ROCK MASS CLASSIFICATION AS AN AID TO ESTIMATING THE STRENGTH OF COAL PILLARS

R. Trueman,1 I.G.T. Thir2 & D.B. Tyler2

ABSTRACT

Coal mass strength properties must be estimated to obtain realistic estimates of coal pillar strength. The limitations of existing techniques for approximating these properties are discussed. The coal mass is anisotropic. The Hoek and Brown approach to rock mass property estimation is modified to allow for this. This approach requires the Rock Mass Rating (RMR) for the strata. In the normal case where bedding is sub-horizontal, these major planes of weakness have little effect on the strength of pillars. As a result of this, the RMR must be measured parallel to bedding. This means that a significantly higher rating than that usually obtained for coal is observed.

The use of mass strength property estimates in extant empirical relationships is outlined. At high width to height ratios, an acceleration in the rate of increase in pillar strength with increasing width to height ratio has been observed. The empirical relationship developed by Salamon (the so-called squat pillar formula) takes account of this. This relationship was found to have significant limitations with respect to its universal application. Modifications are made to Bieniawski’s empirical formula to extend its use to large width to height ratio (squat) pillars. This new squat pillar formula has none of the disadvantages associated with Salamon’s relationship.

Strain softening was incorporated into non-linear finite difference numerical modelling to estimate pillar strengths. The technique outlined above is used to obtain peak coal mass properties. Modelled pillar strength was found to be sensitive to both peak and post peak mass strength properties. Post peak properties were found to be difficult to obtain and required some back analysis. Modelling results were used to estimate both the strength of squat pillars and parameters for use in a new squat pillar empirical strength relationship.

1. Introduction

Coal is a relatively weak rock. Mining at depth requires large pillars for adequate ground control. This is particularly the case for longwall barrier and chain pillars, as these carry large abutment stresses. The generation of pillar support elements in an orebody results in either temporary or, more likely, permanent sterilisation of fully proven and developed mining reserves. If the most economic design is to be made, then coal committed to pillar support must be minimised whilst still assuring stability. A realistic estimate of pillar strength is required to achieve this. Knowledge of mass strength properties is a prerequisite to realistic estimates of pillar strength; thus, this knowledge is fundamental to economic design.

To date there is no universally applicable practical method of obtaining these mass properties. This is despite the fact that coal is one of the few rocks where significant numbers of large scale in-situ tests have been made. The Hoek and Brown approach is increasingly utilised to determine isotropic rock mass properties. This is attractive since mass properties can be determined from a knowledge of the RMR. This parameter can be relatively easy and economical to measure without resorting to large scale in-situ tests. However, the technique cannot be directly used for coal, because of its anisotropic nature.

Observational data indicates that squat pillars are stronger than predicted by most empirical strength relationships. A squat pillar relationship has been derived. However, the size effect component of that formula is specific to average South African coal, which means that it cannot be universally applied. A squat pillar formula that can take into account the variation in strength properties of coal is required.

Modifications are made to the Hoek and Brown approach to make the technique applicable to anisotropic rock masses, such as coal. A more universally applicable squat pillar formula is developed.
Thus, more accurate assessment of the strength of coal pillars is possible. This will lead to a safe and economic coal pillar design.

2. Empirical Approach to Pillar Design

When pillar strength is estimated, both size and shape effects must be considered. The size effect is related to the presence of discontinuities within the coal mass. Therefore, mass strength is less than the strength of intact laboratory sized samples. The shape effect describes the increase in the strength of pillars as the width (W) to height (H) ratio increases. This is due to an increase in confining stress within the pillar.

2.1 Shape Effect

The constants used in the empirical formulae above are given in Table 1.

It can also be observed in laboratory size samples. A number of empirical formulae have been developed to estimate pillar strength ($S_p$), all of which have been applied to coal. Generally, they give similar results where the coal mass strength properties are the same. Three basic expressions predominate:

\[ S_p = S_i (A + B \frac{W}{H}) \]  
\[ S_p = S_i W^\alpha H^\beta \]  
\[ S_p = K W^\beta H^\gamma \]

These expressions describe the shape effect. $K$ and $S_i$ describe the size effect.

It must be noted that the shape and size effect cannot be totally separated in equation (3). For the same width to height ratio, pillar strength will decrease with increasing width. Effectively, rock mass size will never be achieved. Most authors accept that rock masses will reach a critical size (volume) at which no further decrease in rock mass strength will occur. In-situ measurements on large samples have confirmed this for coal. This means that formulae based upon equation (3) cannot be used where coal mass strength properties are significantly different, without modifications to both the size and shape components. This effectively rules out the universal application of these formulae.

2.2 Size Effect

The empirical formulae require estimates of $S_i$ and $K$. The term $S_i$ is the strength of a cube of coal ($W/H = 1$) at mass size. Mass size for coal is generally accepted to be in the region of 0.7 to 3.4 m$^2$. $K$ is considered to be the strength of a 1 m$^3$ sample in magnitude.

2.2.1 Coal Mass Properties

Salamon and Munro performed a statistical analysis of stable and failed pillars. They determined a value for $K$ of 7.2 MPa. This was equated for all South African Coal. With additional data, Madden re-assessed the value of $K$ to be 5.24 MPa. In addition to this, they also included a change in the shape factor constants, because size and shape are not separated in the form of formula used by these authors.

Table 1 Shape effect constants for empirical formulae in common use

<table>
<thead>
<tr>
<th>Formula</th>
<th>A</th>
<th>B</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obert &amp; Davall/Wang</td>
<td>0.778</td>
<td>0.222</td>
<td></td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Bresawaki</td>
<td>0.64</td>
<td>0.36</td>
<td></td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>Holland</td>
<td></td>
<td></td>
<td>0.3</td>
<td>-0.5</td>
<td>(2)</td>
</tr>
<tr>
<td>Salamon &amp; Munro</td>
<td></td>
<td></td>
<td>0.46</td>
<td>-0.66</td>
<td>(3)</td>
</tr>
<tr>
<td>Madden</td>
<td></td>
<td></td>
<td>0.63</td>
<td>-0.78</td>
<td>(3)</td>
</tr>
</tbody>
</table>

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authors. These values only apply to South African coal, and cannot be used elsewhere. They represent average results, and could give misleading estimates of strength even in that country. Additionally the shape effect constants would need to be re-evaluated for use elsewhere.

Coal is one of the few rocks for which significant amounts of large scale in-situ strength testing has been carried out. Fussler and Feltz concluded the following expression from a number of in-situ and laboratory tests on coal:

\[ \sigma_c = \left( \frac{\sqrt{D}}{\sqrt{0.914}} \right) \]

Here \( \sigma_c \) is the uniaxial compressive strength of a laboratory sized cube of coal with an edge dimension (in metres) of D. The 0.914 relates to the edge dimension (in metres 1 yd) of a full scale cube of coal. Equation (4) only takes into account variations in the intact strength of coal. It also assumes that mass size for all coal is 0.764 m³ (1 yd³). Marks, in a review of this empirical relationship, noted that the effect of discontinuities were ignored. Even in the USA, where the formula was developed, misleading results have been reported when using this expression.

It is clear that no universally applicable method to estimate the strength of a cube of coal at mass size has been developed yet. This is the case even though a significant number of expensive in-situ large scale tests have been carried out worldwide on this type of rock.

3. Hoek and Brown approach to rock mass properties.

Hoek and Brown related the Rock Mass Rating (RMR) geomechanics classification to rock mass peak strength properties \( m \) and \( s \) for isotropic rock masses. For undisturbed rock masses the following empirical relationships have been presented:

\[ s = c^{0.016-0.140} \]
\[ m/m_c = c^{0.203-0.140} \]

Here \( m \) is the rock constant \( m \) for intact rock determined from laboratory triaxial tests. The uniaxial compressive strength (UCS) of the rock mass (\( \sigma_{UCS} \)) can be calculated from the following relationship derived from the Hoek and Brown failure criterion:

\[ \sigma_{UCS} = \sigma_c \left( \frac{m}{m_c} \right)^{0.5} \]

Here \( \sigma_c \) is the uniaxial compressive strength of a laboratory sized intact sample (preferably 50 mm diameter). However equation (7) is not the strength of a cube at rock mass size. The strength of cubes is approximately 15% greater than the UCS because of the shape effect. The strength of a cube at rock mass size (\( \sigma_c \)) can thus be estimated from the following equation:

\[ S_c = 1.15 \left( \frac{\sqrt{c}}{\sqrt{0.914}} \right) \]

The use of equation (8) to estimate the strength of a rock mass size cube for input into empirical pillar strength formulae is attractive. The necessary parameters can be measured relatively easily and economically. In addition, the influence of both the intact rock and jointing are included in the determination of the RMR. This means that both intact rock and joint rock strength influence the strength of the rock mass. However this approach can only be used where the rock mass is isotropic. This is not the case for coal. The implications of this are discussed in the following section.

4. Modifications to Hoek and Brown approach for coal

Coal is of sedimentary origin and exhibits marked rock mass anisotropy. If the parameters for spacing, RQD and condition of joints are measured vertically and horizontally, significantly different results will be noted. When beds are flat, as is normally the case, the RMR measured in the horizontal direction is significantly greater than that in the vertical direction. This is because bedding and joints parallel to bedding are measured in the horizontal direction. In the horizontal direction bedding is usually not observed. Bedding and joints parallel to bedding are both weaker and more persistent than the other joints.

The majority of rocks will exhibit some degree of rock mass anisotropy, but not normally to the extent of sedimentary strata. Where rocks are not of sedimentary origin this anisotropy can be ignored as its influence on rock mass behaviour is usually insignificant. In sedimentary strata, the rock mass anisotropy will tend to dominate the behaviour of the rock mass and must be considered. The joint orientation adjustment incorporated into the RMR classification system does not account for this.

Coal pillars are usually loaded normal (or sub normal) to the bedding planes. In terms of mass strength, this is the most favourable direction. Slip on
these planes of weakness cannot occur. Due to their position in the rock mass, no other mechanisms of failure of these discontinuities are likely. This is not the case with the other steeper joint orientations, where slip or buckling failure will be possible. Normally, this means that horizontal bedding and parallel joints will not significantly influence the strength of coal pillars.

If rock mass rating is to be used to infer rock mass strength properties of coal pillars, then the RMR measured in the horizontal direction must be used; the joint condition rating should exclude bedding, the RQD should be obtained from horizontal drill core, and joint spacing should be for two rather than three joints. A case study is used to outline this approach.

4.1 Case Study

Large scale tests were carried out by Bieniawski in South Africa. The strength of a rock mass size cube of coal ($S_0$) was measured at 4.5 MPa. Using raw data from the same coal seam, the following rock mass and intact properties were determined:

<table>
<thead>
<tr>
<th>RMR</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR parallel to bedding (RMR$_p$): 61</td>
<td></td>
</tr>
<tr>
<td>UCS of intact samples: 30.8 MPa</td>
<td></td>
</tr>
<tr>
<td>m, (not used in empirical formula): 8</td>
<td></td>
</tr>
</tbody>
</table>

The RMR value assumes three joint sets, whilst the RMR$_p$ assumes two sets. The above properties are used in equation (8) to estimate the strength of a mass size cube. When using the RMR normal to bedding (RMR)$_n$ the estimate of the rock mass cube strength is 2 MPa. When the RMR is measured parallel to bedding (RMR$_p$), effectively ignoring bedding, a value of 4.1 MPa is estimated. It is clear that a much better estimate of the mass strength of pillars will be made if the dominating effect of bedding is removed from the determination of the RMR. This can be achieved by determining the parameters for the RMR from underground mapping and core in a direction parallel to bedding. Of course this will only be the case where bedding is normal (or sub normal) to the applied load.

Following the recommendations of Hoek and Brown, the RMR values outlined above do not take into consideration orientation adjustments. The orientation adjustments outlined by Bieniawski are for tunnel surfaces only and should not be used for rock mass properties. For excavation surfaces, Trueman et al note that these orientation adjustments must be made on either the RMR, or the RMR in sedimentary strata, depending upon the orientation of the surface.

The approach for estimating $S_0$ outlined above should be applicable to all sedimentary strata loaded normal to the bedding. Trueman et al note a similar effect in a hard rock limestone. The strength of a limestone pillar was predicted using the modified Hoek and Brown approach for estimating the mass cube strength (using RMR$_p$). The predicted strength matched in-situ observations and measurements, further suggesting the applicability of the technique shown above.

5. Squat Pillars

A number of authors have noted that pillars with a high width to height ratio (squat pillars) have a strength in excess of that predicted by the majority of empirical formula recently used. Salamon has attempted to quantify this effect by modifying the Salamon and Muir head empirical strength formula:

Equation (9)

$$S_0 = \frac{R^b}{y^n - \frac{R}{y^n} - 1}$$

Figure 1: Pillar strength inferred according to limestone squat pillar formula and data obtained using the Salamon & Muir head solution.
Where \( R \) is the critical width to height ratio
(assumed to be 4)
\( R_c \) is the actual width to height ratio
\( \varepsilon \) is the rate of strength increase
(conservatively assumed to be 2.5 for South African coal)
\( a \) is 0.0667
\( b \) is 0.9593

The effect of this modification is shown by Fig 1. The marked increase in pillar strength over the Salamon and Munro formula for width to height ratios in excess of about 4 is apparent.

As with equation (3), there is a volume component contained within equation (9). The assumption again is that mass size is never reached in coal pillars. This means that the procedures outlined in section 4 cannot be used to estimate size effect components in equation (9). The formula is not appropriate to all coal because of the variations in mass strength properties. Changes to \( K \) will also necessitate changes to other constants, as is the case with formulae based on equation (3). This means that the universal application of this squat pillar formula is not possible.

Modifications have been made to the Bieniawski empirical pillar strength formula to include a squat pillar component. The original formula is maintained up to a critical width to height ratio, after which an exponential relationship is used. Therefore the following formulae are appropriate to all width to height ratios:

\[
S_p = S_0 (0.64 + 0.36W/H) \text{ for } W/H < C \tag{10}
\]

\[
S_p = A_c \exp(B(X-C)^N) \text{ for } W/H \geq C \tag{11}
\]

\[
A_c = S_0 (0.64 + 0.36C) \tag{17}
\]

Where \( X \) is the \( W/H \) for which the strength is to be determined, \( C \) is the critical width to height ratio, \( B \) and \( N \) are constants. The critical width to height ratio \( (C) \) occurs when the rate of strength increase becomes non-linear. The constants \( B \) and \( N \) control the rate of strength increase after this point.

Numerical modelling of the case study outlined in section 4 was carried out (see section 5). This gave estimates of the parameters to be used in the new squat pillar formula. The size and shape effect is totally separated in equation (10). This is unlikely to be fully the case in the squat pillar extension.

However, the parameters should not be significantly influenced by changes in mass properties (size effect) and should be typical for most coal, which is not the case for the Salamon squat pillar formula. Further studies are planned in order to investigate the influence of mass properties on the new pillar strength relationship. The following values were suggested from the modelling work:

\[
B = 0.296
\]

\[
C = 8.0
\]

\[
N = 0.744
\]

6. Numerical Modelling

The FLAC finite difference program was used to investigate the strength of coal pillars. Model results were sensitive to peak strength properties. Hence strain softening was simulated. Thus the program required the input of both peak and post-peak properties. When strain softening is used, modelled results can exhibit sensitivity to element size. In order to minimise this, a fine grid was established for all pillars. Pillars with a height of 2 m were simulated. A typical mesh is shown for a 12 m wide pillar (Fig 2).
The elastic properties of the coal were assumed to be those outlined by Bieniawski,2 which are $E = 3.6$ GPa and $v = 0.2$. The properties of the roof and floor rock were $E = 12.6$ GPa and $v = 0.28$. The roof and floor were kept elastic for all models.

6.1 Peak mass strength properties

The coal properties outlined in the case study in section 4 were used. A non-linear analysis was performed. RMR was used in equations (5) and (6) to obtain the peak rock mass strength constants $m$ and $s$ for the study; these were determined to be 0.013 for $s$ and 1.99 for $m$. The Mohr-Coulomb peak strength properties $c$ and $\phi$ are used for a non-linear analysis in FLAC. The Mohr-Coulomb failure envelope is linear, whilst the Hoek and Brown relationship is non-linear. It is generally accepted that the Hoek and Brown failure envelope is more realistic. Hoek has developed an approach that relates $m$ and $s$ to $c$ and $\phi$. In this approach instantaneous values of the Mohr-Coulomb parameters, $c$, and $\phi$, are determined. These parameters are confining stress dependent; for the same rock, $c$ will increase and $\phi$ decrease with increasing major principal stress. Thus Mohr-Coulomb parameters can be determined from the Hoek and Brown parameters.

6.2 Post-peak mass strength properties

The post-peak mass properties are much more difficult to predict. The residual strength envelope must be known. Simplifications had to be accepted in the estimation of this.

The residual strength envelope was considered to be linear; this only requires two points to be fixed on the failure envelope. The uniaxial compressive strength of the broken strata ($c_b$) was determined from the following relationship:

$$c_b = (V_d) (\sigma_u)$$

(13)

Here $V_d$ is the value of $s$ for disturbed rock masses. Hoek and Brown derived the following relationship for this parameter:

$$V_d = e^{[5000 + 1600\log(e)]}$$

(14)

It was considered that broken strata would be isotropic. Thus RMR was substituted in equation (14), to give a $c_b$ of 0.4 MPa for the coal under investigation.

Mogi made a study of the failure characteristics of a number of intact rocks. He concluded that the brittle-ductile transition for most rocks occurs at an average principal stress ratio $\sigma_1/\sigma_3 = 3.4$. It is accepted that the transition will vary and may not be the same for intact rock and rock masses. With the absence of further information, this value was used for this study. The brittle-ductile transition occurred at $\sigma_1$ (strength) = 37.9 MPa and $\sigma_3$ = 11 MPa using this relationship (Fig 3). The estimates of the peak and residual strength envelopes on a $t$ vs $c_b$ graph (used in FLAC) is shown in Fig 4.
6.3 Post-peak deformation response

Pillars fail progressively from the outside towards the pillar core. During the failure process, parts of the pillar rock will be elastic, whilst other parts will be post-peak. This means that the post-peak deformation response will influence the overall pillar strength. At present there is no adequate data concerning this response that can be used for design. The work of Ozbay and Healy leads to the inference that the post peak stiffness is proportional to the confining stress. Back analysis was used to approximate the post peak deformation response.

It was assumed that the empirical strength formulae shown in Table 1 would give reasonable estimates of pillar strength in the range \(1 \leq W/H \leq 4\). The peak and residual strength properties shown above were used. The stress-strain response up to the brittle-ductile transition assumed in the model is shown in Fig. 5. The plastic strain at which residual strength was reached \(\epsilon_p\) was varied as a function of the confining stress. For the case study the best fit between modelled and empirically derived pillar strengths was found to be:

\[
\epsilon_p = 0.001 \sigma_y \tag{15}
\]

Equation (15) was used to estimate the post-peak deformation response for greater width to height ratios, up to the brittle-ductile transition. Past this point the coal mass post peak response was assumed to be perfectly plastic. Strain hardening will undoubtedly occur at high levels of confining stress; this was not taken into consideration due to a lack of experimental data.

![Diagram](image)

Figure 5: The stress-strain response up to the brittle-ductile transition.

6.4 Modelling procedure

The parameters \(a\), \(c\) and \(e\) are confining stress dependent. Thus an elastic model was run in the first instance in order that these properties could be determined. These properties varied throughout the pillar with the level of confining stress. The model was then run non-linearly with strain softening. In all cases the roof and floor rock remained elastic.

Failure was considered to have occurred if the imposed elastic stress could not be carried by the pillar. If the peak stress was significantly different to the elastic stress, then the model was re-run elastically to obtain new peak and post peak properties. This was required as the initial stress imposed on the pillar influenced the level of confining stress within elements. Thus a manual iterative technique was employed to derive model pillar strengths. Obviously this is both time consuming and tedious to do; thus modifications to do this automatically, without manual intervention, are being considered.

6.5 Model results

The modelled pillar strengths in the range \(1 \leq W/H \leq 20\) are outlined in Fig 6. These are compared to the empirical relationships of Bieniawski and Obert and Duvall, assuming \(\sigma_y = 4.5\) MPa, which is an actual measurement for this particular seam. As the data is for South African coal, the Salamon squat pillar formula is also presented for comparison. The model results can be approximated to a straight line relationship up to a width to height ratio of 8. This compares favourably with the results from both the Bieniawski and Salamon squat pillar formulae. However the modelled rate of increase in strength then accelerates; in comparison the Bieniawski formula remains linear. The model strength results are higher than those predicted by the Salamon squat pillar formula. However this difference is insignificant. Salamon’s formula uses a conservative rate of increase in strength due to uncertainties in determination of some of the parameters used.

The pillar strengths predicted for width to height ratios in excess of 4, using the numerical approach above, were as expected. The estimation of parameters for input into the new squat pillar formula from modelling results appears to be valid. To date there is insufficient in-situ data to completely validate this approach. However, the Salamon squat pillar formula, which has other limitations on its use, cannot be completely validated either.
7 Conclusions

Coal pillar rock mass peak strength parameters can be derived from the Hook and Brown approach, providing that the RMR values used are measured parallel to bedding. These parameters can be used to estimate the size effect for coal, for use in some existing empirical pillar strength formulae. This is also true for pillars in all sedimentary strata, where bedding is sub-horizontal.

The estimates of coal mass properties can also be used in numerical models to investigate pillar strength. However, more data is required on the post-peak deformation response of coal. Simplications had to be accepted for some model input parameters. The influence of these simplifications on model results requires further study.

An empirical squat pillar formula has been developed which should be more universally applicable than the present relationship. Some parameters for this new formula have been developed from numerical modelling studies. Further work is required to refine these parameters and test their general applicability.

References

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