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INVESTIGATION INTO A NEW APPROACH FOR ROADWAY ROOF SUPPORT DESIGN THAT INCLUDES CONVERGENCE DATA

Terry Medhurst

ABSTRACT: The results of a recent investigation into roadway roof support design using the Geophysics Strata Rating (GSR) are presented. A key aim of the investigation was to identify an ability to relate changes in roof conditions and support performance to our primary roof stability indicator, roof convergence. By developing these links, an ability to differentiate between operating factors such as support type and installation practice; and traditional geotechnical factors can be established. This paper outlines progress on the development of a convergence based roof support design method that is complementary to the current TARPS based strata management process. Some examples are provided.

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 roof support design. Whilst existing methods have served the industry well, an ability to identify specific factors affecting roof support performance is required. Through recent ACARP projects we have developed the Geophysical Strata Rating (GSR) to be an objective measure of rock quality. GSR results can be modelled in 2D and 3D along with other parameters derived from geophysical logs such as the clay content. By developing such models at various mines it has become evident that this information may improve the link between roof behaviour and strata characteristics. Roof displacement monitoring provides the main source of information in most strata control management systems. GSR is also fundamentally related to the stiffness of the rock mass and thus can be directly linked to displacement based estimates of failure processes.

The investigation was directed towards developing an analytical framework to quantify/establish stress related impacts and/or strain/displacement correlations with support data. An analytical method was proposed as it can be more easily adopted as a site based tool. The proposed model is based on beam-column principles and incorporates bending, horizontal loading and shear. Using this model, 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 Geophysics Strata Rating (GSR), roof bolt pull-out stiffness/load, H:V stress ratio and UCS. An ACARP funded study (Project C22008) was undertaken to assess the viability of the concept at a few sites to determine if a more comprehensive design methodology can be developed. The full results of the study are provided in the project report (Medhurst, 2014).

ANALYSIS METHODOLOGY

Strata characterisation

The Geophysics Strata Rating (GSR) is based on physical measurements that are related to the composition, density and elastic properties of the strata. This means that parameters such as strata modulus can be estimated from the GSR borehole analysis. The details of the GSR will not be repeated here but can be found in previous project studies (Hatherly *et al.*, 2008; Medhurst *et al.,* 2009). Table 1 shows an indicative range of rock quality as it relates to GSR.

GSR provides a continuous measure through the borehole column over the full height of the strata. This allows a measure of the change and distribution of rock mass quality over the supported interval. Such features are amenable to assessing changes in bending stiffness and section properties for beam analysis. 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 (Estrata). Previously, these have been chosen simply as a function of bolt length without regard to the strata. Various methods are available to

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estimate in-situ modulus from rock mass quality estimates such as GSI, Q and RMR. Through previous work on development of GSR comparison with Q and other classification systems have been undertaken. Using these results, the current Bowen Basin data and in-house experience extraction a basic estimate of strata modulus has been developed where:

Table 1: GSR applied to Australian coal measures

GSR Range		Description
0	15	Very poor
15	30	Poor
30	45	Fair
45	60	Good
60	80	Very good
80	100	Extremely good

$$E_{strata} = 1.75e^{3 \cdot GSR/100} \quad \text{(GPa)} \qquad (1)$$

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 accomplished by transforming the dimensions of the beam parallel 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.

Beam formulation

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 analytical procedure is based upon classification of four different types of roof conditions as shown in Table 2. The beam models require estimates of strata modulus and beam section properties which are obtained from analysis of GSR logs over the relevant bolting interval.

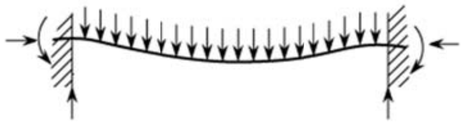
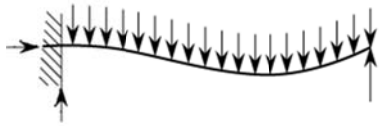
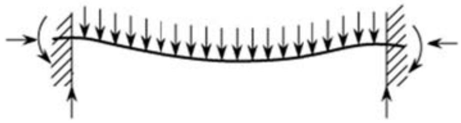
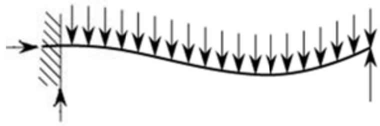
The beam models also include the influence of horizontal loading on deflection. The beam deflection due to bending is estimated using the standard method and the influence of the horizontal load (P) is treated as a multiplier (u) on both the deflection and maximum bending moment. The formulation for Type 1 (fixed end beam) conditions is shown in Figure 1.

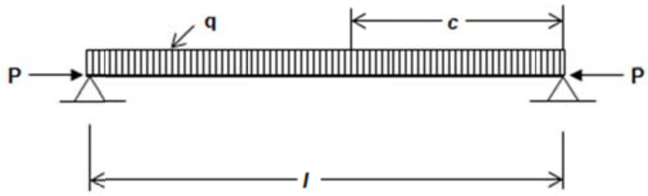
The multiplying effect produced from the horizontal load is a function of beam thickness via the 2nd moment of area (I). Areas of high deformation/low confining stress occur at the boundary of the excavation, and are concentrated in the immediate roof. In this case there is a critical strata/beam thickness 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 in highwall mining found that for each set of roof conditions, there is a critical beam thickness at which failure occurs. This minimum thickness can be defined by a mechanism of snap-through at the mid-span (CSIRO, 1996) as shown in Figure 2.

If the span (roadway width) is known and an estimate of modulus is available from GSR then the critical thickness (t) for snap-though can be obtained. This critical thickness can then be used to estimate the multiplier (u) in the beam models. In other words, roof convergence caused by horizontal stresses is estimated based on a critical thickness for snap-thru of the beam rather than just conventional bending analysis.

In the case where stresses might be very high or the roof is very weak, then plastic beam analysis might apply, i.e. Type 3 analysis in Table 2. This is generally applied to beams of ductile material that do not ordinarily fracture under static loading but fail through excessive deflection. In this case the plastic section modulus, Zp, is used rather than the elastic section modulus, Z = I/y. For this condition, the plastic section modulus is used (Roark and Young, 1975).

Table 2: Summary of beam analysis methodology

Case	Beam Type
1. Fixed end beam Moderate to strong roof conditions Minimal stress influences No jointing effects	
2. Propped cantilever Moderate to strong roof conditions Potential stress influences (guttering) and/or influenced by sub-vertical jointing effects	
3. Plastic fixed end beam Weak roof conditions characterised by potential yielding and inelastic roof behaviour	
4. Plastic propped cantilever Weak roof conditions characterised by excessive yielding, guttering and bedding plane shear	



Deflections

when load is in centre of beam

$$\delta = (y)_{x=l/2} = \frac{ql^4}{384EI}\frac{12(2\sec u - 2 - u^2)}{5u^4} \quad \text{where} \quad u = \frac{kl}{2} = \frac{l}{2}\sqrt{\frac{P}{EI}}$$

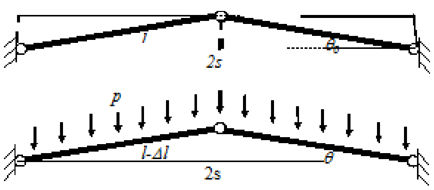
$$u = \frac{\pi}{2}\sqrt{\frac{P}{P_{Cr}}}$$

Maximum Bending Moment

$$M_{max} = \frac{ql^2}{8} + \frac{ql^4}{384EI}\frac{12(2\sec u - 2 - u^2)}{5u^4}P \quad \text{where} \quad I = \frac{t^3}{12}$$

t = beam thickness

Figure 1: Beam formulation for Type 1 conditions



$$S = 2s = 2\cdot\left[\frac{4}{3\sqrt{3}}\right]^{1/4}\cdot t\cdot\left(\frac{E}{p}\right)^{1/4}$$

Figure 2: Definition of critical thickness for beam snap-thru

By following through this analysis, it can be seen that roof deflections can be estimated from an estimate of vertical surcharge load (p), horizontal stress/load (P), GSR, and roadway width. The vertical load (p) is simply estimated by choosing the height (or range) of softening above the roadway and the horizontal load (P) by the normal in-situ stress regime and concentration factors about roadways.

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. It can also be used to estimate load-convergence relationships across a range of roof conditions as a function of differing end constraints and includes a term to allow for increased deformation in the immediate roof due to localised failure. 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 beam based analysis. Hence an ability to estimate the combined stiffness of the roof strata and roof support is required.

Support characteristics

In the case of a coal mine roadway, the above mentioned beam formulation can be used to estimate roof convergence as a function of height of softening (or surcharge loading) for a given support pressure. One then needs 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 as follows:

Support stiffness

$$\frac{1}{k_b} = \frac{W}{N_b}\left(\frac{4L}{\pi d_b^2 E_b} + Q\right) \tag{2}$$

Where W = roadway width
N_b = number of bolts or cables
L = 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. This provides the estimate of roof stiffness used for analysis.

Mark *et al.,* (2002), provides 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.

A final consideration is estimation of roof beam stiffness where roof failure has developed. In this case an estimate of strata stiffness in its residual state is used rather than intact strata stiffness. Previous experimental work on coal is used as a guide (Medhurst and Brown, 1998). In general terms a 50% reduction in stiffness is typically encountered in coal and strata of similar strength. This reduction was used for estimating roof beam stiffness in failure zones within the analytical model.

Pull-out load is an important parameter for any roof support element and there are a range of methods to estimate this. 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. Littlejohn (1993) provides one measure, which requires an estimate of the cohesive strength of the resin/rock interface. Farmer (1975) provides a similar but simpler expression based on the unconfined compressive strength (UCS) as follows:

$$P = 0.1 \cdot UCS \cdot \pi \cdot R \cdot L \tag{3}$$

Where *P* = pull-out load
R = borehole radius

L = 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 load is used.

Bolt placement

Several experimental studies in the 80's into the effectiveness of bolt placement showed that roof deflections reduce as the number of bolts increases, but it's effect becomes less significant after about 6 bolts/m. However, this effect is most effective when extra bolts are installed close to the roadway abutments (Spann and Napier, 1983; Stimpson, 1983).

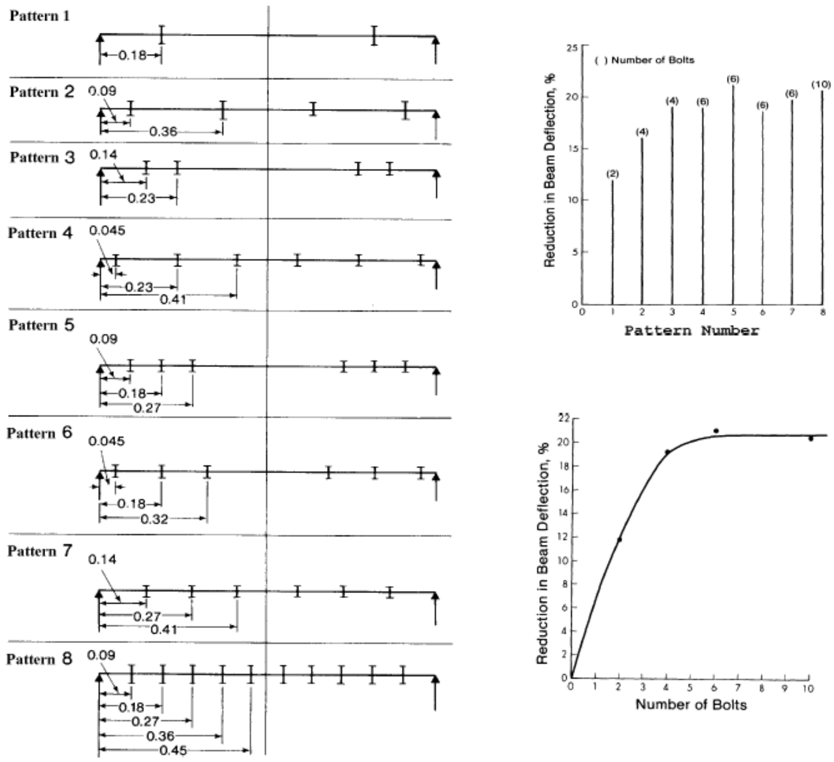
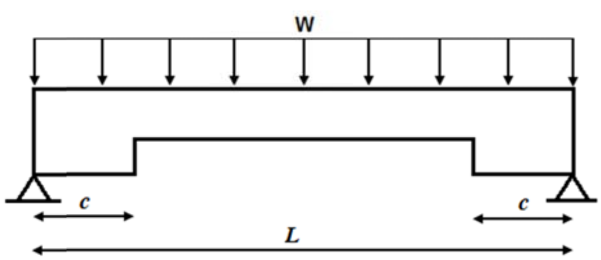


Figure 3: Effect of bolt placement on roof behaviour (Stimpson, 1983)

This effect is well known in structural engineering in which beams and suspended slabs are often thickened at the supports or in this case corners as an efficient way to increase stiffness and reduce shear stresses. These are known as drop panels and specific formulae have been developed to estimate deflections of these "stepped" beams (Yamamoto, 1985), as shown in Figure 4.



$$\Delta_{C\!\!L} = \frac{WL^4}{EI_2}\left[\frac{1}{384} - \frac{c^3(4-3c)}{24}\right] + \frac{WL^4}{EI_1}\left[\frac{c^3(4-3c)}{24}\right]$$

Figure 4: Deflection of fixed end stepped beam

If the distance (c) is taken as the position of the extra intermediate bolt, for example in a 6:2 pattern, then an estimate of deflection can be made using the stepped beam formula. This can result in up to a 20% reduction in roof deflection.

STABILITY ASSESSMENT

Ground response

Brown *et al.,* (1983) provided the first real analytical framework in which to calculate tunnel support pressure and roof convergence relationships, or ground response curves (Figure 5). It should be noted that ground response curves (GRC) are a generic tool in which to plot the results of stability analyses. They are not a design method as such, but are the simplest way in which to assess support pressure in conjunction with roof convergence.

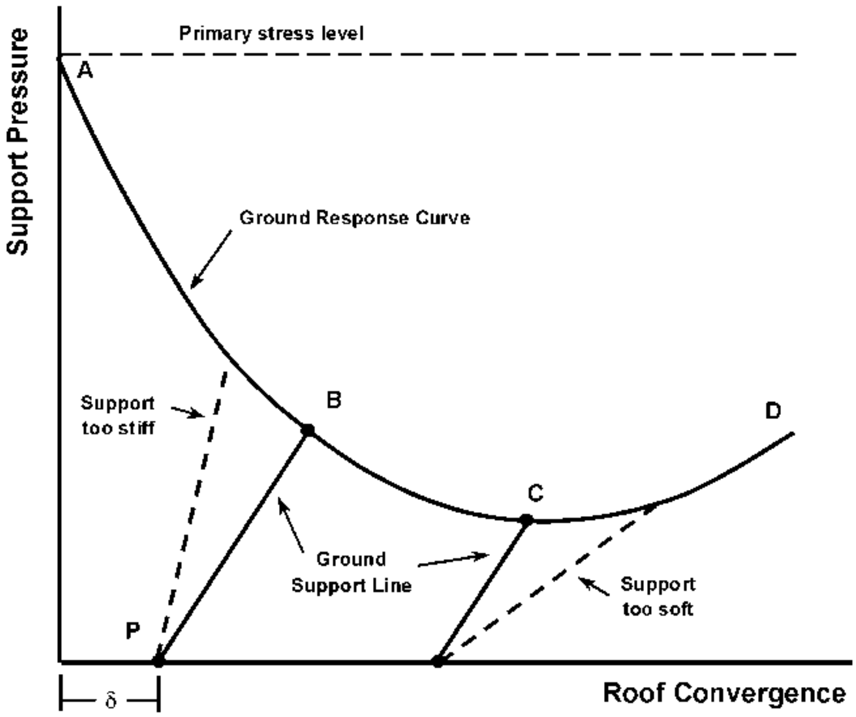


Figure 5: Ground response curve

The aim of the approach is to optimise support requirements, i.e. to determine the best load/convergence balance for a given set of conditions. Seedsman (2014) recently noted that the classic discussion of the GRC concept involves the early installation of stiff support. This in fact is not the intention of the GRC approach, but it is true that this concept has been used in the past to argue for stiffer support as a means to reduce roof convergence. Whilst such debate may have occurred it is important to reiterate that a GRC is simply the plotting of estimates of load and convergence from any particular analysis model.

A key aspect of GRC analysis is it can only represent the results from the model in which they were generated. In the case of elastic analysis under one set of boundary conditions, a single GRC can be generated bounded by the virgin load on the vertical axis and on the horizontal axis by a convergence limit bounded by the elastic state. In the progressive failure case, it can be envisaged that once one elastic state has been achieved and failure begins to occur, then a second set of conditions/properties/geometry may apply with a different curve; and a third and so on.

In order to overcome the limitation of elastic analysis in a practical manner, one approach might be to use an appropriate analytical model and then apply it at different stages in the loading and supported condition and plot it on a cumulative basis. Again, this is a simplified approach, but potentially avoids the requirement to undertake plasticity analysis whilst capturing increasing levels of deformation that cannot be estimated by a single elastic analysis. The general concept is shown in Figure 6.

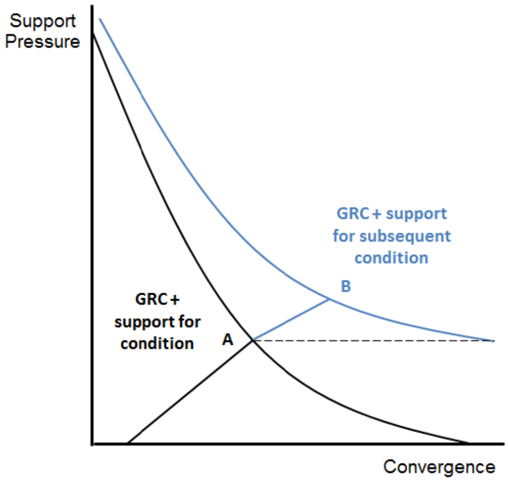


Figure 6: General concept of cumulative GRC analysis

Longwall installation road in weak roof

In this example, the roadway was driven in conditions where the immediate roof was weak, with a UCS ≈ 10 to 15 MPa and GSR ≈ 22 to 29. Support generally comprised 8 AX bolts/m and secondary support of 2 x 7 m Megabolts/m on the first pass and another 1 x 7 m Megabolt every 2m on the second pass. Roof conditions and monitored roof convergence is shown in Figure 7.

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

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 an alternative term will be used called the Serviceability Factor (SF) = ratio of nominal support capacity to the estimated support pressure for a given roof convergence. This is intended to be more representative of the load generated in the roof, and to develop the relationship between observed conditions and the ability to assess the risk of instability.

Figure 8 shows the analysis using the supplied data. The extensometer data indicated that roof convergence was about 20 mm on first pass development. The corresponding analysis shows a height of softening (HoS) of 2 m at this convergence level as denoted by the intersection of the 2 m Primary GRC and the AX bolt support line (the intersections of the curves are marked by the dotted red lines). The outcome here suggests that the HoS may be around the 2 m level and some load sharing between bolts and megabolts would occur that develops about 17 t/m^2 capacity.

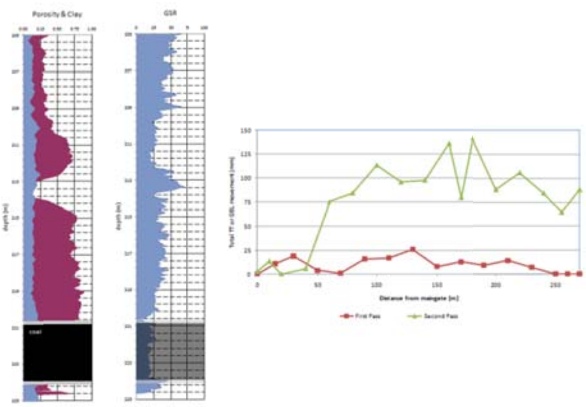


Figure 7: GSR and convergence for weak roof

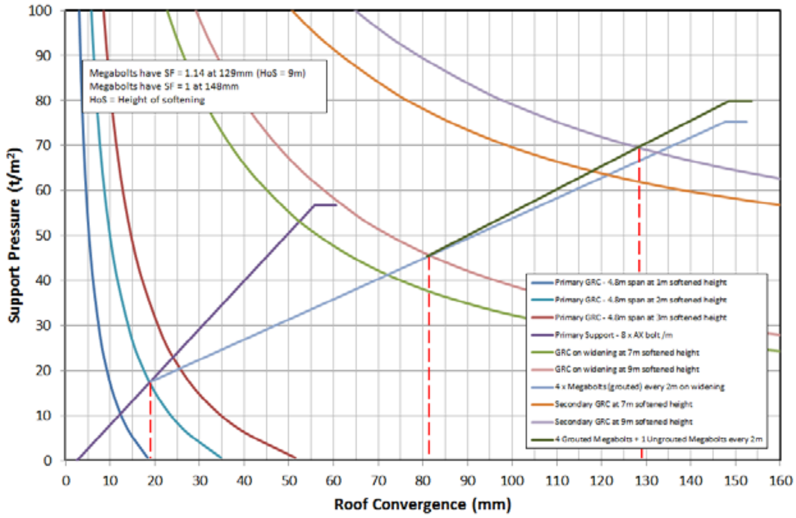


Figure 8: Stability analysis for weak roof

Upon widening roof convergence levels initially increase to about 80mm. The analysis suggests that this corresponds to a height of softening of about 9m upon widening with the initial four megabolt per 2 m pattern installed, i.e. prior to the additional tendon being installed. This is consistent with underground observations. Support demand at this point is around the 45t/m^2 level, however the HoS is above the length of the megabolts. At this point the potential for bedding plane shear needs to be checked. For the 7 m long tendons, the neutral axis of the beam was calculated to be 4.1 m above the roof using the GSR data. Based on a shear flow analysis for beams this yields a Factor of Safety (FoS) = 0.8 for the 4 megabolt per 2 m pattern. On this basis it can be presumed that the roadway would continue to deform.

The ground response characteristics for the 5 megabolt pattern (additional ungrouted tendon installed) are also shown in Figure 7. The analysis predicts that the roof would stabilise at the 129 mm level with a SF = 1.14 based on the 0.82 MN capacity of the megabolts. The megabolts were also estimated to reach serviceable capacity, SF = 1, at about 148mm of roof movement.

There are several factors that need to be considered to follow the analysis. Firstly, how to determine the height of softening upon primary development? In an operating environment, this can simply be based on telltale data or other monitoring information. This then provides the basis for prediction of the next stage of excavation. In the case of a virgin site, it could be based on previous monitoring data, comparison with roof conditions via GSR, or other geotechnical data.

Type 3 was initially selected for primary development since GSR ≤ 30, i.e. poor roof (Table 2). The reason to choose Type 4 for widening is based on the extent of damage that developed in the roadway, indicated by either large values of monitored roof convergence and observed damage or the calculation check on shear flow high in to the roof strata. Alternatively, the ratio of GSR/σh, i.e. ratio of GSR to horizontal stress can be used as a trigger for assessing whether roof softening is likely to be above the primary bolt horizon. In this and other examples, GSR/σh < 3 has been found to provide a useful threshold.

The second issue becomes checking the adequacy of the secondary support. Again, monitoring is the first option. The alternative, however, is to check the potential for bedding plane or horizontal shear in the roof as demonstrated. The beam analysis here provides some indication of the zone of maximum shear and provides an estimate of the load generated. This can be checked against installed/designed capacity. The criterion being that the roof would stabilise when the FoS ≥ 1 for horizontal shear and the Serviceability Factor SF ≥ 1. It is noteworthy that shearing of megabolts did occur in the roadway. Discussion with staff indicated that significant movements were recorded above the 4.5m GEL and some above the 7m GEL extensometers.

Intersection in strong, jointed roof

In this example, the roadway was driven in conditions where the immediate roof was strong with a series of intersecting joints, with a UCS ≈ 47 MPa and GSR ≈ 62. Roof support consisted of 6 x 1.8 m bolts/m plus 2 x 4 m superstrands every 2m. Bowen cables (6m) were installed at intersections. Roof conditions and monitored roof convergence is shown in Figure 9.

Figure 10 shows the analysis using the supplied data based on a Type 2 model (Table 2). The analysis includes the initial analysis based on the roadway width and the use of the diagonal span for the intersection. The extensometer results showed initial roof convergence up to 20mm at the 1.5 m anchor horizon. The corresponding impact on the superstrands is also present in the analysis. The loss of end constraint on the roof beam suggests that the HoS = 4 m could be reached in the roadways at about the 44 mm roof convergence level and the superstrands would reach serviceable capacity at about the 48 mm mark. This suggests that roof convergence in the roadways was probably around the 40mm to 50 mm level given that roof convergence later increased in the intersection, i.e. HoS was greater than 4m and might have increased up to 6 m.

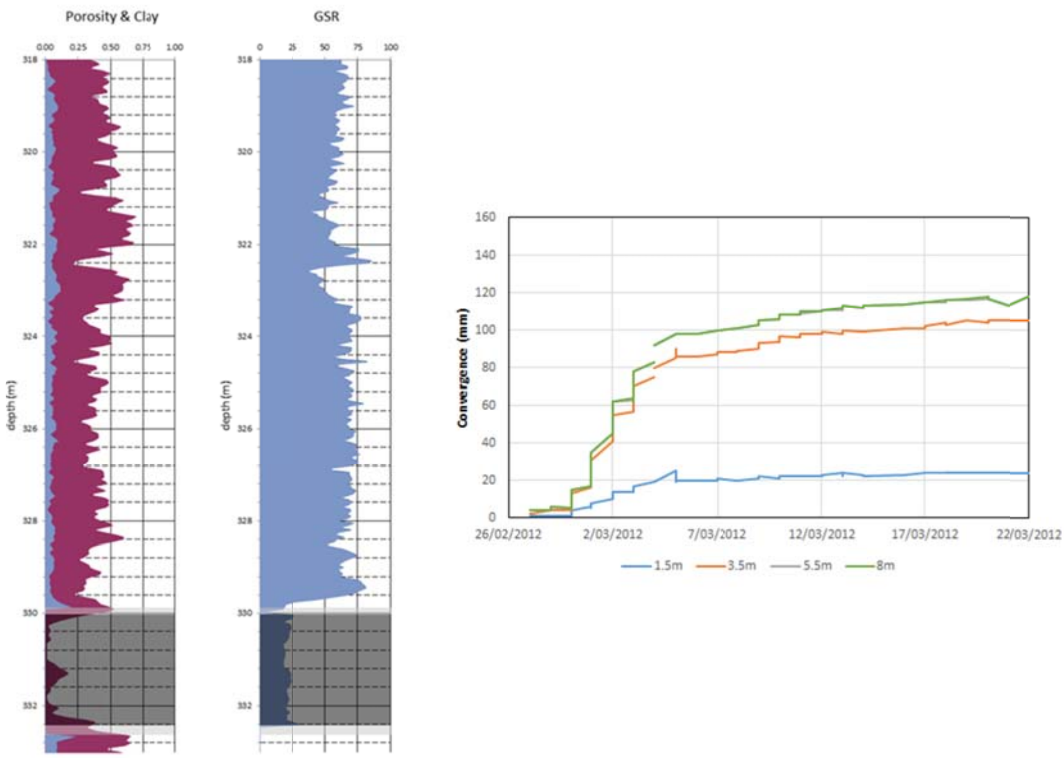


Figure 9: GSR and convergence for strong, jointed roof

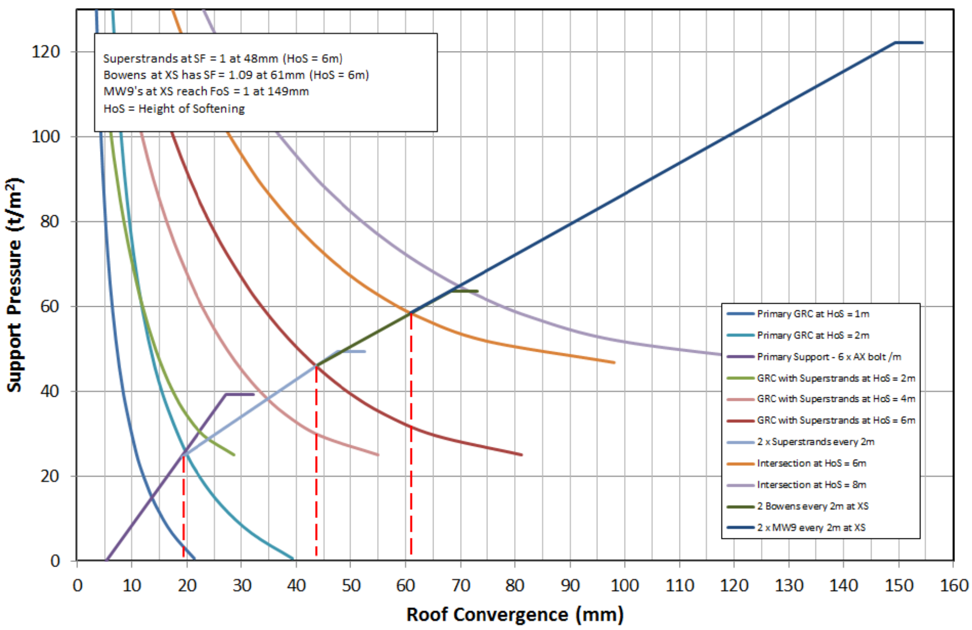


Figure 10: Stability analysis for strong, jointed roof

At the intersection roof convergence initially increases at a higher rate to about 80mm high into the strata before reducing to a lower rate from 80mm to 110 mm. The analysis suggests that the HoS = 6 m was reached at the intersections at about 60mm and the Bowen cables reached serviceable capacity at about 70 mm corresponding to a softening height of about 7 m. At this point it is understood that 11 m MW9 cables were installed at around 80mm displacement to stabilise the area.

The analysis shows that the installed support was unable to control the roof movement when it reached 70mm. At this point it is estimated that the softening height was above the cable length, i.e. > 6 m. Roof convergence increased relatively quickly to about 80mm then extended up to about 120 mm over a steady rate. This is reflected in the analysis as it appears that when the Bowen cable capacity was overcome at about the 70 mm mark, the MW9 cables were mobilised to maintain stability.

CONCLUSIONS

Through analysis of various examples, relationships were identified between roof conditions, depth, bolt placement, bolt length, support density and timing of installation. It allows an estimate of roof convergence and provides an ability to calculate load sharing between the support elements and within the roof itself. In particular the project has been able to quantify the relative roles of primary and secondary support and thus provide an opportunity to optimise the support cycle.

The approach provides the ability to investigate support behaviour in relation to different types of roof conditions and support strategies. This flexibility, whilst powerful for investigating different behaviour mechanisms, also requires further work in its application. Detailed stability analysis in combination with convergence monitoring has many obvious benefits. In some instances, the height of softening, choice of roof interval and associated trigger point may be easy to define. In other cases it will not, such as that governed by complex stress/structure affected zones or unidentified blocky roof behaviour.

The initial work has provided some indicators at to what may guide various inputs. For example, the GSR/σv ratio and particularly the GSR/σh ratio appear to be a useful first pass indicator of potential conditions when no other information might be available. In combination with GSR models, additional tools could be developed in combination with stress maps to allow better prediction and hazard planning assessments. Further research is proposed to extend this approach to a more general framework and design methodology applicable to all underground mines. In the interim, it appears useful for site specific applications provided monitoring data is available.

ACKNOWLEDGEMENTS

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