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WHY UNIAXIAL COMPRESSIVE STRENGTH AND YOUNG'S MODULUS ARE COMMONLY POOR INDICATORS OF ROADWAY ROOF STABILITY – EXCEPT IN THE TAILGATE

Mark Colwell¹ and Russell Frith²

ABSTRACT: For many years underground rock mechanics and in particular, roadway/tunnel roof stability has been underpinned by the often unchallenged assumption that roof strength (as defined by the UCS) and stiffness (E) are key stability controls. This has logically led to the proliferation of laboratory testing of rock specimens and the development of indirect geophysical methods to gain estimates of these two rock parameters. Furthermore, many design methods are significantly focussed on replicating rock mass behaviour through either intact or failed constitutive models. Demonstrably the strength and stiffness of the host rock material is commonly used as one of the key indicators of excavation roof stability and it finds either direct or indirect use in just about every rock mass rating system in use today.

In more recent times there has been a common move to consider and apply (even if only conceptually at the current time) structural engineering type principles (eg, buckling) to coal mine roadway roof (and rib) stability. Similarly our knowledge of the *in situ* stress environment and its likely origins has improved significantly, largely through stress measurements and subsequent analysis. This paper combines knowledge in both of these fundamental areas through a deterministic model for roadway roof stability and in combination with field examples, reaches the almost certainly controversial conclusion that UCS and E are commonly irrelevant, albeit that the former may provide an indication of other relevant geotechnical parameters (eg, bedding cohesion).

As with all hypotheses or rules, there are naturally exceptions and in this case, the most obvious is the tailgate of the longwall panel (with adjacent goaf). Due to the significant change in the strata loading environment of a longwall tailgate as compared to first workings for example, the stability equation materially changes so that UCS and E become critical controls.

The point of the paper is to present a different perspective on a traditional mining problem and to challenge geotechnical professionals to keep thinking “outside of the square” in the never-ending endeavour to improve our understanding of the engineering problems we regularly face. Such an understanding impacts upon such issues as geotechnical data collection from borecore, support hardware requirements and design capabilities. Therefore making the assumption that our understanding is always fundamentally correct could in fact be limiting the development of new and improved engineering.

INTRODUCTION

Material strength is a convenient engineering property. The statement that something is “strong” conjures up certain images and conversely something that is “weak” is readily understood by all. Furthermore material strength is a relatively straightforward material parameter to ascertain through laboratory testing. Therefore it is understandable that in rock mechanics and strata control, the terms “strong roof” and “weak roof” proliferate. Major research projects have been undertaken (SCT 2000) simply focusing on weak strata on the assumption that it is somehow a different genre to “strong” roof and is perhaps governed by a totally different set of constitutive laws and controls.

As a fundamental tenet, the load-bearing ability of any engineered structure is always related to the external and internal loads acting. A structural engineer would never state that a structure is “strong” simply because it is made out of high grade steel for example and conversely, an earth bank can accommodate very high applied loads, even though it is made from materials that are “weak” in comparison. To generalise on the stability of an engineering structure based solely on material strength is clearly inappropriate.

This paper explores the hypothesis that a significant portion of the *in situ* stress applied to the roof of a mine roadway is directly related to the strength of the rock material that it is contained within. Therefore on the basis

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that the ability of the roof to accommodate an externally applied stress is also related in some way to its material strength, leads to the inevitable conclusion that its overall stability or instability (as defined by a Factor of Safety measure) should have a tenuous link to the material strength involved. If true for the roof of coal mine roadways, there should be ample evidence available to support this hypothesis.

Demonstrating such an outcome has significant potential ramifications to both geotechnical analysis and future strata control research. In terms of geotechnical studies it would surely prompt a re-assessment of the basis of numerical codes, which are highly reliant upon laboratory strength test data and typically make broad assumptions regarding the general magnitude of the *in situ* stresses.

At the current time there is also a significant move underway to further classify strata conditions from down-the-hole geophysical data (eg, sonic velocity, gamma etc – Medhurst and Hatherly, 2005). This is underpinned by the well known link between sonic velocity and UCS (albeit site specific calibration linked back to laboratory derived values is generally required to provide credible guidance on local material strengths), the intent also being to try to link such geophysical data from boreholes to a rock mass rating system such as the Coal Mine Roof Rating.

This would indeed be a quantum step forward in rock mass characterisation, but it is vital that such a process does not inadvertently overlook any of the critical rock mass parameters, which may not always include material strength. This paper is being written to provoke further thought and discussion as to how rock masses in underground coal mining need to be classified and what other pieces of information are vital when undertaking a credible geotechnical assessment.

GENERAL OVERVIEW

In order to evaluate the stability of an unbolted mine roof few would probably disagree that the essential requirement is one of comparing the applied ground stresses against the ability of the rock mass to accommodate such stresses (termed “competence” herein to differentiate from material strength).

Using the analogy of coal pillar stability and design, a Factor of Safety argument or stability measure can be applied to the natural stability or self-supporting ability of a coal mine roof along the lines of:

$$\text{stability} = \text{roof competence}/\text{applied stress} \quad \dots(1)$$

Note that equation (1) is a simplified version of the equation that also includes the role of ground support, namely:

$$\text{stability} = (\text{roof competence} + \text{ground support})/\text{applied stress}$$

The role of ground support is not being considered by this paper, hence the removal of the term from the stability equation.

Unlike current coal pillar design, the assignment of credible values for both roof competence and applied stress is not generally agreed upon by the strata control fraternity. There is no roof stability equivalent to the fundamental work of either Salamon or Bieniawski that, in the aftermath of the Coalbrook disaster in South Africa, set the framework for the current understanding and design ability in the stability of coal pillars.

Yet the fundamental nature of the problem in the roof of a mine roadway is not materially different. Stresses are applied to the roof structure and according to its makeup, it will either be stable or unstable. The technique of cut and flit roadway development either lives or dies by this basic issue. What is less straightforward is a means by which credible numerical values can be applied to the key parameters and consideration of this leads to the suggestion stated in the title of the paper; that UCS and E may not be quite as important to roof stability as has perhaps been assumed in the past.

A MODEL FOR HORIZONTAL STRESS IN COAL MEASURES STRATA

When putting any explanatory model forward, its validity may be no greater than the measured data on which it is based and even if it proves to have more widespread application, the existence of data that disproves the theory is always a possibility. Nevertheless any model, even if limited in its application, is better than none at all as others will invariably refine and improve it based on their own data and knowledge. It is with this limitation that the model for horizontal stress is described herein.

The model is not new and has been published by others (Nemcik et al 2005), the focus here being on demonstrating the validity of the model as an input into the roof stability equation.

The model uses the assumption that there are two primary sources of horizontal stress in the ground, one being the vertical stress through Poisson's Ratio or K_0 effects, the other being tectonic strain induced as a result of large-scale plate movements. Therefore:

$$\sigma_H = \sigma_v \cdot (v/1-v) + E \cdot \varepsilon \quad \dots(2)$$

$$\sigma_h = f(\sigma_H) \quad \dots(3)$$

$$\sigma_v = \rho \cdot g \cdot h \quad \dots(4)$$

where: σ_H = major horizontal stress
 v = Poisson's Ratio
 E = Young's Modulus
 ε = tectonic strain (also referred to as the "Tectonic Stress Factor" by Nemcik et al 2005)
 σ_h = minor horizontal stress
 σ_v = vertical stress as given by weight of overburden considerations
 $(v/1-v)$ = numerical determination of K_0

It is noted that the potential for a residual horizontal stress in the ground (emanating from Poisson's Ratio effects with much higher depths of cover that has been removed via erosion over geological time), is not considered herein as it is outside the scope of the paper. Suffice to state that it is acknowledged as a potential source of horizontal stress and in some coalfields (e.g. Southern Coalfield of NSW) significant magnitudes can be reliably inferred from the analysis of *in situ* stress measurement data. However it will not be considered further by this paper, accepting that it is a relevant consideration in some geotechnical environments.

Figures 1 and 2 show the results of a basic analysis of stress measurement data from an Australian longwall mine, the measured horizontal stresses having been adjusted for depth of cover and K_0 effects so that tectonic horizontal stress components can be directly evaluated. Note that in all cases, the curve fits used have not been forced to go through the origin.

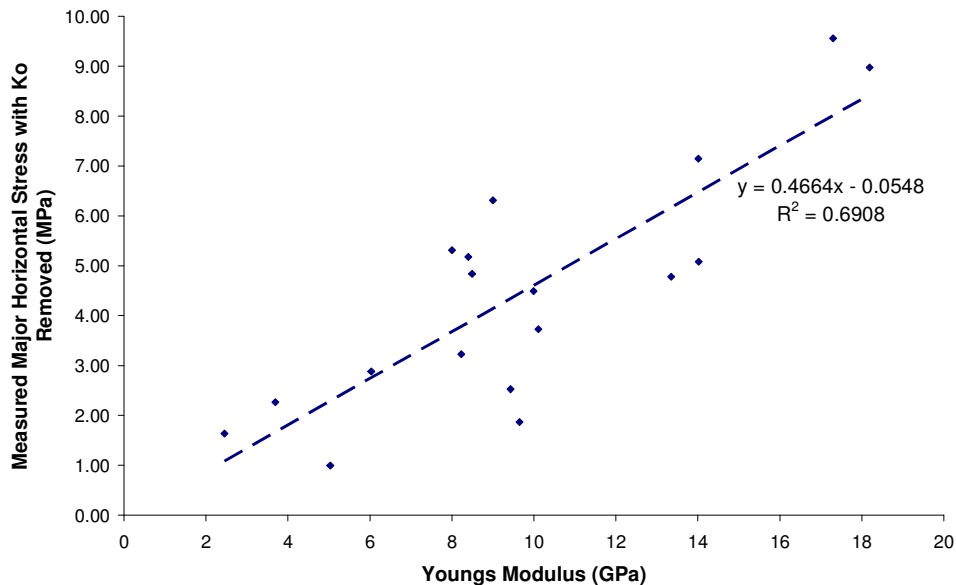


Fig. 1 - Measured major horizontal stress (with K_0 component removed) versus Young's Modulus of host rock

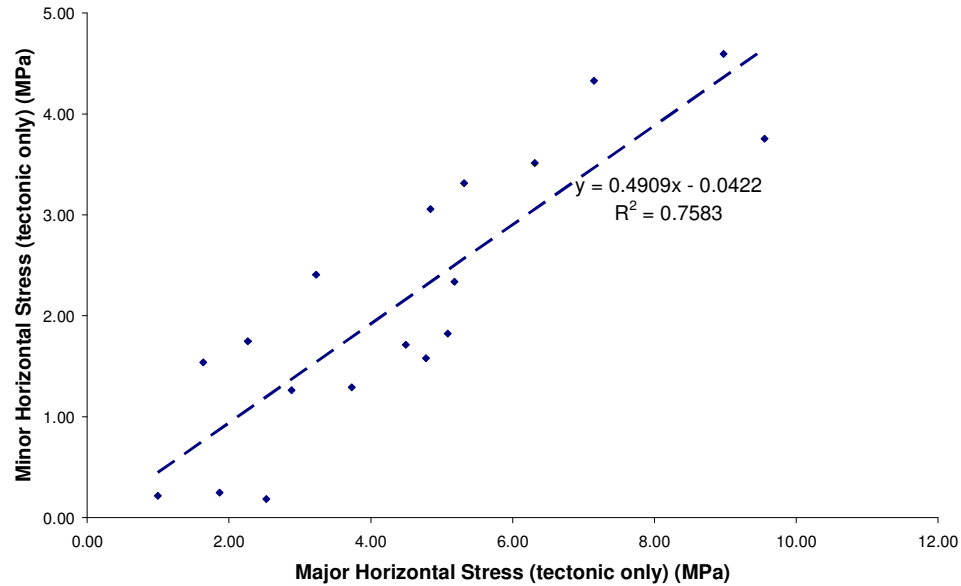


Fig. 2 - Measured major horizontal stress versus measured minor stress (both with K_0 components removed)

Based on the outcomes shown in Figures 1 and 2, the following are evident:

- As suggested by equation (2), the tectonic component of the major horizontal stress is strongly if not uniquely linked to the Young's Modulus or stiffness of the host rock material.
- The tectonic component of the minor horizontal stress is strongly linked to that of the major horizontal stress. It is interesting to note that if the gradient (0.5) of the curve fit in Figure 2 is taken to be an *in situ* estimate of K_0 (as stated in the first component of equation (2)), a back-calculated value for Poisson's Ratio of around 0.33 is found, this not being outside the credible limits for coal measures strata.

The point to be made is that a significant proportion of the horizontal stress in the ground is often (although not always – e.g. a coal deposit adjacent to steep topography) directly linked to the Young's Modulus or stiffness of the host material. This is a critical principle for the remainder of the paper.

IS A STIFF ROCK TYPE NECESSARILY A STRONG ROCK TYPE?

Accepting that in general terms, rocks with a higher Young's Modulus contain a higher level of tectonic horizontal stress (all other factors being equal), the next logical question to ask is whether stiff rocks are also strong rocks.

Figure 3 shows laboratory rock testing results from a mining project in Australia, in terms of the relationship between Young's Modulus and UCS.

It is clearly evident from the results and curve fit shown in Figure 3 that the UCS and Young's Modulus are strongly linked, albeit that there is some scatter in the data set. Nonetheless statistically the two parameters are linked with a high confidence level and data sets from other mining projects show exactly the same relationship, with surprisingly similar correlations.

As a result, it can be stated with confidence that as a general rule, stiff rocks are also strong rocks. When this is combined with the finding of the previous section, it is also true to say that rock types containing higher levels of horizontal stress are also the stronger rock types.

Referring to equation (1) and taking the simplistic view that in some way the competence of a rock mass is a function of its material strength, it is evident that the UCS (and hence Young's Modulus as the two are generally

interchangeable) is potentially a major contributing factor to both the numerator and the denominator (which for roadway development relates to the *in situ* horizontal stress). Therefore UCS or E effects largely cancel out of the equation and leads to the conclusion that the roof stability "Factor of Safety" may not always be strongly linked to the UCS or modulus of the host material.

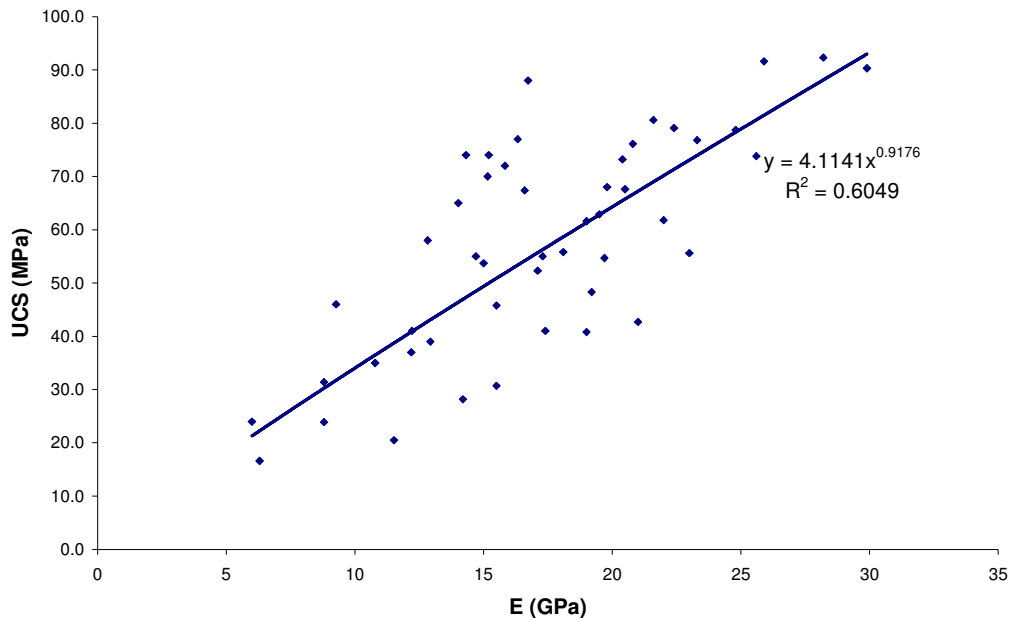


Fig. 3 - UCS versus Young's Modulus relationship as found from laboratory testing data

Before this concept is taken any further, it is necessary to examine whether it holds true when tested by reference to a more comprehensive model of roadway roof stability, this being that presented by Frith 2000 when examining the issue of cribless TG's.

A GENERAL MODEL FOR ROADWAY ROOF BEHAVIOUR IN A HORIZONTALLY LAYERED STRATA SEQUENCE

A fundamental issue to consider in roadway roof stability is the mode of roof behaviour occurring as the roadway is being formed and/or during subsequent mining activities. This will have a wide ranging effect (varying from none to highly significant) on such issues as the self-supporting ability of the rock itself, bolting requirements, timing of support installation and ultimately the potential for roof instability.

There are two primary modes of roof behaviour (STATIC and BUCKLING) which have been identified and generally proven through extensive monitoring studies at a large number of mines in Australia. Both can lead to stable roof conditions, but both have one or several associated roof failure modes which can potentially lead to a roof fall situation if not adequately controlled.

The two basic modes of roof behaviour will now be described.

Static roof: this involves roof conditions whereby the level of horizontal stress across the roof is insufficient to cause bedding plane separation, which thus prevents the roof measures breaking down into thinner discrete units. Essentially, the roof measures "absorb" the stress changes due to roadway formation without undergoing any change in state apart from primarily elastic movement.

The lower the horizontal stress across the roof, the more likely that static roof will persist. Similarly in general terms, increased bedding plane cohesion should also increase the likelihood of static roof conditions being maintained as this is the primary rock parameter that acts to prevent bedding plane failure and separation.

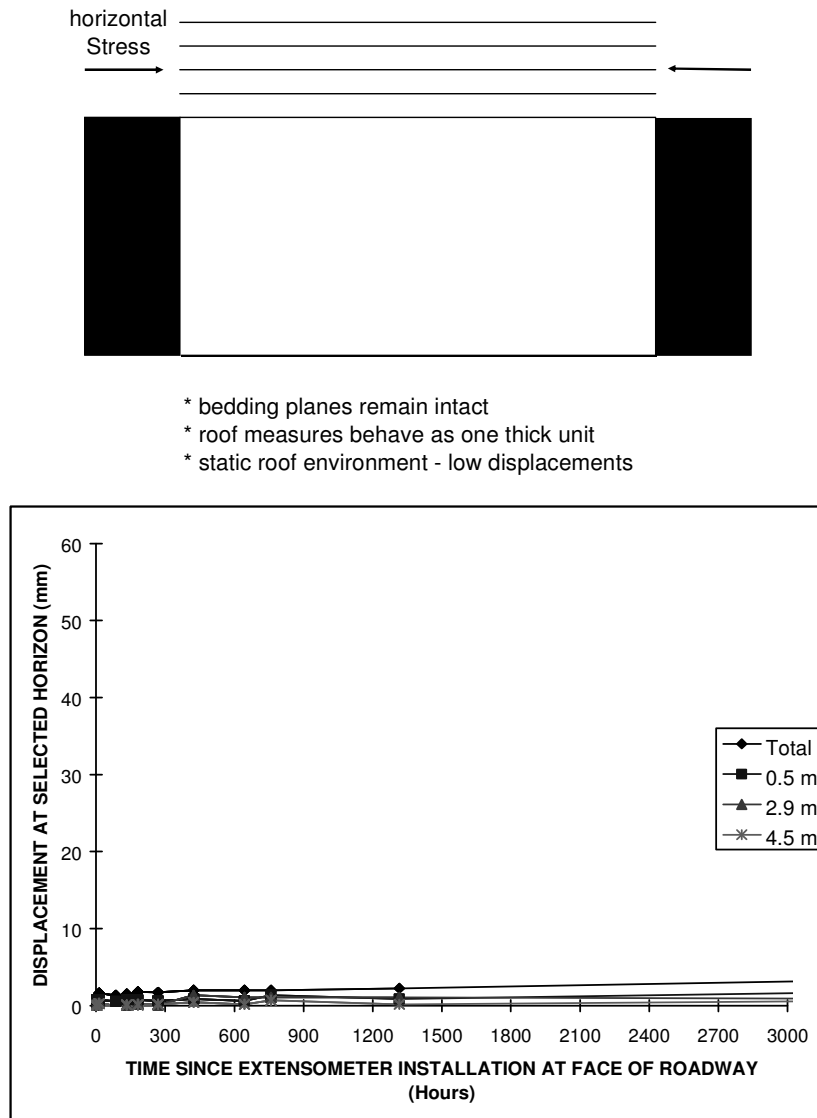


Fig. 4 - Schematic Illustration of static roof behaviour and associated extensometry data

In terms of extremes, a highly stressed roof environment at 500m depth of cover can exhibit static behaviour in combination with thickly bedded or massive roof measures. In contrast, lower horizontal stresses can cause buckling type behaviour in a thinly bedded roof environment. The point is that both the stresses and the nature of the roof must be considered in combination when assessing the likely mode of roof behaviour, as also covered in equation (1).

Typically, a static roof environment will undergo < 5 mm of roof movement as a result of roadway formation and in some instances, no discernible roof movement can be detected by roof extensometry. It is the most stable roof condition and is typically self-supporting, it being the fundamental requirement for stable extended cuts during development as will be discussed later.

Figure 4 illustrates a static roof schematically and gives an example of associated extensometry data.

Buckling roof: buckling roof behaviour occurs once a portion of the roof measures undergo tensile and/or shear bedding plane failure resulting in the formation of a number of thinner discrete units (“columns”) acting under the action of horizontal stress. For the purpose of this paper, this behaviour will be termed as buckling, recognising that it is not a strictly correct use of the term.

The mode of deflection of the roof measures changes with the onset of buckling from primarily elastic expansion in a static roof to downwards buckling of the roof measures. This causes a large increase in the magnitude of roof displacement for any given horizontal stress due to a reduction in the overall stiffness of the various thin independent strata units.

The main point of relevance herein in relation to a buckling roof environment is that it is not necessarily self-supporting and generally relies upon the application of specific ground support to ensure stability is maintained. Unlike a static roof environment, the occurrence of a buckling roof would be expected to be highly detrimental to the stability of extended cuts during roadway development, to the point that it commonly necessitates the use of a miner/bolter installing roof support in sequence close to the development face.

Figure 5 illustrates the occurrence of a buckling roof schematically and presents typical time-dependent displacement trends in the roof leading to an equilibrium condition being attained.

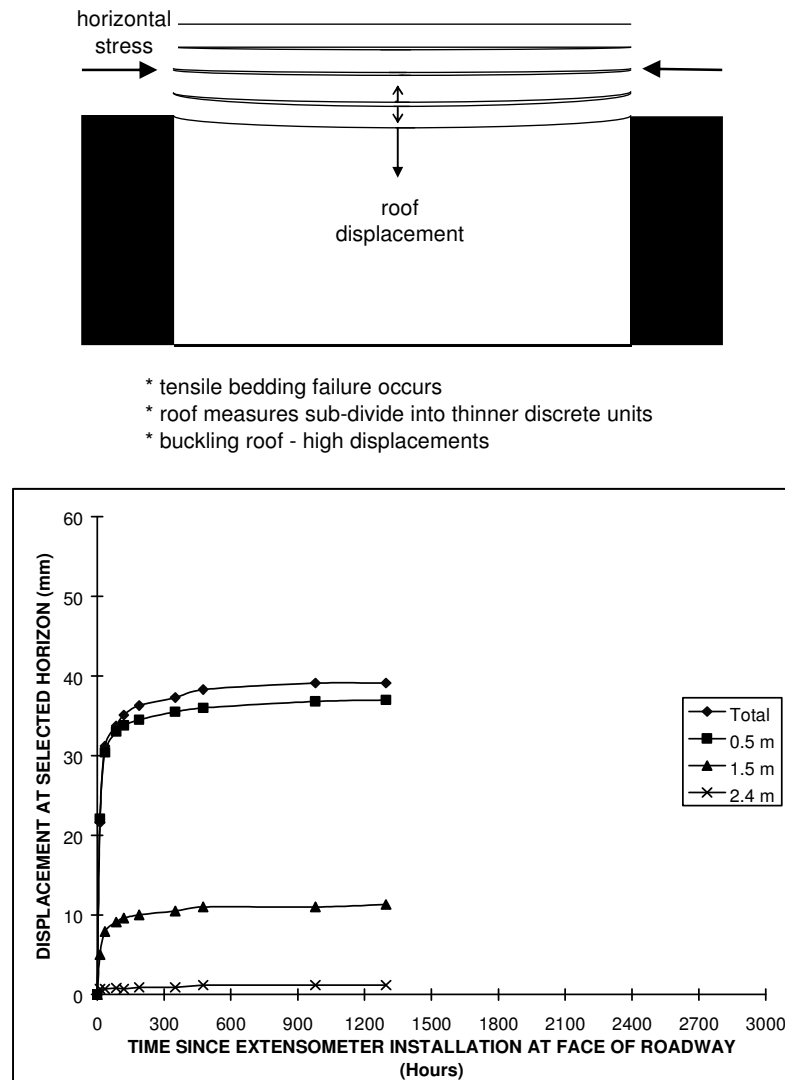


Fig. 5 - Schematic illustration of buckling roof behaviour and associated extensometry data

As a point of interest, Figures 6, 7 and 8 show extensometer data examples of what are taken to be buckling roof environments in Australia, the US and the UK, the similarity in their form being self-evident.

ANALYSIS OF THE US DATABASE ON THE STABILITY OF EXTENDED CUTS

The US database on the stability of extended cuts during development is an invaluable assessment tool, as it is one of the few roadway or tunnel roof stability databases that does not include the effect of installed support. It is as good a representation of equation (1) as can be found and the provision of information contained within the database by Dr Chris Mark of NIOSH is duly acknowledged.

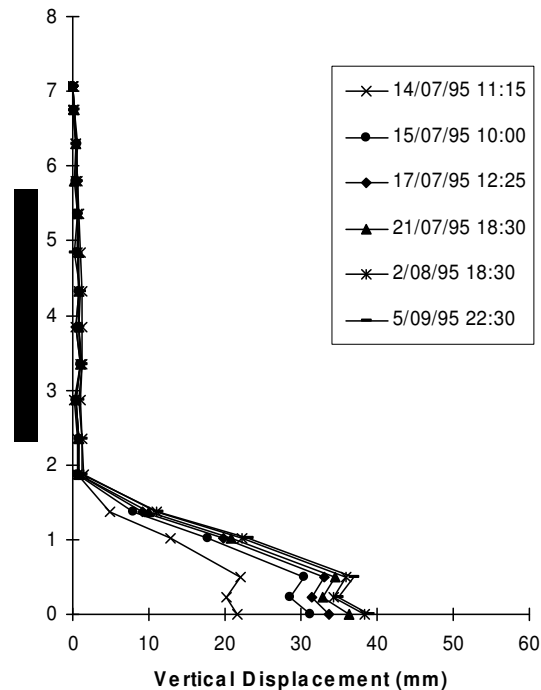


Fig. 6 - Roof extensometry data from Australia suggesting the occurrence of a "Buckling" roof environment

The database classifies the stability of extended cuts at a number of US coal mines according to whether they were "always stable", "sometimes stable" or "never stable". In addition to these mining outcomes, the database also includes many of the basic geotechnical parameters of interest, including depth of cover, roadway width and the Coal Mine Roof Rating (including the individual CMRR parameter ratings) – Mark 1998.

Combining equations (1) and (2) with the hypothesis that for the occurrence of either a static or buckling roof condition, bedding plane cohesion is the key rock mass parameter, the following is apparent:

$$\text{stability} = \frac{f(\text{bedding cohesion})}{f(\text{depth}) + f(\text{UCS or E})} \quad \dots(5)$$

For equation (5) to be generally true, the following statements should in theory be supported by the contents of the US extended cut database:

- (a) There should be some form of relationship between bedding plane cohesion within the immediate roof of the roadway and the depth of cover, stable cuts requiring higher cohesion levels at higher depths of cover for "always stable" outcomes.
- (b) If cohesion and UCS are dependent variables (along the lines of that shown in Figure 3 for UCS and E), a poor correlation with stability outcomes should be found when the two are plotted against each other. However, if they are independent variables or there is significant scatter in the relationship between the two, some correlation with stability outcomes may be evident in the same plot.

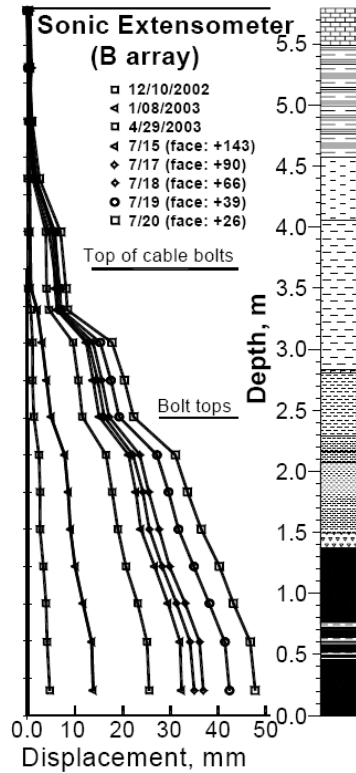


Fig. 7 - Roof extensometry data from the US suggesting the occurrence of a “Buckling” roof environment (Oyler et al 2005)

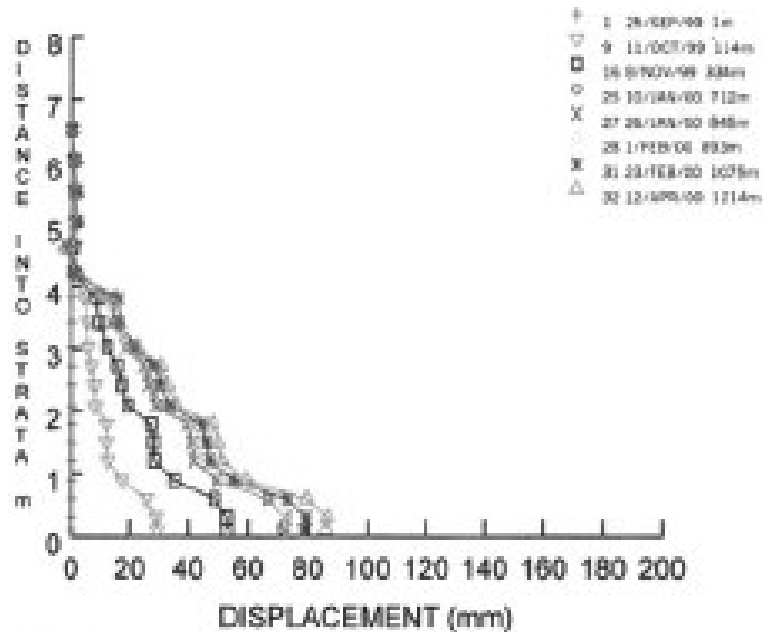


Fig. 8 - Roof extensometry data from the UK suggesting the occurrence of a “Buckling” roof environment (Adams 2003)

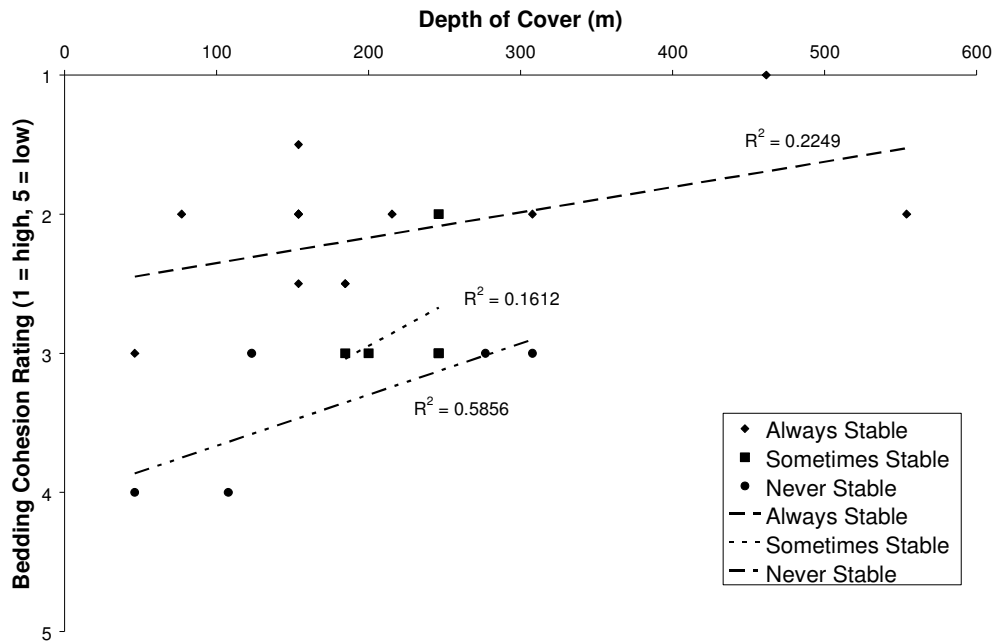


Fig. 9 - Stability outcomes in the US extended cut database against depth of cover and bedding plane cohesion rating

Figure 9 shows (for all of the single strata unit cases within the database) the bedding plane cohesion rating against depth of cover, the cases being sub-divided into the three stability outcomes. From this figure it is evident, at least in terms of general trends, that:

- for any given depth of cover (especially up to 300 m which covers the majority of the case histories), the most stable outcomes relate to the highest levels of bedding cohesion, and
- as the depth of cover increases, so does the bedding plane cohesion associated with each of the three stability cases.

Therefore it would seem, as implied by equation (5), that there is some correlation between depth of cover, bedding plane cohesion and the stability of extended cuts.

Figure 10 shows the bedding plane cohesion rating plotted against the material strength rating for each of the single roof unit cases, as well as the cut stability outcome in each particular case.

The following outcomes are apparent from the data contained within Figure 10:

- Whilst there is a general trend for bedding plane cohesion to increase in line with material strength (as shown by the dotted line), there is a significant degree of scatter. This is not surprising as bedding planes often comprise different material (e.g. mica, carbonaceous material) as compared to the host rock, therefore a significant scatter would be expected.
- Accepting that the Strength Rating is also a possible indicator of the tectonic component of horizontal stress acting, the “never stable” cases are all associated with weaker levels of bedding cohesion, as compared to the “always stable” cases which tend towards stronger cohesion. As would be expected, the “sometimes stable” cases are located in between with overlap into both the “always stable” and “never stable” populations.

The data set is perhaps not comprehensive enough to be absolutely definitive on this issue, but the apparent trends certainly support the suggestion that the stability of extended cuts is a function of both bedding plane cohesion and material strength (i.e. UCS).

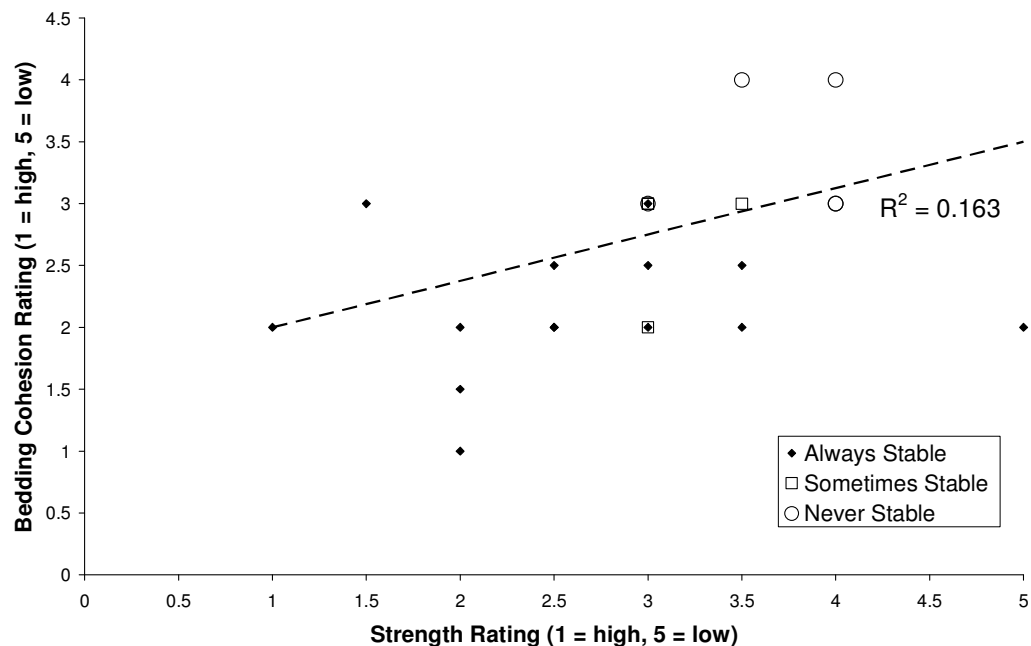


Fig. 10 - Stability outcomes in the US extended cut database against bedding plane cohesion rating and material strength rating

Overall the general trends found within the US database on extended cut stability lead to the conclusion that material strength (i.e. UCS or E) in isolation does not allow a reliable prediction of cut stability to be made. This can also be clearly seen in Figure 10 whereby the stable cases cover the full range of material strength ratings from 1 to 5. Therefore, other factors also need due consideration including bedding plane cohesion and depth of cover as a minimum.

It is interesting to note that the relative importance of the material strength rating within the Coal Mine Roof Rating has down-graded on at least one occasion. This is also perhaps evidence of the relative insignificance of UCS and E to the overall roof stability equation, although as will be discussed later there are some notable exceptions whereby it becomes a critical stability parameter.

BUCKLING THEORY AND THE SIGNIFICANCE OF MATERIAL STRENGTH

The behaviour of thin columns under load is covered by a number of theoretical treatments that, in combination, can be used to provide an estimate of load-bearing capacity across a full range of column geometry. For the purposes of this paper, use will be made of Euler Buckling theory to demonstrate key principles.

Euler Buckling theory defines the critical buckling stress (σ_{cr}) of a thin column (i.e. the stress at which uncontrolled buckling and structural failure will initiate) as follows:

$$\sigma_{cr} = \pi^2 E / (L_e/r)^2 \quad \dots(7)$$

where: E = Young's Modulus
 L_e/r = Slenderness Ratio = f(column length, thickness)
 L_e = effective length of the column
r = radius of gyration

It is noted that Euler Buckling theory only applies to a certain range of Slenderness Ratios and does not define the complete behaviour of thin columns. It is being used for illustrative purposes only.

Therefore it is clear that the maximum load-bearing capacity of a thin buckling column is a direct function of both its Young's Modulus and dimensions. However it was shown earlier that Young's Modulus can be replaced with UCS, so that it is also true that the maximum load-bearing capacity of a thin buckling column is directly related to the strength of the host material.

The above basic analysis demonstrates a fundamental tenet of structural analysis, namely that the maximum load-bearing capacity of a structure is determined as a proportion of the material strength of the structure, the proportion being related to its geometry.

When this finding is substituted into equation (1) it can be shown that for a buckling roof in a predominantly tectonic horizontal stress environment, stability has almost no link to material strength, but more to the problem geometry (i.e. column length and thickness).

For the roadway roof stability problem these two parameters are given by roadway width and bedding thicknesses respectively. Few geotechnical engineers would disagree that in aggressive conditions, roadway or tunnel roof stability decreases in line with increasing roof span and similarly, the roof becomes less stable and more difficult to control as bedding thicknesses decrease in the host rock mass.

GENERIC SUPPORTING EXAMPLES

In order to complete the discussion, it is worth citing some generic examples that further confirm the suggestion that UCS and E are commonly poor indicators of roadway roof stability.

Thick Coal Roof

The most obvious example to consider is that of a thick coal roof. Mining experience dictates that the presence of a thick coal roof is commonly a more favourable environment for roadway development purposes, as compared to some of the rock sediments above. However coal is far from being the strongest of material when compared with many of the rock types commonly encountered.

Two geotechnical issues are relevant to coal as a development roof environment. Firstly due to its low strength it also has a low Young's Modulus so that the tectonic component of horizontal stress is reduced as a direct result. The low strength of the material is directly compensated for by the low Young's Modulus and its inability to attract high levels of tectonic horizontal stress.

The second issue is that bedding thicknesses within many coals are significantly greater than thinly bedded rock sediments such as shales and laminates. Therefore any buckling within the coal roof that may want to occur under the action of the *in situ* horizontal stress will be better accommodated as compared to a thinly bedded rock roof.

In this regard it is also interesting to note that a number of Australian longwall mines in thick seam environments have found that not only does the leaving of a coal skin in the immediate roof decrease roof flaking and small pieces dropping out, but if a sufficient thickness of coal roof is left in place (typically in excess of 1 to 1.5 m), the global stability of the roof can also be improved.

Seam Splits

Within the Australian coal industry, it has been recognised that areas containing splits in the roof of the coal seam can be associated with far more difficult roof conditions, than areas whereby the seam is coalesced as a single unit.

One of the features that is commonly found when evaluating strata competence in seam split locations is that the frequency of bedding planes/fractures (in both the coal and immediate roof) in borecores increases significantly, as compared to areas remote from a seam split. However the variation in material strengths in and around seam splits can be marginal at best and nowhere near the same magnitude of change as compared to the bedding fractures.

Therefore, the most obvious link between the deterioration in roadway roof stability in proximity to a seam split and geotechnical parameters from local borecore commonly relates to fracture spacing within the measures, not reductions in material strength.

Thickly Bedded to Massive Strata

At the other end of the scale, some of the most competent roadway roof conditions encountered relate to the presence of thickly bedded or massive strata in the immediate roof. Even at depths of cover down to 500 m, the presence of a thickly bedded to massive immediate roof environment can be associated with very benign development roof conditions, allowing extended cuts to be used and minimal roof support densities.

Massive strata contains few if any bedding planes so that the mechanism for a buckling roof environment (i.e. bedding plane failure) is not present. In thickly bedded strata, even if bedding plane failure does take place, the resultant strata units are sufficiently thick to still have a considerable amount of self-supporting ability prior to the installation of roof support. Either way, the self-supporting ability of the roof measures remains high.

WHAT HAPPENS IN THE TAILGATE OF THE LONGWALL ?

As with all theories and concepts, there will always be exceptions and in this particular case, whilst there are several possibilities (e.g. coal seams within hillsides, very weak roof whereby self-weight effects dominate the loading environment), the most obvious is in the tailgate of a longwall face with adjacent goaf.

Frith 2000 discussed the issue of cribless tailgates and presented the roof loading model shown in Figure 11.

The basis of the loading model is that:

- a significant proportion of the *in situ* horizontal stress acting across the roadway has been eliminated due to the presence of an adjacent goaf and its inevitable horizontal stress relieving ability
- the primary source of strata loading during TG loading is in the form of vertical stress, this driving increased spalling of the coal ribs (which can give rise to an increased roof span) and also the development of increased horizontal stress across the roof via Poisson's Ratio of K_0 effect.

If this loading mechanism is correct, the increase in horizontal stress across the roof of the TG will be some function of Poisson's Ratio or:

$$\text{horizontal stress increase} = f(K_0) = f(v/[1-v]) \quad \dots(8)$$

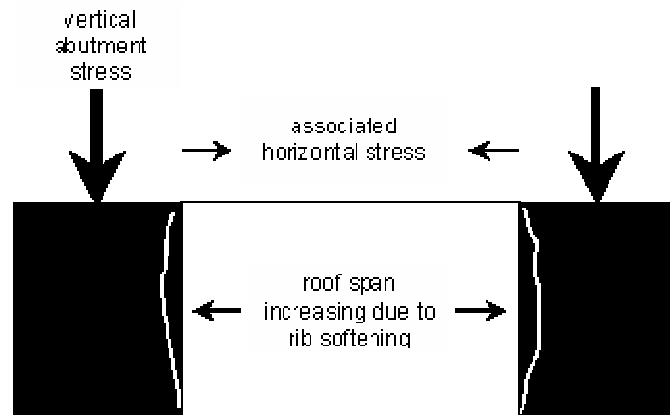


Fig. 11 - Schematic illustration of general TG loading conditions (from Frith 2000)

Poisson's Ratio is not always captured as part of laboratory rock testing programs and is probably the most difficult parameter to determine accurately. However Figure 12 shows a trend relationship found between Poisson's Ratio and Young's Modulus for one particular mining project and the general trend amongst the inevitable data scatter is for Poisson's Ratio to decrease as Young's Modulus increases.

As a result equation (8) can also be written as:

$$\text{horizontal stress increase} = f(K_o) = f(E^{-1}/[1-E^{-1}]) \quad \dots(8)$$

Therefore as Young's Modulus decreases, the value of K_o may actually increase, such that the value of horizontal stress being generated across the TG roof also increases. This is in direct contrast to the model for the *in situ* horizontal stresses discussed earlier, which shows that Young's Modulus and the tectonic component of the horizontal stress are directly rather than inversely proportional.

Returning to the general stability equation given by equation (1) and substituting in the specifics for a longwall tailgate and a buckling roof environment, the following is apparent:

$$\text{stability} = \frac{f(E \text{ or } UCS)}{f(\text{depth, } 1/E \text{ or } 1/UCS)} \quad \dots(9)$$

Unlike the case of roadway development or indeed the MG end of the face whereby the *in situ* horizontal stresses acting are of most significance to roadway roof stability, roof stability is now not independent of UCS or E, but directly related to UCS or E.

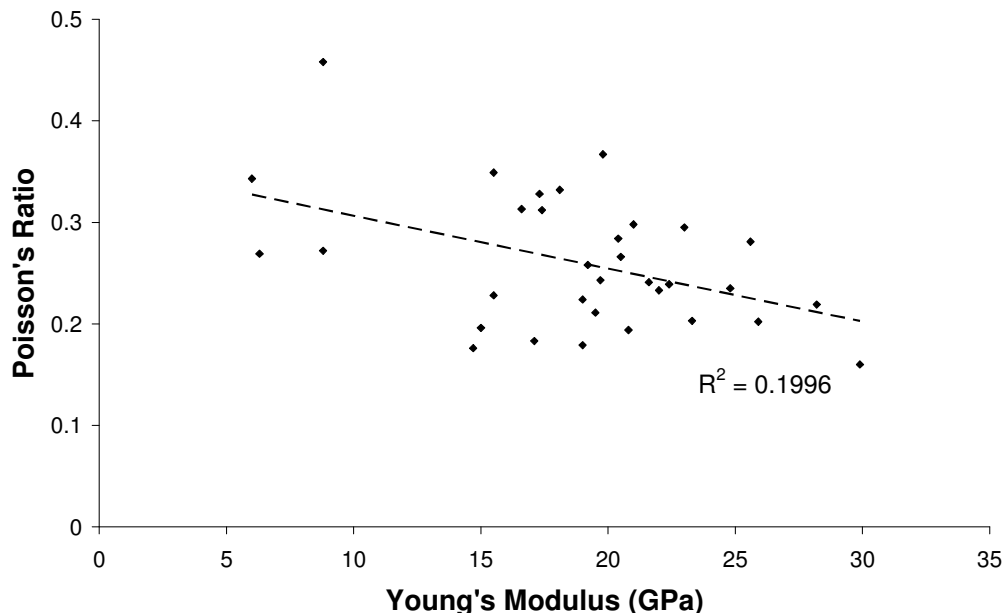


Fig. 12 - Laboratory derived values for Young's Modulus and Poisson's Ratio for a mining project

If the concepts described herein and equation (9) have any credibility, longwall mining experiences should show that for low strength or modulus roof material (in particular a thick coal roof), roadway roof stability can reduce significantly and rapidly as part of TG loading, whereas prior to this (i.e. development and MG loading), roof stability had been quite benign and of minimal concern.

The Australian coal industry contains a number of examples whereby gateroad roof stability relates to the presence of a thick coal roof. It would be misleading though to simply suggest that those mines developing gate roadways with a thick coal roof are typically associated with very high levels of roof instability during TG loading (ground support controls mitigate against this risk).

However in the general experience of the authors, despite the thick coal roof often providing relatively benign roof conditions during development and through to MG loading, such longwall mines tend to be associated with generally more aggressive roof conditions in the TG. In other words a clear link with roof conditions prior to the onset of TG loading may not be evident in a thick coal roof scenario.

Therefore if roadway roof conditions prior to TG Loading are not clearly indicative of likely future TG conditions, inadequate levels of secondary support can be installed, the inadequacy only becoming evident once difficulties are experienced in close proximity to the approaching longwall face.

In the experience of the authors, the above described scenario is most likely to occur in conjunction with the presence of a thick coal roof, as it is being protected by its low Young's Modulus before the onset of TG Loading, but then de-stabilised by its low Young's Modulus during TG Loading.

SUMMARY

The paper has developed and presented a series of arguments that lead to the conclusion that as a general rule, the material strength of a coal mine roadway roof in isolation is not a particularly good indicator of likely roof stability under the action of the *in situ* horizontal stress (i.e. development and the approach of the longwall at the MG end of the face). The primary issue is that in those environments whereby the *in situ* horizontal stress is significantly influenced by tectonics, highly stressed strata units will also be high strength units.

Nonetheless, it is common to hear mining personnel classifying future mining areas based on whether the immediate roof material has tested as being either "strong" or "weak". In some cases, mine site exploration activities even dispense with the collection and rating of roof core, this being replaced with a roof strength index derived solely from the borehole sonic log.

Only in those cases whereby the UCS of the host material provided a reasonable indirect indication of both bedding plane cohesion and/or bedding thicknesses, would future roof stability during development be well linked to material UCS. It is beyond the scope of this paper to consider this in detail, but presumably would vary from site to site dependent upon local geotechnical conditions.

Another possible exception relates to the presence of very weak roof material (in the order of only a few MPa) in conjunction with very weak bedding cohesion. In this situation, despite the low Young's Modulus and so low potential for tectonic horizontal stresses, it is possible that the self-weight of the roof material itself becomes the significant driver for bedding plane failure and hence, roof instability without installed roof support

Demonstrably, the situation of a longwall tailgate with an adjacent goaf does not conform to the general findings for roadway development. Mining experiences fit with the theoretical treatment that suggests that the strength and stiffness of the host material is in fact a significant determining factor in TG roof stability during extraction.

The change in the strata loading environment that occurs between the MG end of the face and subsequent TG Loading is a material change in that it is driven by two totally different processes and has a significant impact upon roadway roof stability. As a result, the roof stability rules will also inevitably change and a conceptual appreciation of both is required if ground support practices are to be appropriately tailored.

The concepts presented in this paper lead to three basic questions that need to be posed for consideration by the strata control fraternity:

- (i) Are we in danger of missing out on vital geotechnical information if we dispense with the collection and analysis of borecore in favour of indirect down-the-hole geophysical methods?
- (ii) If UCS and E are relevant to roof stability in some scenarios, yet not in others, is there a case for removing it from the Coal Mine Roof Rating altogether or modifying the makeup of the Coal Mine Roof Rating according to the problem in question?
- (iii) If UCS and E are perhaps second order considerations in roadway roof stability as compared say to bedding properties and thicknesses, are our numerical models unbalanced in terms of their relative ability to representatively incorporate the properties of the host material as compared to bedding and other discontinuities?

The answers to these questions are far from certain at the current time, but are critical in the on-going development of methods of geotechnical characterisation and design for underground coal mining purposes. They constitute a significant focus of on-going industry funded research and collaboration between the authors in their efforts to continually improve the geotechnical design tools available to the coal industry.

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