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ROOF SUPPORT AND ROADWAY SERVICEABILITY ASSESSMENT USING BEAM-COLUMN PRINCIPLES

Terry Medhurst¹ and Peter De Roma

ABSTRACT: This paper outlines the development of a roof support assessment method that takes account of differing roof conditions, effect of support type and stiffness that can be used in the strata management (TARPS) process. The proposed model is based on beam-column principles and incorporates bending, horizontal loading and shear. Estimates of roof convergence for various heights of softening (or surcharge loading) above a roadway can be obtained for a given support pressure. The model relies upon inputs from the Geophysical Strata Rating (GSR), roof bolt pull-out stiffness/load, H:V stress ratio and UCS.

INTRODUCTION

Mining at increasing depths of cover, in weaker and more variable strata conditions and with greater emphasis on optimisation of mining practice is driving the need for improvements in strata characterisation, mine planning and design. From a geotechnical perspective, the use of geophysics data was traditionally limited to UCS estimates and experienced based interpretation of sonic logs for strata characterisation. In response to this, the Geophysics Strata Rating (GSR) was developed in order to capture these basic principles traditionally applied by minesite geologists and to extend it to quantitative analysis for geotechnical applications (Hatherly et al., 2016).

GSR is now routinely used in several Australian coal mines for strata characterisation. GSR results can be modelled in 2D and 3D along with other parameters derived from geophysical logs such as the clay content (Medhurst et al., 2010). The application of these strata characterisation models for hazard planning has driven demand for design applications. With the support of ACARP funding, investigations into open cut mining (ACARP C20025), longwall caving (ACARP C20032) and roadway roof support assessment (ACARP C22008) have been undertaken. An approach was developed for longwall support assessment based on support density, stress conditions and convergence limits (Medhurst et al., 2014). Preliminary investigations into the application for roof support design suggested a similar principle may apply and an analytical model was developed using beam-column principles (Medhurst, 2015). Development and testing of this approach has been underway (Medhurst et al., 2016) and this paper discusses the latest developments and summarises the results of the most recent project (ACARP C24015).

ANALYTICAL BEAM-COLUMN MODEL

Section Properties

GSR analysis provides a continuous measure through the borehole column over the full height of the strata, as shown in Figure 1. Beam stiffness and therefore roof convergence will vary according to the distribution of hard and stiff units within the strata. GSR is based on physical measurements that are related to the composition, density and elastic properties of the strata. This means that the variation in strata stiffness within the roof beam can be estimated from GSR. A basic estimate of strata modulus has been developed where

\[
E_{\text{strata}} = 1.75 \times 10^3 \left( \frac{\text{GSR}}{100} \right) \quad \text{(GPa)}
\]

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Beam analysis requires section properties such as the 2nd moment of area (I), the position of the neutral axis of the beam (y) and a measure of strata modulus (E_{strata}). Previously, the conventional approach had been chosen simply as a function of bolt length without regard to the strata. With the new approach each layer can be treated as a material of different stiffness and the theory of composite materials can be applied to obtain equivalent beam properties. The general concept is shown in Figure 2.

The position of the neutral axis over a given beam thickness can be estimated using the parallel axis theorem. Using this approach the beam is treated as being comprised of many layers of different stiffness, which is determined from the GSR analysis. The true bending behaviour of the beam is then assessed by transforming the dimensions of the beam according to the ratio of the elastic modulus of the materials. This is the standard approach for the design of composite beams in structural engineering.

Figure 1: Example of GSR analysis for a borehole
For the purposes of this study a model was developed based on beam-column principles that incorporates both bending and axial loading (Timoshenko and Gere, 1963). The beam deflection due to bending is estimated using the standard method and the influence of the horizontal load (P) is treated as a multiplier (u) on both the deflection and maximum bending moment. The general formulation for a fixed end beam is shown in Figure 3.

\[ \delta = (9/32)u^2 = \frac{5WL^4}{384EI} \left( 2 \sec u - 2u^2 \right) \]

where \( u = \frac{P}{EI} \) and \( I = \frac{t^3}{12} \)

The effect produced from the horizontal load (P) in the roof will increase the amount of roof deflection. Areas of high deformation/low confining stress are generally concentrated in the immediate roof. In this case there is a critical strata/beam thickness in which this deformation occurs that is not related to that defined by the bolt length, but more about the strata properties in the immediate roof. Previous studies conducted to estimate the stability of unsupported roadways found that depending on roof stiffness, there is a critical beam thickness at which failure occurs (CSIRO, 1996). This minimum thickness can be defined by a mechanism of snap-through at the mid-span as shown in Figure 4. This critical thickness (t) can then be used to estimate the multiplier (u) in the beam-column model. In other words, the additional roof convergence caused by horizontal stresses in the immediate roof is estimated based on a critical thickness for snap-thru of the beam rather than just conventional bending analysis.
By following through this analysis, it can be seen that roof deflections can be estimated from an estimate of vertical surcharge load \((q)\), horizontal stress/load \((P)\), GSR, and roadway width. The vertical load is simply estimated by choosing the height (or range) of softening above the roadway and the horizontal load \((P)\) by the normal \textit{in situ} stress regime and concentration factors about roadways.

**Stress Inputs**

The distribution of bending moment and therefore deflections vary depending upon the end constraints of the beam. In coal mining environments, several conditions may exist depending on stresses and/or damage in the roof beam, which can be represented by different end constraints as shown in Figure 5. A procedure has therefore been developed to calibrate beam end constraints and section properties relative to the stress and strength conditions present based on the GSR to mining induced stress ratio.

![Figure 5: Beam end constraints and bending moment distribution](image)

The influence of roadway orientation relative to the angle of the major principal stress \((\sigma_1)\) also has to be considered. The standard approach is to consider the angle of the roadway relative to angle \((\beta)\), which takes account of 2D orientation to \(\sigma_1\) using the following

\[
\sigma_R = [0.5 \times (\sigma_H + \sigma_h) - 0.5 \times (\sigma_H - \sigma_h) \times \cos(2\beta)]
\]

Where \(\sigma_H\) and \(\sigma_h\) are the major and minor stresses in the horizontal plane.

In development, 3D stress effects need to be considered to assess stress concentrations. Following a series of 3D model calibrations, the maximum stress in the roadway can be estimated using

\[
\sigma_M = SCF \times \sigma_R
\]

Where if virgin \(\sigma_H/\sigma_v \geq 2\) then \(SCF = 1.2\)

if virgin \(\sigma_H/\sigma_v \leq 1\) then \(SCF = 2\) then \(SCF = -0.8 \times (\sigma_H/\sigma_v) + 2.8\)

A general form of the beam-column formulae can then be used to take account of the differing stress conditions in the roadway.
The maximum roof deflection is given by the following equation:

\[ \delta = \frac{5WL^4}{EI} \left( \frac{2sec u - 2 - u^2}{5u^4} \right) \]

Where if \( 1 < \frac{GSR}{\sigma_M} < 4 \)

\[ X = 100e^{\frac{\left( \frac{GSR}{\sigma_M} \right)}{3}} \]

The final consideration is that for coal roof, in which correction factors need to be applied due to the difference in stresses and bending behaviour that generally exist, the following should be considered. Firstly, there is a requirement to establish conditions in which a coal roof will act as a beam. In order to maintain moment carrying capacity at the roadway corners, a minimum span to thickness ratio of 4:1 is required for a coal roof to develop an active beam. It should be noted that some judgement is required to determine that the minimum coal thickness is comprised of competent coal and roof stability is not influenced by weak planes within that horizon, such as by a series of interbedded layers of coal and thin partings or penny bands. Under these conditions, the following rules would apply:

**Coal Roof**

- Coal thickness ≥ \( \frac{1}{4} \) roadway width
- \( \sigma_h/\sigma_v = 1 \)
- SCF = 1
- GSR multiplied by 1.4 for coal component of roof beam GSR

In contrast to previous beam models used for support design, the aim here is to provide an analytical model that does not require estimates of cohesion, friction angle, tensile strength or other properties that are commonly difficult to measure or estimate. However in order to estimate roof convergence, the effect of the roof support must also be considered. Roof support has the effect of increasing roof stiffness, which is also usually not present in conventional beam based analysis. Hence an ability to estimate the combined stiffness of the roof strata and roof support is required.

**Roof beam stiffness**

In the case of a coal mine roadway, the above mentioned beam-column formulation can be used to estimate roof convergence as a function of height of softening (or surcharge loading) for a given support pressure. It is then necessary to estimate the change in stiffness of the roof beam as a function of the installed roof support. Brady and Brown (2004) provide detailed analytical solutions for rock-support interaction analysis and show that the support stiffness can be treated as two springs connected in series one being the stiffness of the roof bolt and the other the stiffness characteristics of the bolt/anchor system under pull-out load or so-called grip factor. The support stiffness is given by

\[ \frac{1}{k_s} = \frac{L_S}{N_b} \left( \frac{4L_d}{\pi d^2 E_b} + Q \right) \]

Where
- \( L = \) roadway width
- \( S = \) average bolt row spacing
- \( N_b = \) number of bolts or cables per row
- \( L_d = \) debonded length of bolt or cable
- \( d_b = \) diameter of bolt or cable
- \( E_b = \) bolt or cable modulus
- \( Q = \) load deformation constant or grip factor of bolt or cable in mm/kN
The combined stiffness of the roof beam can then be treated as the strata stiffness and the support stiffness acting in parallel, which is the summation of the two. The roof beam stiffness used for the beam-column analysis is given by

\[ E = E_{\text{strata}} + k_b \]

Mark et al (2002), provides an estimate of grip factors for fully resin grouted bolts in both Australian and U.S. coal mines. However Q values can also be obtained by short encapsulation pull-out tests or other related data. Thomas (2012) provides an outline of a series of lab-based tests on cable anchorages commonly used in Australia. Using available pull-out data estimates of load deformation factors for both bolts and cables were developed as a function of roof quality (GSR)

Load deformation factor for bolts

\[ Q = \frac{1}{6.5e^{\left(GSR/100\right)}} \]

Load deformation factor for cables

\[ Q = \frac{L_{od}}{30e^{\left(GSR/100\right)}} \]

Finally the pull-out capacity of the bolts needs to be estimated. The yield capacity of the bolt or cable itself is one measure, or another that includes some measure of the rock strength itself is also common, depending upon the length of anchorage. Farmer (1975) provides a simple expression based on the unconfined compressive strength (UCS) as follows:

\[ P_c = 0.1 \cdot UCS \cdot \pi \cdot R \cdot L_b \]

Where \( P_c \) = pull-out capacity
\( R \) = borehole radius
\( L_b \) = bond length

The UCS can be obtained from relevant test data or estimated from sonic velocity derived values as is often used at most operations. Depending upon the support installation, the lesser of the bolt yield capacity or pull-out capacity is used.

**Bedding plane shear**

Laminated and/or micaceous roof in deep or high stress zones is one of the key issues governing the selection of Trigger Action Response plans (TARPs) triggers and determining minimum installed support density in development for many Australian operations. The development of excessive shear stresses causing failure in weak strata is mostly driven by excessive roof movement due to bending in combination with horizontal stresses and/or bedding plane shear, as shown in Figure 6.

The development of steep sided shear failure surfaces often follows this initial triggering mechanism. An important indicator is therefore to establish conditions in which bedding plane shear is induced relative to the height of softening and/or imposed stresses. This requires an estimate of shear forces per metre length across the roadway. This concept is known as shear flow and is the standard approach for sizing bolts to resist shear in structures subject to bending, as shown in Figure 7.

Traditional approaches to checking for shear failure, i.e. estimating the material mass that could overcome the cohesive strength of the overlying strata generally yield high factors of safety, even in weak materials. This approach is generally too simplistic and requires a range of assumptions to
arrive at a suitable answer, unless a specific joint, fault or pre-defined surface can be used as the potential failure plane. Where such geological structure is not present, excessive yield or shearing of bolts should be checked against the maximum shear flow which occurs at the neutral axis of the beam. The beam section properties are obtained from GSR analysis. It is then possible to derive an estimate of Factor of Safety (FoS) against bedding plane shear using the shear flow calculation divided by the shear strength of the bolts.

![Figure 6: Typical failure behaviour in laminated roof](image1)

![Figure 7: Shear flow in beams](image2)

**ROOF STABILITY ASSESSMENT**

**Roof behaviour model**

The analytical beam-column model is intended to capture the main features governing the bending and shear failure of a roadway roof beam. Distinct mechanisms such as wedge failure, or localised influence around geological structure need to be treated separately for design and within the strata management framework. The formulated roof behaviour model follows engineering statics principles in which the combined effects of varying strata conditions and the installed support are integrated into one mechanistic model. A schematic view of the roof beam model is shown in Figure 8.
The analytical model can be used to estimate both load and convergence behaviour of the roof beam. Roof convergence is estimated from the vertical surcharge load (W), horizontal stress/load (P), GSR, and roadway width. The vertical load is estimated by choosing the height of softening above the roadway and the horizontal load (P) by the in situ stress regime and the appropriate stress concentration factors about the roadways.

The output from the analytical model can be plotted as a series of graphs of roof convergence versus the installed support density. By varying the support density, the relationship between roof convergence and support load can be estimated and plotted as a curve, known as a Ground Response Curve (GRC). Several curves can then be plotted for different heights of softening and/or stress conditions. Different curves can also be plotted depending on the staging of excavation or support installation, such as after widening of a longwall installation road or installing additional support after a TARP trigger. In some cases these relationships can also be used to investigate the adequacy of the TARP’s triggers themselves.

**Strata-support interaction**

A typical example of ground response analysis is shown in Figure 9. The intersection points between the installed support (straight line) and the GRC provide a measure of the estimated support demand and roof convergence for a given condition. This example shows that at 30 mm of roof convergence the primary bolt pattern reaches its maximum height of softening (2 m) and would attract a support load of about 35 t/m². Assuming cables were then installed at a 30 mm trigger level then the analysis suggests that the roof would stabilize at about 70 mm at a height of softening of 4 m.

A key aspect of this approach is that by introducing a convergence measure then serviceability limits can be used as design criteria. For example, a typical operational situation might be when cable support has been designed with a strength limit (Factor of Safety, FoS = 1.5), but roof convergence levels may be in excess of say 100mm leading to the requirement for further support defined in the TARPs. The issue here is the uncertainty between the relationship between roof load, the size of the failure zone in the roof and convergence, and whether further support is required.

The approach here attempts to address this issue in which a new measure is introduced based on the support pressure generated that includes the effect of cumulative roof convergence. In this case the use of serviceability criteria may provide a more representative assessment of support performance. Two methods can be used depending upon the support and site conditions. The general definition is described as the Serviceability Factor (SF) = ratio of nominal support capacity to the estimated support pressure for a given roof convergence, as shown in Figure 10. Note the difference in support stiffness for the 4, 6 and 8 bolts per metre support patterns. The ratio for the 8 bolt pattern is shown. In experience to date, a SF > 1.4 is generally recommended.
An alternative approach, which may be particularly useful for primary development support is the ratio of the estimated roof convergence at the maximum bolt height to the nominated trigger level. An example based on a 20 mm trigger is shown in Figure 11. This measure may be useful for example, to assess the risk of height of softening reaching the bolt height and the need to install long tendon (cable) support.

When long tendon support is installed it is relatively rare that heights of softening reach beyond the length of cables. And if such a risk does exist, close monitoring via extensometers and TARPs control are usually implemented. In weak ground conditions, the choice of cable type, pattern density, convergence triggers and grouting requirements/triggers become critical in managing both roof stability and development productivity. From this perspective, the ability to estimate load-convergence interaction between the ground and installed support becomes a useful tool. An example is shown in Figure 12. A grouted and point anchored cable pattern assuming a height of softening of 4 m and with the cables installed after 25 m of roof convergence is shown.
The analysis suggests that a 2 x 2 pattern of grouted cables combined with an 8 bolt pattern is about three times stiffer than the point anchored pattern. Previously no measures have been available to quantify this effect other than pull-out tests on cables. Monitored levels of roof convergence in roadways with grouted cables are often significantly greater than bolt head displacements from pull-out tests. This highlights that pull-out data alone is unlikely to be a suitable indicator of the interaction between strata and the support and its effect on roof convergence. The analytical beam-column model therefore provides an estimate of the effect of grouting on the stiffening of the roof beam. Further confirmation work is required in this area, but the model at least provides an ability to quantify the effect of grouting on roof convergence and its relationship to potential TARPs triggers.

Support analysis

Several examples of the use of ground response curves for stability assessment have been provided elsewhere (Medhurst, 2015). This approach is useful for assessing a particular set of conditions such as an area of different strata or where a roof support change is proposed (Medhurst et al, 2016), but can be somewhat cumbersome for design purposes. This is because the analysis is able to present many design options that require the determination of a suitable workflow, i.e. appropriate heights of softening, convergence and/or triggers need to be chosen.
In order to overcome this limitation a mathematical solution was developed to find relevant intersection points from the ground response analysis. The solution was based on a generalized logarithm for exponential-linear equations (Kalman, 2001). Design curves could then be developed between support pressure, roof convergence and height of softening for any depth, roof quality (GSR) or trigger (convergence) level.

Figure 13 shows an example of a set of design curves for a 4, 6 and 8 primary support bolt pattern (X Grade) at a depth of 300m. The plots show Factor of Safety (FoS) for bedding plane shear and Serviceability Factor (SF) versus Height of Softening (HoS) for GSR values of 30 and 50 for a roadway parallel to the major principal stress (Angle = 0). Note the change in position of the ground response curve for the different GSR values. The difference in strata conditions is also reflected in the design curves. For example at a HoS = 2 m, FoS = 1 (GSR = 30) and FoS = 1.5 (GSR = 50) for bedding plane shear for the 4 bolt pattern. Similarly, SF varies from SF ≤ 1 (GSR = 30) to SF ≥ 2 (GSR = 50) at a HoS = 2 m.

Using a minimum SF = 1.4, it can be seen that the maximum allowable height of softening in weak Roof (GSR =30) is about 1m for a 4 bolt pattern and about 1.5 m for an 8 bolt pattern. Whereas at GSR = 50, SF > 1.4 for all patterns at 2 m height under relatively low stress conditions (Angle = 0). The variation between different roof types is also apparent when examining the estimated roof convergence versus height of softening. This demonstrates the applicability of the 20mm trigger level often used in weak roof, since roof convergence is estimated at greater than 30 mm at 2 m height for GSR = 30. Conversely, roof convergence is estimated at between 15mm and 20 mm at 2 m for GSR = 50. Trigger levels of 15 mm are often used for primary support in stiff roof.

The effect of varying stress using the beam-column model is shown in Figure 14. In this case, the roadway angle has been changed from parallel (Angle = 0) to perpendicular (Angle = 90) as would be the case for a cut-through. Note again the change in the position of the ground response curve and the corresponding influence on the FoS and Serviceability Factor for different heights of softening. A GSR = 40 would represent average roof conditions in Australia and here again the design curves match typical support and operating practice.

Similar estimates can be undertaken for cable support. Figure 15 shows an example using a typical 2 x 60t cable support pattern installed at 1 m, 2 m and 4 m row spacing in weak roof, assuming installation after 20mm of roof convergence. The ground response curve at 4 m height of softening is shown. Applying a minimum FoS =1.5 for bedding plane shear and a minimum SF = 1.4 for bending, it can be seen that 2 m spacing would be suitable in the gateroads (Angle = 0) but inadequate in the cut-throughs (Angle = 90) at heights of softening greater than 6 m.

The analysis also suggests the influence of bedding plane shear on cable support is most distinct. For example, wide spaced cables (4 m) installed in the cut-throughs give a FoS = 1 at HoS = 4 m, suggesting failure under these conditions. The difference in the convergence plots is also apparent with an increase on average of about 25 mm from gateroads to cut-throughs. Note also the relative increase in roof convergence at heights of softening > 4 m. Experience shows that strata management issues often develop in roadways when heights of softening increase beyond 4 m.
Figure 13: Example of design curves for primary support with varying GSR
Figure 14: Example of design curves for primary support with varying stress
Another consideration is the timing of cable installation and its relationship to TARPs. Figure 16 shows an example in which the cables have been installed after 40 mm of roof movement and compared to the previous example of installation after 20 mm in a cut-through. Note the change in position of the ground response curve and associated change in support demand. Further inspection shows that this has no effect on FoS for bedding plane shear but a significant effect on roof bending. A significant reduction in the Serviceability Factor is shown with a commensurate increase in estimated roof convergence when the cable support is installed at 40 mm. This demonstrates the flexibility of the analysis method how it can reflect installation practice. Further examples are provided in the final research report (Medhurst, 2017) and it is intended to extend the approach to gateroad stability under longwall abutment loading conditions.

Figure 15: Example of design curves for cable support with varying stress
CONCLUSION

A method has been developed based on beam-column principles for use in coal mine roof stability assessment. It provides an ability to estimate both support load and roof convergence relative to the height of softening in the roof and therefore provides an ability to match analysis results against underground measurements and observations. The method relies upon inputs from the Geophysical Strata Rating (GSR), roof bolt pull-out stiffness/load, H:V stress ratio and UCS. And thus avoids the
requirement to estimate parameters such as cohesion and friction angle, which can be highly variable at roadway scale and therefore difficult to measure or estimate.

The method is aimed at providing a practical tool for support design and assessment, and has been tested at a number of Australian underground operations. It is based on conventional engineering statics and follows the basic mechanics of roof beam behaviour under bending and shear. Distinct mechanisms such as wedge failure, or localised stress influences around geological structure are not applicable to this method and need to be treated separately for design and within the strata management framework.

Estimates of Geophysical Strata Rating (GSR) are inherent to the formulation which include estimation of beam section properties, roof stiffness, influence of stress on beam fixity and installed support stiffness. An appropriate estimate of GSR is therefore critical to the reliability of the method. In some Australian mining operations, the presence of very thinly laminated strata or micaceous layers that degrade on exposure can result in overestimating the GSR when based on standard borehole geophysics measurements. Methods to correct the GSR for these conditions have been identified and are currently being tested. It is also intended to extend the approach to gateroad stability under longwall abutment loading conditions.

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