Coal Operators' Conference	Faculty of Engineering and Information Sciences

2011

Why Dead Load Suspension Design for Roadway Roof Support is Fundamentally Flawed within a Pro-active Strata Management System

Russell Frith
University of New South Wales

Follow this and additional works at: https://ro.uow.edu.au/coal

WHY DEAD LOAD SUSPENSION DESIGN FOR ROADWAY ROOF SUPPORT IS FUNDAMENTALLY FLAWED WITHIN A PRO-ACTIVE STRATA MANAGEMENT SYSTEM

Russell Frith

ABSTRACT: Risk-based roadway roof support design is now a critical part of the Australian Coal Industry. Safe and efficient mining demands that roof support be tailored to the prevailing geotechnical conditions and legislation in both NSW and QLD is clear in requiring that formalised roof support design be undertaken.

The assumption of dead-load suspension of an otherwise unstable roof has been used in roadway roof support design for many years. However longevity does not necessarily translate into either best or even reasonable practice in the current industry, particularly when pro-active strata management systems are now routinely used and reinforcing support design methods are available.

The paper discusses why the assumption of dead-load suspension is fundamentally incorrect in almost all instances when pro-active or reinforcing roof support is being applied and how it can easily result in misleading and potentially under-designed roof support systems under various circumstances. The commonly used design methodology of balancing the installed axial capacity of long tendons with the assumed "weight" of a future roof fall is summarised and several fundamental flaws are identified. The critical area of selecting the design Factor of Safety is also discussed in detail.

Accepting that under certain circumstances the roof of a roadway will require to be "suspended", suggestions for how a robust support system can be developed, designed and applied are given.

INTRODUCTION

How many times has a roadway roof fall occurred, the long tendons broken as a direct result and the back-analysis concluded that there must have been something faulty with the steel due to the dead-load of roof material that fell out being insufficient to fail the installed tendons? In other words the question is asked as to why the roof was not stabilised by roof support that appeared to have more than sufficient carrying capacity to fully suspend the roof material that fell in. This type of roof fall back-analysis is almost always based on a basic roof suspension design that inevitably leads to a misleading conclusion about the primary causes of the fall and in the same way, if used for roof support design in the first place is equally flawed. This paper explores the flaws in such a design process and cautions the industry about its continued use.

COMMONLY PRACTICED SUSPENSION DESIGN

Suspension design is commonly practiced in roadway roof support design due to the perception that (a) it is relevant and (b) that it is straightforward (which it isn't). Furthermore until more recently the availability of design methodologies that directly address roof reinforcement have been limited. Faced with a legislative requirement to undertake roof support design and with few choices in terms of alternative methodologies, it is easy to understand why suspension design is commonly practiced. However, common use and longevity do not demonstrate that such a design methodology is appropriate though, simply that it is popular.

Suspension design is a key part of the design methodology put forward by Seedsman *et al.* 2009. In three of the four defined collapse modes for roof instability (i.e. non-vertical joints, compressive failure and tensile failure) the recommended method of support design is that of suspending a dead load. Furthermore as part of his current ACARP Project on the design of roof support in wide roadways, Colwell 2010 confirmed that suspension design is commonly practiced by mine site geotechnical personnel and also some geotechnical consultants for primary and secondary roadway roof support. Lastly Canbulat

School of Mining Engineering, University of New South Wales, Australia, rfrith@idl.com.au

2010 when discussing roof support design practices within Anglo American's Metallurgical Coal's operations in Australia lists design against "*suspension failure*" as one element of the overall process. The following quotations are taken from Canbulat 2010:

"The suspension mechanism is the most easily understood roof bolting mechanism. The design of roof bolt systems based on the suspension principle has to satisfy the following requirements (Canbulat and van der Merwe 2009):

- *The strength of the roof bolts and/or long tendons have to be greater than the relative weight of the loose roof layer that has to be carried.*

- *The anchorage forces of the roof bolts have to be greater than the weight of the loose roof layer".*

Based on the above it is clear that the use of suspension theory for roadway roof support design is currently "endemic" to the Australian Coal Industry at both a mine site and consulting level. Therefore it is fully appropriate to critique the manner in which the method is being used as part of assisting the on-going process of geotechnical design improvement.

DEFINITION OF THE CURRENT DESIGN APPROACH

It is clear that the basic suspension design methodology in common use in the coal industry utilises the following generic equation:

$$\text{Factor of Safety (FoS)} = \frac{\text{carrying capacity of the installed support}}{\text{weight of the dead load that needs to be suspended}} \qquad (1)$$

At a basic level this makes sense and is appropriate to solving a simple suspension problem as illustrated in Figure 1.
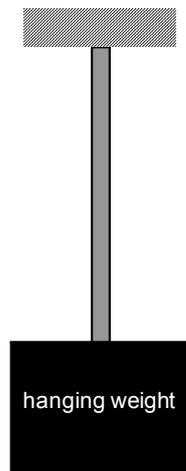

Figure 1 - Simple suspension problem involving a dead load and a vertical restraint

In the simple suspension problem shown in Figure 1 the load of the hanging weight is fixed (and presumably known) and the suspending capacity of the restraint is its axial strength. With these two parameters being readily defined, an outcome can be designed according to whatever Factor of Safety is deemed appropriate for use.

In reality this appears to be no different to the manner in which suspension design for roadway roof support is currently being undertaken in the Australian Coal Industry. It certainly fits exactly with the description provided earlier according to Canbulat 2010 and is commonly observed in numerous third-party roof support design reports.

Unfortunately the design problem is nowhere near as simple as that shown in Figure 1 when it is applied to roadway roof support. The following subject areas require further consideration:

- The weight of the dead load to be suspended is not necessarily a constant but can vary over time when for example secondary extraction is considered and the ground stresses acting will inevitably change.

- Not all suspending support elements are installed vertically (e.g. cable slings or angled long tendons – see Figure 2) hence they are not solely loaded in axial tension but will be subjected to both axial and shear components.
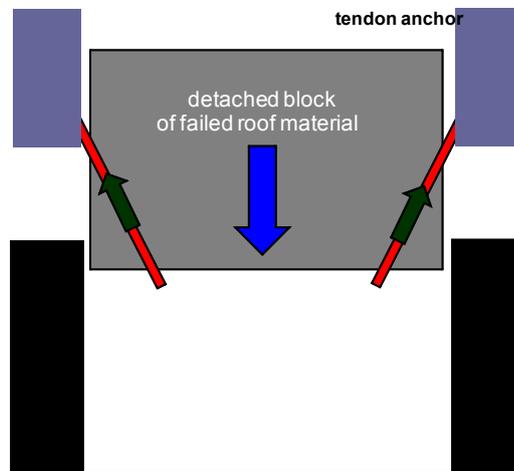

Figure 2 - Schematic illustration of suspension roof support using inclined long tendons

- On the assumption that secondary roof support in the form of either tendons or cables is installed prior to the roof being in the fully failed state that requires suspension (which it must be otherwise it would not be safe to install such support), such support will inevitably be subjected to additional stress-driven ground movements before the roof reaches a fully failed and critically unstable state, these movements including the development of horizontal shear along bedding planes.

- No industry guidance is available as to what may constitute a suitable design Factor of Safety which is particularly concerning given that the result of an inadequate design is by definition a major roof collapse with attendant safety and business risks.

Each of these subject areas will now be discussed in more detail as part of examining the true complexities and limitations involved in undertaking credible roof support design using suspension theory.

DETERMINING THE SIZE AND WEIGHT OF THE UNSTABLE ROOF BLOCK

The first and most obvious problem to be solved is in assigning a credible value to the size and hence the weight of the unstable roof block that needs to be suspended. It is evident that several different approaches can be applied to this aspect of the design process.

The size of the unstable roof block is defined by a span, height and in some cases a shape. The span is relatively straightforward as it is defined by the roadway width plus any large scale rib spall that may have occurred when the roof enters its design condition.

The shape of the roof block is one of either vertical or non-vertical sides, resulting in either a rectangular roof block as illustrated in Figure 2, a triangular or trapezoid block as shown in Figure 3 based on joint inclinations (after Seedsman, et al 2009) or the development of a roof failure "arch" as shown in Figure 4 (after Payne, 2008).

Some practitioners utilise the "Height of Softening" method whereby roof extensometry or borescope observations are used to physically measure or infer the height of a potentially unstable roof block. Alternatively Seedsman *et al.* 2009 provide basic equations whereby the likely height of roof failure is linked to such parameters as the ratio between the horizontal and vertical stress (K) and the Roof Strength Index or RSI. Obviously in some circumstances the roof strata may contain a unit that acts as a

"capping band" such that roof failure is unlikely to progress any higher than its lower limit. This also allows a likely roof failure height to be determined.
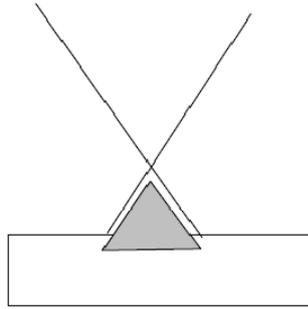

Figure 3 - Non-parallel joints defining triangular prisms (after Seedsman *et al.*, 2009)

Figure 4 - Standard "Failure Arch" roadway roof fall cavities at Crinum Mine (Payne 2008)

The main problem area identified in this paper is in determining whether the height of roof failure is likely to increase between the time that suspension support is installed and when the roof is in its final designed condition (for suspension). An increase in the height of roof failure could occur as a result of either ground stress changes as a result of secondary extraction (e.g. corner of the MG belt road) or roof geometry changes due to roadway widening (e.g. longwall installation roadway).

There are various methods by which the height of a failed roof block can be determined; however when subsequent changes in ground stress or roadway geometry are considered it is clearly not as straightforward as is commonly portrayed.

The remainder of the paper will focus on the far more complex and relevant issues of determining a realistic carrying capacity for a tendon system that is required to suspend the roof and defining an appropriate design Factor of Safety.

ANALYSING AXIAL AND SHEAR LOADS IN INCLINED TENDONS

The use of long tendons for roof suspension purposes angled at say 20° to the vertical (as illustrated in Figure 2) will not allow the full axial capacity of each tendon to be generated as vertical support resistance (which is what is required for suspension design). Each tendon will inevitably be loaded both axially and in shear if it crosses a vertical shear plane in the roof and is therefore deformed by vertical shearing. If a shear component is generated in the tendon the available axial capacity is reduced by some amount and this is well catered for in general reinforcement design for concrete as will now be detailed.

Figure 5 (from Simpson Anchors 2010a) shows the combined "allowable stress" condition for a structural element that is loaded both axially and in shear. The combined allowable stress condition is given by the following equation as found in Simpson Anchors 2010b:

$$(T / T_{all})^n + (V / V_{all})^n \leq 1.0 \tag{2}$$

Where: T = tension or axial load being applied;
  T_{all} = maximum allowable tension in the element;
  V = shear load being applied;
  V_{all} = maximum allowable shear in the element;
  n = constant that determines the shape of the allowable stress condition line (see Figure 5).

What Figure 5 and the above equations indicate is that if there is no shear on the element, then the full axial strength can be utilised. Conversely if there is no axial tension on the element then the full shear strength can be utilised. However if both axial and shear loads are being generated, neither the full axial nor shear strength can be generated in the tendon as it will inevitably undergo yield and/or failure as a direct consequence.
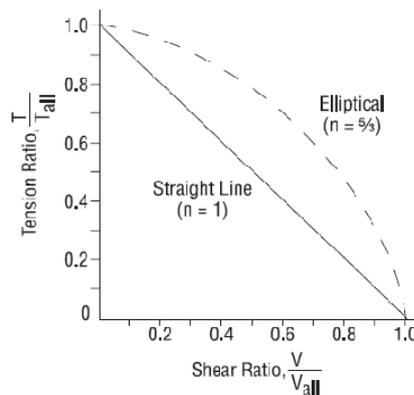

Figure 5 - Combined allowable stress condition for axial and shear loading (after Simpson Anchors, 2010a)

In relation to Equation 2, Simpson Anchors 2010b state the following:

"For anchors subjected to simultaneous tension and shear loading, the following Equation (2) must be satisfied where the value of n is product-specific. Use a value of n = 1 unless otherwise specified in the applicable products load table".

Equation 2 will now be used assuming n = 1 to illustrate the reduction in vertical load-carrying capacity of a tendon inclined at only 20º to the vertical (refer Figure 6 which provides for a graphical illustration).
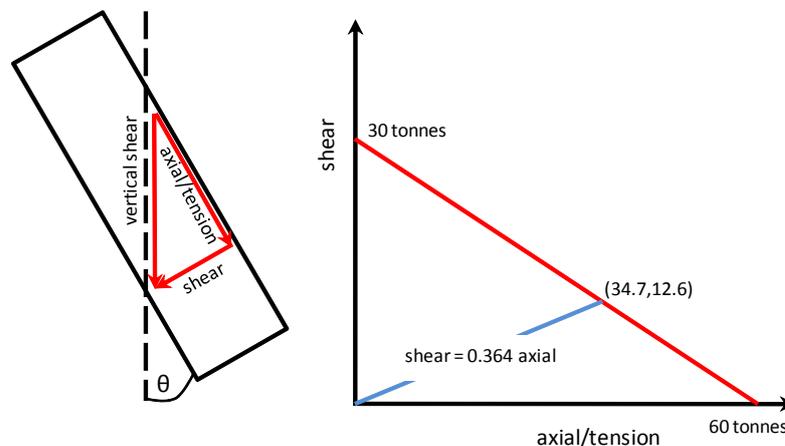

Figure 6 - Work1ed example in graphical format

At an inclination of 20º a tendon being subjected to vertical shear movement (as is likely if the roof has become a dead-load and is moving downwards under self-weight) will generate 0.364 t of shear load for every 1 t of axial load, this being governed by tan20º. This is plotted on the graph in Figure 6 to show the developing axial and shear load condition in the tendon as the roof continues to move downwards.

Assuming the use of current day long tendons with an axial capacity of 60 t and a shear strength of around 50% of this at 30 t, the allowable stress condition (in absolute terms) can also be plotted on Figure 6 (noting that no strength reductions have been applied to account for what are useable axial and shear capacities in practice as compared to the rated ultimate strengths). Where the two lines intersect is the maximum allowable stress condition in terms of both axial and shear loading. In this particular example it is evident that this is defined by an axial load of 34.7 t and a shear loading of 12.6 t.

When these values are substituted back into Equation 2 it is found that:

$$(12.6 / 30)^1 + (34.7 / 60)^1 = 1$$

This is as expected and represents the absolute highest combination of axial and shear loading for a tendon inclined at 20º to the vertical when being loaded in vertical shear.

Referring back to Figure 6 these two load components can be combined to find the resultant maximum vertical loading of the tendon using simple trigonometry, as follows:

maximum vertical loading = $(34.7^2 + 12.6^2)^{0.5} \approx 37$ s.

In other words by inclining the long tendon by only 20º off the vertical, the impact of shear in the tendon reduces the vertical load-carrying capacity from 60 t to 37 t. This is a highly significant reduction yet is rarely if ever considered in suspension design analysis in the Australian Coal Industry.

Clearly then if the roof of a roadway is required to be suspended using long tendons, inclining them by as little as 20º in order to anchor them over the adjacent coal pillars (as shown in Figure 2) which is common practice, significantly reduces their vertical load carrying capacity. This must be brought into the suspension design process if the resultant FoS value is to have any credibility and risk-based meaning.

STRESS DRIVEN GROUND MOVEMENTS FOLLOWING TENDON INSTALLATION

Following on from the discussion on inclining the tendons and inducing shear across the tendons, the same effect can also occur if the tendons are installed early in the roof deterioration process (as is commonly the case when pro-active strata management is being applied) whereby the roof has yet to fully fail (and so become a dead-load problem) and additional external stress driven roof movements are likely to occur and so induce strain in the tendons.
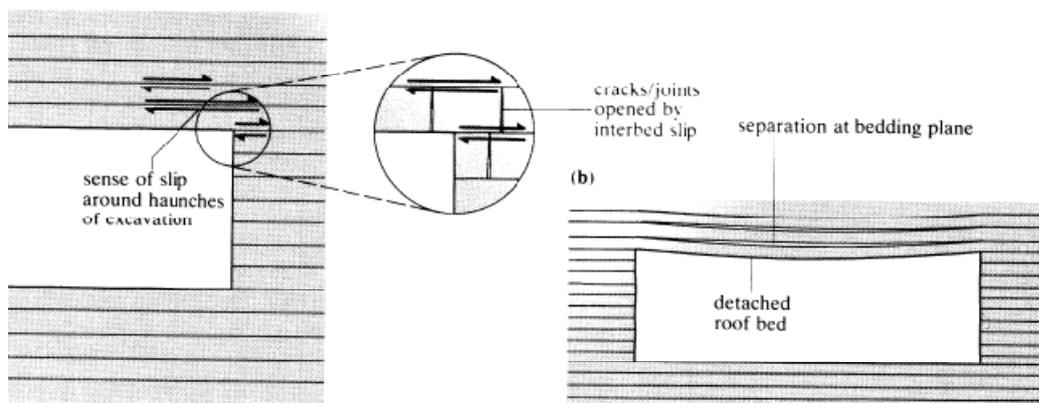

Figure 7 - Slip and separation in a layered roof rock (Brady and Brown 1985)

Seedsman *et al.* 2009 when discussing "delamination failure" as a roof failure mechanism state the following:

"As the roadway is formed, shear can develop along bedding partings, the bedding may open and individual beams of rock develop".

They illustrate this using Figure 7 which is taken from Brady and Brown 1985 and demonstrates that as a roof delaminates and displaces downwards (whether it be by horizontal stress driven buckling or vertically driven bending), bedding plane shear movement is inevitable across all of the roof except the very centre (in a symmetrical bending or buckling profile).

The phenomenon of bedding plane shear can also be reproduced in physical models as shown in Figure 8. This is a snapshot taken from a foam model used by the University of New South Wales (UNSW) to illustrate the phenomenon of roof buckling under the action of horizontal stress. Horizontal shearing along bedding planes is clearly evident.
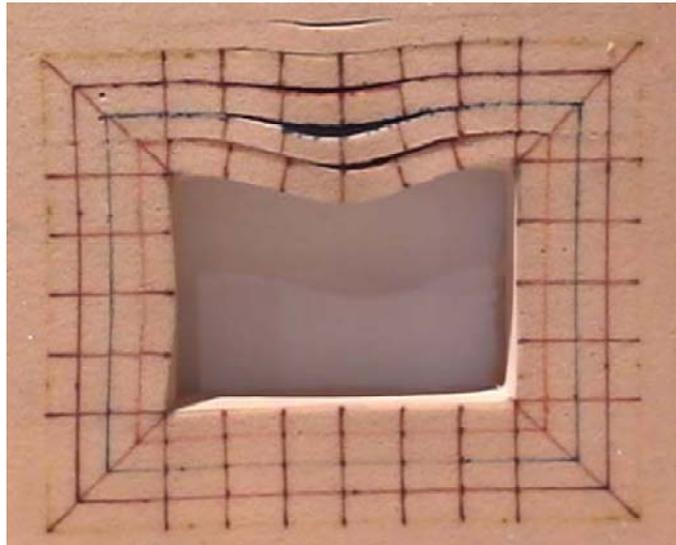

Figure 8 - Snapshot of UNSW foam model illustrating bedding plane shear associated with stress driven roof buckling

Furthermore, anyone who has ever installed a sonic probe extensometer can attest to the frustrating loss of the unit due to shearing of the hole as a result of excessive vertical roof displacement.

The point is that unless suspension tendons are installed at a time when the roof has largely failed and all future movement is purely vertical and driven by self-weight (an example of which will be provided later), they will inevitably be subjected to horizontal shear movement as a result of subsequent stress driven buckling of the roof measures. By the same argument as that presented in the previous section, such shear will reduce the axial load-carrying capacity of those tendons (see Figure 5).

This then explains the statement made at the start of the paper as to why when a roof fall occurs and long tendons are observed to have broken, the suspension back-analysis fails to explain why those tendons have broken and in fact usually indicates that they should not have broken. This inevitably leads to the questioning of the quality of the steel used in the tendons and commences a process of investigation that is almost certainly not warranted in the first place.

A SUITABLE DESIGN FACTOR OF SAFETY

Design Factor of Safety is not a geotechnical consideration but one of an acceptable level of risk based on the design being inadequate. Determining acceptable levels of risk involves mine management in addition to the geotechnical engineer. Therefore it is appropriate herein to at least provide discussion on the subject.

In terms of defining a suitable Factor of Safety for an engineering design, one has to consider the consequences of the design being inadequate. For example a major pillar collapse in an underground coal mine has the potential to result in significant loss of life, as was the case at the Coalbrook Mine in South Africa in 1960 (Van der Merwe, 2006). Similarly the business consequences can also be very

severe. As a result it is common for long-term and mining-critical coal pillars to be designed at failure probabilities in the order of one in one million.

With suspension design for roadway roof support, the consequence of an inadequate design is a major roof collapse as the support is effectively the "last line of defence". If the roof is failed and suspended by long tendons and the tendons fail, a major roof collapse is inevitable. In this regards it is interesting to note that at least one major mining house defines "*not working under a suspended load*" as one of its cardinal safety rules. Whilst this rule was obviously intended to apply to suspended heavy loads in workshops when being lifted by cranes etc. it does at least mirror the obvious safety risks associated with an inadequate roof suspension design in mine roadways where men are working on an on-going basis.

It could be argued that an appropriate standard for determining a suspension design Factor of Safety is found in cranes and hoists whereby heavy loads that are otherwise free to fall are suspended and in some cases such as elevators, persons are directly exposed to the consequences of a design failure. However this would result in design Factors of Safety in excess of 5 being applied which would clearly be costly and uneconomic. The author is not suggesting that the industry necessarily follow this approach, but is simply pointing out the sorts of considerations that would be required for a suspension design to conform to some form of relevant and accepted design standard.

When roadway roof support is designed for reinforcement then the consequences of a design failure is typically the triggering of a TARP rather than a major roof collapse. As a result the design FOS can potentially be significantly lower than in the case of a suspension design. This issue should be considered when selecting a roof support design methodology.

SUGGESTED LIMITS OF SUSPENSION DESIGN

Taking into account everything stated previously in the paper, the one example whereby a suspension design is almost certainly appropriate is where the roof has deteriorated to the point that heavy standing support has been installed but the standing support now needs to be removed for mining reasons. If the roof has already moved say 200 mm to 300 mm and the mine has installed heavy standing support to stabilise the roof it is perhaps reasonable to assume that the roof is now in a failed state such that the design and application of a suspension system is the correct control approach. Figure 9 illustrates the inferred condition of the roof when it has been allowed to deteriorate to such an extent.
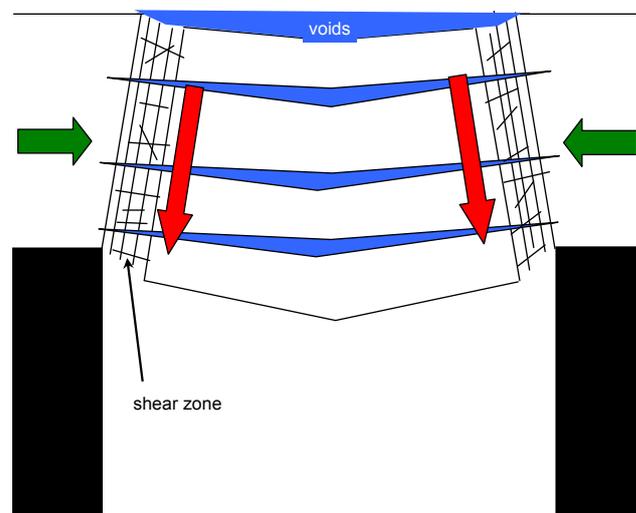

Figure 9 - Schematic of failed roof and flanking sub-vertical shear zones

If it is accepted that little can be done to increase the horizontal stress acting across the sub-vertical shear zone to stabilise the roof, and that even if the horizontal stress could be increased, it might only further exacerbate the condition of the roof material (i.e. cause more fracturing), there are only two control options available:

- to reduce the shear stress acting along the plane by holding up part or all of the roof that would otherwise fall in (i.e. roof suspension)

- to improve the shear characteristics of the surface by filling voids with material (e.g. grout) that has significant shear strength that can be mobilised without relying on horizontal confining stress (i.e. strata consolidation)

As well as the control of broken roof material, other instability mechanisms may also eventuate during longwall retreat for example that may exacerbate an already difficult situation:

- Due to voids within the roof, increased roof buckling and softening may occur higher up in otherwise currently stable strata units. This would inevitably reduce overall roof stability and increase the load to be suspended.

- Stress-induced shear movements may cause additional shear across the tendons thus reducing their available carrying capacity. Therefore tendon load-carrying capacities that were assumed as part of suspension support designs may be compromised in practice.

The most effective solution to both of these mechanisms is logically void filling and re-consolidation of the failed roof mass. Higher softening can only occur if there is a void for the roof to buckle into, therefore by filling such voids with competent material, the potential for further roof buckling and softening during retreat is significantly reduced. Similarly shear movements occur along pre-existing planes of weakness in the rock mass, particularly voids which have no shear strength. Therefore filling such voids reduces the potential for further shear within the roof, thus providing a level of protection to any tendons being used for suspension purposes.

From a design perspective both control approaches of suspension and consolidation can be analysed, the problem being that it is difficult to be certain that the designs have either been implemented as intended (i.e. grout migration cannot be fully defined) or the assumed support capacities are achievable in practice (due to such uncertainties as tendon anchorage and the reduction of tendon capacity through strata shearing effects).

The most reliable approach in this situation is to apply both suspension (using vertical tendons) and consolidation methods as this provides a level of redundancy in the design outcomes. Therefore any implementation uncertainties are far less significant and the combined stabilising effect of void filling and suspension provides for a control approach with far greater robustness than either technique in isolation. It is also noted that the most effective method by which axial load can be generated in a tendon without the development of associated shear is by pre-tensioning. As with roof reinforcement applying as high a pre-tension load to long tendons designed for suspension purposes will improve their overall effectiveness.

CONCLUSIONS

The paper has provided a review of the common use of suspension design for roadway roof support and highlighted a number of critical technical and risk-based issues that are not currently being given due consideration in the design process. Of most concern is that ignoring these issues results in the design being far more optimistic than should otherwise be the case.

The reason that many suspension designs are proving to be effective, thus also potentially convincing the designer that their design was appropriate, is that long tendon support is being applied pro-actively to the roof when it is not in a failed state and so in reality is acting to reinforce rather than suspend the roof. In essence the design process being used is inconsequential as compared to the use of a TARP and the early application of additional roof support. In lay terms the designer using suspension theory is typically getting the right answer for all the wrong reasons and this is a concern.

With the intent of attempting to improve the standard of geotechnical engineering being applied to underground coal mines, it is stated that in reality there is no need to use suspension design for roof support as credible methodologies are now available that directly address the design and application of reinforcing roof support. Methodologies such as ALTS 2009 (Colwell and Frith, 2009), AMCMRR (Colwell and Frith, 2010) and ARBS from the US (Mark, *et al.*, 2001) are all focused on the design of reinforcing roof support within a risk-based framework (noting that acceptable levels of design risk as found in ARBS from the US may not be appropriate in Australia) and can be utilised at a mine site level by appropriately trained and supported strata control engineers. Therefore it is no longer fair to say that suspension design for roadway roof support can be justified on the basis of there being no credible alternative.

All underground coal mines rely on reinforcement mechanisms in order to provide for efficient and economic roof control and few would argue this point. Furthermore reliance on suspension roof support designed to a Factor of Safety appropriate to the exposure of persons to a design failure would in fact render the industry as uneconomic within a very short period. Therefore it is not only advisable that strata control engineers dispense with suspension design for roof support (other than for very specific situations), it is in fact obligatory if the design is to mirror both the manner in which roof support almost always acts to stabilise the roof and also its application within a pro-active strata management process where the design outcome is not in fact preventing a roof fall but in reality is to prevent a triggering of the TARP.

REFERENCES

Brady, B Brown, E T, 1985. *Rock mechanics for underground mining*. George Allen and Unwin, London UK.

Canbulat, I, 2010. Roadway roof support design in critical areas at Anglo American Metallurgical Coal's underground operations. In *Proceedings of 10th Underground Coal Operators' Conference* (Eds: N Aziz and J Nemcik), pp 50-72, Published by Aus.I.M.M. Illawarra Branch. http://ro.uow.edu.au/coal/297/.

Canbulat, I and van der Merwe, N, 2009. Design of optimum roof support systems in South African Collieries using a probabilistic design approach. *SAIMM* Vol 108, pp 71-88.

Colwell, M and Frith, R, 2009. ALTS 2009 – a ten year journey. In *Proceedings of 9th Underground Coal Operators' Conference* (Eds: N Aziz and J Nemcik), pp 36-52, Published by Aus.I.M.M. Illawarra Branch. http://ro.uow.edu.au/coal/70/.

Colwell, M and Frith, R, 2010. AMCMRR – an analytical model for coal mine roof reinforcement. In *Proceedings of 10th Underground Coal Operators' Conference* (Eds: N Aziz and J Nemcik), pp 73-83, Published by Aus.I.M.M. Illawarra Branch. http://ro.uow.edu.au/coal/302/.

Colwell, M, 2010. Personal communication.

Mark, C Molinda, G Dolinar, D, 2001. Analysis of roof bolt systems. In *Proceedings of 20th International Conference on Ground Control in Mining*, pp 218-225. University of West Virginia.

Payne, D, 2008. Crinum Mine – 15 longwalls in weak roof, what did we learn? In *Proceedings of 8th Underground Coal Operators' Conference* (Eds: N Aziz and J Nemcik), pp 22-43, Published by Aus.I.M.M. Illawarra Branch. http://ro.uow.edu.au/coal/2/.

Seedsman, R, Gordon, N Aziz, R, 2009. Analytical tools for managing rock fall hazards in Australian coal mine roadways. *Final ACARP Report, Project C14029*.

Simpson Anchors, 2010a. Example calculation - adhesive anchors (traditional ASD method). Download from Simpson Anchors website www.simpsonanchors.com.

Simpson Anchors, 2010b. Allowable stress design (ASD) method. Download from Simpson Anchors website www.simpsonanchors.com.

Van der Merwe, N, 2006. Beyond coalbrook: critical review of coal strata control developments in South Africa. In *Proceedings of 25th Inernational Conference on Ground Control in Mining*, pp 335-346. University of West Virginia.