The variability of \pm 15MPa is consistent with a variability of 60% of the average unconfined strength of 25 MPa. This observation indicates that the cohesive strength of coal varies approximately \pm 60% of the average unconfined strength.

Strength Variability in the Field

Wagner (1974) describes a full scale field test to determine the strength of a small pillar. However, field measurement of the variability of cohesive strength in full scale pillars is difficult and expensive. An indication of coal strength variability can be obtained by back analysis of coal pillar stability in areas of small pillars. Salamon and Munro (1967) back analysed 98 stable and 27 collapsed pillar geometries in South Africa. They concluded that to account for strength variability of small pillars, it is necessary to have a factor of safety of greater than 1.6.

A factor of safety of 1.6 represents an anticipated strength variability in small pillars of $\pm 60\%$. This variability range is consistent with the variability in unconfined coal strength shown in Figure 2 based on the results of triaxial compression tests. The variability in coal strength indicated by the unconfined tests presented in Figure 5 suggests that the variability in laboratory estimates of cohesive strength may be higher than the variability observed in the field.

The variability of the frictional strength properties of coal in the field is difficult to determine with confidence but any natural variation in the properties of coal is considered likely to be small compared to the variability associated with different geological strata units within the coal pillar system more generally. The properties of low strength bedding planes for instance have a significant influence on the strength of the coal pillar systems because they influence the ability of the pillar system to develop confinement. The variability of the pillar strength component associated with friction is much more likely to be a function of changes in geology and strength of the surrounding host strata than a function of any variability of the frictional strength of the coal itself.

PILLAR STRENGTH BEHAVIOUR

In this section, the behaviour of pillars of different sizes in different geological settings is considered in the context of the two coal strength characteristics identified from laboratory testing.

Small Width to Height Ratio Pillars

Small pillars with a width to height ratio of less than about three are recognised to have a geometry that prevents the development of any significant confinement. Pillar strength for these small pillars is controlled largely by the cohesive strength of the coal and the characteristics of this cohesive strength. In practice, the in situ cohesive strength of coal is observed from the onset of rib spall at increasing overburden depth to be approximately 6 MPa for most Australian coals.

Cohesive strength is recognised to be lost relatively suddenly once coal is overloaded. Small width to height ratio pillars that depend on the cohesive strength of coal are therefore prone to sudden loss of strength if they become overloaded.

Cohesive strength is recognised to be variable. The strength of small width to height ratio pillars is therefore also variable. This variation is managed in pillar design using a so called "factor of safety" (or its equivalence as a probability). The intent of this approach is to have enough margin on the low side of the best estimate of coal strength that any variability in cohesive strength is not enough to cause small pillars to become overloaded.

The concept of providing enough margin is particularly important in the design of small pillars because loss of cohesive strength can occur suddenly. In a large panel of similarly sized pillars, there is potential for the failure of one pillar to cause other adjacent pillars to become overloaded. The instability of one pillar can then lead to the collapse of an entire panel with implications for safety underground and on the surface. The hazards include sudden loss of working room underground, windblast and gas expulsion and sudden changes of the ground level on the surface.

A larger factor of safety is applied when the consequences of a collapse or the timeframe over which a collapse would be intolerable are greater. A factor of safety of 1.6 is typically applied for short term stability and 2.1 for longer term stability.

The acceptability or otherwise of factors of safety against these types of events is ultimately a matter of judgement. Consideration in choosing an appropriate factor of safety or probability of failure should take account of the confidence with which the loading characteristics of the site are known, the coal strength variability is understood, and the consequences of any collapse at some time in the future. The factor of safety used in a generalised empirical formula developed primarily from back analysis of small pillars and by implication cohesive coal strength is not necessarily appropriate for a larger pillar system that relies for its strength on frictional strength of the coal and the confinement able to be generated by the surrounding strata.

Large Width to Height Ratio Pillars

When large width to height ratio pillars become heavily loaded, the coal on the fringes of the pillar is unconfined and becomes overloaded, in the same way that coal in small pillars fails when they become overloaded. When this unconfined coal is overloaded, its cohesive strength is lost causing the coal to fail and rib spall to occur. In a large pillar however, the failure of the rib coal does not mean the pillar system becomes overloaded and loses strength. The failed rib coal instead provides confinement to the pillar edge coal and this confinement increases the strength of the remaining coal in the core of the pillar.

Failure of the rib coal continues deeper into the pillar until the confinement provided by already failed coal, and any other support, generates enough frictional strength in the remaining core of the pillar to support the load on the pillar. A stable equilibrium is then established and pillar edge coal failure stops progressing further into the rib.

External factors such as the presence of a longwall goaf next to a chain pillar or backfill within a roadway significantly increase the rate of confinement provided to the coal rib.

The frictional strength of the coal increases at a rate of about four times the confinement, so a small amount of external confinement leads to a significant increase in frictional strength and hence pillar strength. For coal ribs to be able to generate confinement within the core of a pillar and mobilise the frictional strength of the coal, the strata surrounding the pillar needs to be able to generate an equal and opposite force. This equal and opposite force is typically transferred as shear on bedding and other horizontal planes above and below the pillar.

When the host rock is strong and the roof and floor contacts with the coal pillar are strong, the surrounding strata is typically able to resist the outward shear forces generated in the coal allowing high levels of confinement to be generated within the pillar to mobilise large frictional forces creating very strong pillars. For large pillars in strong roof and floor strata, the confinement provided to the fringe of the pillar by failed coal means the pillar continues to gain strength as it deforms. For these pillars, the upper limit of pillar strength is much greater than the load able to be distributed onto the pillar by the overlying strata.

Figure 6 illustrates the load deformation characteristics of small, medium and large pillars. In large width to height ratio pillars (greater than about 8) and strong roof and floor conditions, pillar strength





increases as the pillar is loaded. There is no single point at which the pillar reaches a maximum load i.e. reached a load that could be regarded as the strength of the pillar. Coal on the edges fail (as illustrated by the red shading) but the confinement that this failed coal provides to the central core is more than compensated for by the increased frictional strength of intact coal in the confined core (yellow shading).

Pillar behaviour is significantly different when the pillars are small, the host rock is not strong enough to allow confinement to be developed, or there are low-strength units between the host rock and the coal or within the host strata above or below the coal Frictional strength of the coal is not able to be fully developed and the strength of the coal pillar is reliant instead on the coal's cohesive strength. In these circumstances, a large pillar may have small pillar strength characteristics.

A particularly significant effect of low strength roof and floor strata is that once the cohesive strength of the coal is overcome, a large pillar in low strength roof and floor strata can be prone to closing up in much the same way as a small pillar does. This may occur suddenly, but more typically large pillars converge slowly in a process extending over some days to weeks and referred to as a pillar creep.

The failure of pillars is commonly observed on the surface as a subsidence event. For small pillars, a subsidence event is clear evidence of pillar strength being reached and through back calculation, this strength can be estimated. The observation of such a subsidence event above large pillars can also be taken as evidence of their failure. However, for such a failure to occur in large pillars, there must be conditions of low strength roof and floor conditions present.

In strong roof and floor conditions, large pillars would continue to gain strength and could not have failed. Subsidence events above large pillars should therefore be used with caution for estimating the strength of large pillars in strong roof and floor conditions.

IMPLICATIONS FOR PILLAR DESIGN

The recognition that coal strength has two components, a cohesive component and a frictional component each with different characteristics, provides a basis to better understand the strengths and limitations of various pillar design approaches.

Small pillars and large pillars in low strength roof and floor conditions rely primarily on the cohesive component of coal strength. The natural variability of cohesive strength and the ease with which it can be determined from back calculation of pillar failures means that statistical analysis of empirical experience is relatively well suited to providing estimates of pillar strength and pillar stability. The concept of a factor of safety to provide a buffer against natural variability in cohesive strength has a credible basis. The factor of safety can be varied to suit the probability of failure considered acceptable for the circumstances.

The concept of a factor of safety to represent statistical variability is less useful for larger pillars that rely for their strength on the frictional component of coal strength. This frictional strength component does not vary to the same degree as cohesive strength and the development of frictional strength depends on external factors such as geological setting and the strength of the surrounding rock strata. These factors are not random variables that can be characterised by

statistics. They are certainly not governed by the same statistical processes that are suited to characterising the natural variability of the cohesive component of coal strength.

A different range of criteria become relevant to the design of large pillars. For instance, a chain pillar designed to protect the gateroads of a longwall panel may be technically stable from a pillar strength perspective, but this stability is irrelevant if the adjacent gateroads are not serviceable because of poor roadway conditions induced by excessive loads on the chain pillar. The estimation of maximum design loading for large pillars is typically not governed by considerations of pillar strength or collapse potential but rather by the serviceability of adjacent roadways.

The design of main heading pillars is another example where pillar strength considerations are not the primary concern. Main heading pillars in strong roof and floor conditions can be designed to be individually stable on development or even under the abutment loading from adjacent longwall panels. However, there have been several examples in the Southern Coalfield where low strength horizons in the roof and floor strata that were not able to be detected in advance became mobilised and restricted the frictional strength able to be developed in the core of the pillar despite the roof and floor strata being otherwise strong.

The presence of these low strength horizons and the stress level at which they became mobilised is difficult to detect in advance of mining and even after convergence starts it is not easy to determine where the primary low strength shear horizons are located. Once low strength bedding plane horizons do become mobilised, it is usually too late to prevent a large scale creep event. Such an event has potential to compromise the serviceability of the main headings and the mine more generally as it has done on several occasions.

One approach to managing the possibility of low strength roof and floor conditions becoming mobilised is to arrange the main heading pillars so that convergence is limited should a creep develop. Four or five headings separated by a much larger central pillar provides a layout that is significantly more robust for convergence control than a large panel of similarly sized pillars.

Characterisation of the strata conditions and the use of numerical modelling and field monitoring provides a pathway for estimating the behaviour of pillars with large width to height ratios that is more credible than reliance on statistical analysis of empirical experience. Statistical experience is readily available for small pillars because small pillars tend to collapse when they become overloaded. It is more difficult to get reliable estimates of strength for large pillars when failure is not defined by a reduction in strength but rather by other criteria such as the serviceability of adjacent roadways. Cassie and Mills (1992) describe the application of field measurements as the basis for a numerical modelling assessment of the behaviour of large pillars, in this case in low strength roof and floor conditions.

Intermediate size pillars with width to height ratios in the range four to six rely for their strength on both the cohesive strength of coal and the frictional strength of coal. For these pillars there is a transition in behaviour. The design of pillars in this range requires an understanding of both the cohesive strength characteristics of coal strength and the geological setting. A blend of statistical methods based on empirical experience and numerical modelling supported by field monitoring experience has been found to be useful for the design of pillars in this range.

Statistical methods based on empirical experience should be used with caution for pillars in the range four to six. Back analysis of the pillar behaviours observed in the Southern Lake Macquarie

area (Mills and Edwards 1997) indicated that pillars in low strength roof and floor conditions are not as strong as similar sized pillars in strong roof and floor conditions. The warning of Galvin *et al* (1999) is particularly relevant for pillars in this size range.

Considerations of coal strength behaviour discussed in this paper indicate that:

- Coal can be characterised as having a cohesive strength component and a frictional strength component, each independent of the other.
- Pillar design methodologies should be applied with recognition of the characteristics of these two components, the external factors that affect them and their influence, in combination, on pillar behaviour.
- Small pillars that rely for their strength on the cohesive component of coal strength can reasonably be characterised using statistical methods, factors of safety and probability of failure.
- The factor of safety chosen should recognise the confidence with which the pillar loading and strength characteristics of the coal pillars are known rather than reliance solely on a generalised probability of failure criteria. If the loading can only be estimated approximately and the coal pillar strength is not known, the factor of safety chosen should be much higher than if the loading and strength are well constrained by field measurement.
- Large pillars that rely for their strength on generating confinement to their core should be designed with consideration for the geological setting in which they are located. A factor of safety is not meaningful for a large pillar in strong roof and floor conditions because pillar strength continues to develop as the pillar becomes more heavily loaded
- The pillar loading of interest for design relates to the serviceability of adjacent roadways even if the pillar itself has not technically failed. Numerical modelling provides a way to characterise this behaviour.
- Understanding of the geological setting, the ability of pillars develop confinement in this geological setting and strategies to limit panel convergence are much more relevant to the design of large pillars than factors of safety or probabilities of failure.

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