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AN ASSESSMENT OF COAL PILLAR SYSTEM STABILITY CRITERIA BASED ON A MECHANISTIC EVALUATION OF THE INTERACTION BETWEEN COAL PILLARS AND THE OVERBURDEN

Guy Reed¹ and Russell Frith

ABSTRACT: Coal pillar design has historically been based on assigning a design Factor of Safety (FoS) or Stability Factor (SF) to coal pillars according to their estimated strength and the assumed overburden load acting upon them. Acceptable FoS values have been assigned based on past mining experience and at least one methodology includes the determination of a statistical link between FoS and Probability of Failure (PoF).

The role of pillar width: height (w/h) ratio has long been established as having a material influence on both the strength of a coal pillar and also its potential mode of failure. However, there has been significant professional disagreement on using both FoS and w/h ratio as part of a combined pillar system stability criterion as compared to using FoS in isolation. The argument being that as w/h ratio is intrinsic to pillar strength, which in turn is intrinsic to FoS, it makes no sense to include w/h ratio twice in the stability assessment. At face value this logic is sound. However, this paper will argue and attempt to demonstrate that there is a valid technical reason to bring the w/h ratio into system stability criteria (other than its influence on pillar strength), this relating to the post-failure stiffness of the pillar, as has been measured in situ, and its interaction with overburden stiffness. By bringing overburden stiffness into pillar system stability considerations, two issues become of direct relevance. The first is the width: depth (W/H) ratio of the panel, in particular whether it is sub-critical or super-critical from a surface subsidence perspective. As a minimum, this directly relates to the accuracy of the pillar loading assumption of full tributary area loading. The second relates to a re-evaluation of pillar FoS based on whether the pillar is in an elastic or non-elastic (i.e. post-yield) state in its as-designed condition, this being relevant to maintaining overburden stiffness at the highest possible level.

The significance of the model being presented is the potential to maximise both reserve recovery and mining efficiencies without any discernible increase in geotechnical risk, particularly in thick seam and higher cover depth mining situations. At a time when mining economics are at best marginal, the ability to remove unnecessary design conservatism without negatively impacting those catastrophic risks that relate to global mine stability, should be of interest to all mine operators and is an important topic for discussion amongst the geotechnical fraternity.

INTRODUCTION

The majority (if not all) of the established coal pillar design methodologies are statistically derived and typically utilise a “classical” pillar strength formulae divided by full tributary area loading (i.e. full cover depth loading) to provide a FoS against core pillar failure. Pillar w/h ratio is typically included as a variable within the pillar strength formulae but otherwise is not formally used to help validate likely pillar stability outcomes as part of a combined system stability criterion. Similarly, potential design parameters such as W/H ratio and/or the presence of thick massive strata units within the overburden (both of which could significantly influence the overburden load acting on individual pillars within a panel) are seldom directly considered.

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The practical consequence of the inability to use these additional parameters when designing mining layouts incorporating load-bearing pillar systems is potentially overly conservative stability outcomes resulting in the unnecessary sterilisation of mining reserves and reduced mining efficiencies.

This paper will demonstrate that there are a number of valid technical reasons to incorporate these factors into the pillar design process via the implementation of a series of logical mechanistic arguments resulting in a more holistic pillar design approach as will now be explained.

**COAL PILLAR FAILURE MECHANICS**

In order to understand the technical justification for the mechanistic pillar system design approach being proposed, it is necessary to consider briefly coal pillar failure mechanics and the key parameters that are involved.

**Figure 1: Illustration of stable and unstable post-failure behaviours**

Figure 1 illustrates the well-established concept for stable and unstable behaviour of a structure (a coal pillar system in this instance) once it reaches its ultimate or maximum loading-bearing condition. This includes the two critical elements of (a) the post-failure stiffness of the structure (K_p), and (b) the stiffness of the system that is directly loading the structure (K_M). It is not necessary to explain this in significant detail other than to make the following points:

(i) It is obviously first necessary for the applied load to exceed the maximum load-bearing ability of the structure in order to drive the system as a whole into a post-failure condition. Without this the structure remains in a pre-failure state and is naturally stable irrespective of the characteristics of the loading system.

(ii) In the post-failure state, if the stiffness of the loading system (K_M) is less than the post-failure stiffness of the structure (K_p), the system as a whole becomes naturally unstable; as the structure will lose its load-bearing ability at a faster rate than the loading system. As such, whilst ever this condition remains the structure will inevitably progress to a fully collapsed state.

(iii) Conversely, if the stiffness of the loading system (K_M) is greater than the post-failure stiffness of the structure (K_p), the system will tend to remain naturally stable despite the maximum load-bearing ability of the structure having been exceeded. This is because the structure will lose its load-bearing ability at a slower rate than the loading system hence the system as a whole can attain post-failure equilibrium.

In coal pillar mechanics, the structure is obviously the pillar itself and the loading system is the overburden above it. Therefore, it is necessary to consider both the post-failure stiffness of coal pillars and also overburden stiffness in order to develop a more comprehensive pillar design approach.

Post-failure stiffness of coal pillars has been evaluated by other researchers using both lab-based testing of coal samples (Figure 2 after Das 1986) and in situ testing of coal pillars (Figure 3 after Chase et al, 1994). These two figures demonstrate the following points, noting that more confidence
is logically placed in the *in situ* test data shown in Figure 3 as it more accurately represents real-life field conditions present in an underground coal mine, as compared to the lab-tested samples shown in Figure 2 and the “filled-in” (i.e. non *in situ*) data points shown in Figure 3:

(a) Post-failure stiffness decreases as a function of increasing w/h ratio – both data sets clearly demonstrate this principle.

(b) By reference to Figure 3 and the *in situ* test data only, post-failure stiffness becomes “asymptotic” with increasing w/h ratio above about 2. This is in contrast to the post failure stiffness of cases that have w/h ratio values of <2 whereby, post-failure stiffness increases rapidly with ever-decreasing w/h ratio (NB increasing post-failure stiffness is detrimental to coal pillar system stability).

(c) Post-failure stiffness transitions from negative to positive (which is highly beneficial to system stability) at a w/h ratio, based on an extrapolation of the *in situ* test data in Figure 3, as low as 5.

![Figure 2: Stress-strain behaviour of coal for varying width to height (w/h) Ratio (Das, 1986)](image)

**Figure 2:** Stress-strain behaviour of coal for varying width to height (w/h) Ratio (Das, 1986)

![Figure 3: Post-failure stiffness of coal pillars as a function of width to height (w/h) ratio (Chase et al 1994) – NB open symbols represent *in situ* tests](image)
The data in Figures 2 and 3 allows two other very important statements to be made in relation to the stability and hence design of stable coal pillar systems:

1. For w/h ratios of >7 or 8, coal pillars are almost certain to work-harden (or strain-harden) as a post-failure behaviour and can therefore be classified as “indestructible” under normal overburden loading conditions (i.e. non-bump prone loading conditions) even though they will still compress significantly if loaded to a high level.

2. For w/h ratios above 2, coal pillar system collapse requires the overburden to have little or no inherent stiffness in order to overcome the potentially re-stabilising influence of the asymptotically low post-failure stiffness of the pillars.

The integrity of these two statements will now be tested in further detail by reference to known failed pillar cases.

**AN EVALUATION OF COAL PILLAR FAILED CASES**

The previous section of the paper has listed a number of coal pillar system design “rules” by reference to the stress-strain behaviour of coal according to varying w/h ratio. This section will examine those rules by reference to published cases of pillar system failures.

The listed “rules” are evident in the coal pillar failure representation first put forward by Hill (2005) (see Figure 4) whereby:

(a) the majority (i.e. >50%) of the failed pillar cases included in that database had a design FoS of <1.5 and a pillar w/h ratio <2,
(b) the density of failed cases starts to reduce for w/h ratios >2 and is effectively almost zero for values >5, and
(c) the only documented failed case at a w/h ratio of >5 (in the order of 8), which has been the subject of some industry discussion in recent times, has an FoS <1 and was likely to be a floor bearing failure rather than a core pillar failure; this being based on the geotechnical setting, which comprised thick soft floor with a history of allowing remnant coal pillars to punch through (Colwell, 2010).

![Figure 4: Database of pillar collapses – width to height ratio vs. FoS (Hill 2005)](image-url)
The failed cases data in Figure 4 is also mirrored in the US failed cases described by Mark et al (1997) (see Table 1) and summarised in Figure 5. In this regard, it is noted that ten out of the sixteen failed cases have a w/h ratio of ≤2 (with none being >3) while all SF values are <1.5. Again, the substantial stabilising effect of combining a design FoS of at least 1.5 with a pillar w/h ratio no less than 3 to 5 is clearly evident.

![Figure 5: ARMPS SF v pillar w/h ratio for pillar collapses and other case histories (NIOSH 2013)](image)

What this all leads to, is a potential resolution to the arguments and disagreements that have arisen due to the original publication of Figure 4. Galvin (2006) made the point in relation to the representation in Figure 4, that pillar w/h ratio was included in both axes; as it was already part of the FoS calculation through its inclusion in pillar strength formulae. This is absolutely correct and at face value appears to justify that this type of graphical representation of failed cases has no merit and could in fact be misleading. However, if it is accepted that pillar w/h ratio also has a significant influence on post-failure pillar stiffness, and this has a controlling influence on whether a coal pillar collapse will occur or not, then the Hill (2005) representation has significant merit. The argument that w/h ratio is included in both axes of the graph is not a valid reason to dispense with the representation.

The other coal pillar system design “rule” emanating from Figure 4 relates to pillars with w/h ratios <2 and their seeming ability to be prone to failure-collapse at FoS values that should otherwise not occur. The commonly stated reason for this is that at such low w/h values, coal pillar strength can be significantly compromised by the presence of localised geological structures, such as joint swarms,
faults, dykes etc. as compared to higher w/h ratios whereby a confined pillar core is likely to be developed irrespective of the weakening defects within the pillar. This issue simply dictates that other pillar system stability controls need to be put in place when developing a panel or mine layout incorporating large numbers of coal pillars with w/h ratios of <2 as will now be described in relation to using the stiffness of the overburden as a pillar stability control.

THE ROLE OF OVERBURDEN STIFFNESS

Having detailed the influence of both pillar FoS and w/h ratio as independent parameters influencing the role of the coal pillar in pillar system failures, it is now necessary to address the role of the overburden. Based on Figure 1 it is evident that the post-failure stiffness of the overburden needs to be suitably low for coal pillars to be driven to a state of full collapse once they have been over-loaded (as described previously).

An instructive way to address overburden stiffness is to use the established concepts of “sub-critical”, “critical transition” and “super-critical” surface subsidence as illustrated in Figure 6 with actual subsidence data being provided in Figure 7 (this representation being known colloquially in Australia as a “Holla” curve after the late Lax Holla).

The point of this is to demonstrate that it is only in the super-critical range, whereby the entire overburden to surface loses most (if not all) of its inherent stiffness so that it effectively then behaves as a “detached” loading block (with no inherent stiffness), that can drive over-loaded coal pillars to a full state of collapse. Conversely, in the sub-critical range, at least a portion of the upper overburden is demonstrably being controlled by either the excavation geometry or the spanning capabilities of massive strata units (or both), which by definition must therefore retain some level of stiffness within part of the overburden in that its natural settlement at surface under gravity is being restricted.

Evidence for the controlling influence of W/H ratio on coal pillar system failures can be found in Table 1 and also the un-published results of a study into pillar failures in highwall mining where large numbers of coal pillars with very low w/h ratios are commonly used. The US data presented in Table 1 contains minimum W/H ratio values of >0.9 but typically >1.5 for all collapsed cases with the unpublished highwall mining collapsed cases again being exclusively associated with W/H ratio values >0.9. It is noted that failed cases information published by the University of New South Wales (UNSW) are insufficiently detailed to allow this same analysis.

Figure 6: Schematic representation of the mechanics of sub-critical (“deep” beam) and super-critical (“shallow” beam) subsidence behaviour (Ditton and Frith, 2003)
The significance of a W/H value in the order of ≥0.9 is immediately obvious in Figure 8, which contains measured surface subsidence data ($S_{\text{max}}$) for cover depths in the range 70 m to 150 m. The red dotted line represents the “mid-point” of the critical transition, whereby values of W/H >0.8 tend towards being super-critical but values <0.8 tend towards being sub-critical. The point is that a minimum W/H value of 0.9 has been found in two separate studies on two different continents as being the lower defining value for failed pillar cases. This strongly confirms (a) the important role of super-critical overburden behaviour and hence low overburden stiffness to surface in pillar collapses and just as importantly, (b) the potential additional stabilising influence of W/H values <0.8 when coal pillars have been designed for full tributary area loading.

Following on from the description of the influence of W/H ratio on overburden stiffness to surface according to different surface subsidence conditions, the influence of lithology on overburden stiffness for a given panel width will now be considered.

Two fundamental studies will be referred to in this regard, one relating to the influence of thick near-seam massive strata units on overburden periodic weighting and caveability as it effects longwall face stability (Frith and McKavanagh, 2000) and the other related to the ability of massive strata units to influence surface subsidence magnitudes (Ditton and Frith, 2003).

Without digressing into significant technical detail, the periodic weighting classification developed by Frith and McKavanagh 2000 (see Figure 9) provides a useful first approximation as to how a massive strata unit may behave (i.e. collapse or span an opening) based on its thickness, the extraction panel width and its material type (specifically conglomerate or sandstone). The defined “bridging shortwall” outcome is likely to result in overburden spanning and therefore, inevitably a reduction in surface subsidence due to overburden sag from which, the retention of significant overburden stiffness can be reliably inferred.
Figure 8: Measured $S_{\text{max}}$ values analysed according to extraction height (T), panel width (W) and cover depth (H) for depths ranging from 70 m to 150 m (Ditton and Frith, 2003)

Figure 9: Periodic weighting classification (Frith and McKavanagh, 2000)
The potential spanning phenomenon associated with thick and massive strata units in the overburden was also recognised and defined by Ditton and Frith (2003) in relation to the ability of certain strata units to reduce levels of surface subsidence over and above what W/H ratio alone would suggest. Figure 10 is provided as a reference source relating to what is termed as “Subsidence Reduction Potential” (or SRP).

![Diagram showing Subsidence Reduction Potential (SRP) according to strata unit thickness, location of strata unit above the seam and panel width (Ditton and Frith, 2003).](image)

Figure 10: Subsidence reduction potential (SRP) according to strata unit thickness, location of strata unit above the seam and panel width (Ditton and Frith, 2003)

As an example, for a panel width of 120 m, the strata unit thickness above which spanning of that unit can be reliably inferred is just <20 m (marked as red circles in Figures 9 and 10). In other words, two different classification schemes that were developed to address different mining outcomes show a very close correlation in terms of the onset of strata unit spanning across an extraction panel of given width.

Figure 10 allows the analysis to be taken a stage further as it brings in the varying location of a thick massive unit within the overburden, the higher the unit above the extraction horizon (as given by y/h in Figure 10), the lower the unit thickness required to develop high Subsidence Reduction Potential (SRP). This makes sense when natural arching and consequent narrowing of the span above an extraction panel due to caving is considered (refer Figure 6 for an illustration of this concept). At a distance of half the cover depth above the extraction horizon (i.e. y/h = 0.5), the unit thickness required to modify surface subsidence across a 120 m wide panel is only 50% of that required when the unit is present in the immediate roof (i.e. y/h = 0).

Therefore, with knowledge of the W/H ratio of a proposed panel of pillars combined with the thickness and location of significant lithological units within the overburden, it is possible to make credible predictions of whether coal pillars will be loaded under full tributary area loading to surface by a “soft” loading system (as is commonly assumed in pillar design) or whether the overburden has the ability to re-distribute overburden load to adjacent barrier pillars or solid coal due to its inherent stiffness. This is a useful layout aspect to bring into the pillar design process and further develops the design...
criterion contained within ARMPS-HWM whereby the number of HWM plunges between barriers is limited to 20.

OVERBURDEN LOAD DISTRIBUTIONS WITHIN A PILLAR SYSTEM

If one uses the concept of sub-critical panel width between barrier pillars (or solid abutments) in coal pillar design, the concept of coal pillar FoS is modified to coal pillar system FoS. In practical terms what this means is that the stability of any smaller coal pillars between the larger barrier pillars needs to be evaluated with the barrier pillars also included within the overall pillar system. This changes the definition of a barrier pillar from one that has the ability to truncate a coal pillar run, to one that has the ability to prevent the pillar run in the first instance.
Figure 11 contains an illustration of a coal pillar system containing small pillars located between larger barrier pillars and illustrates the basic scenario of individual pillar loading being based solely on individual pillar width. This allows individual pillar FoS values under full tributary area loading to be determined, along with an overall system FoS for the combined influence of both the small pillars and the barriers.

To demonstrate how one may evaluate the potential influence of overburden load re-distribution due to the sub-critical nature of the spans between barriers, Figure 12 presents the same sub-critical panel layout of small pillars with the initial load exceeding their strength. Due to the sub-critical nature of the panel, overburden load is re-distributed to the adjacent larger barrier pillars. The worst-case example of this is found by assuming that an extraction goaf or gob has effectively formed between the adjacent panel barriers (or solid abutments) so that:

a. the overburden load acting on the barrier pillars increases, but
b. the overburden load acting on the smaller in-panel pillars consequently decreases

It is not being suggested that such a situation, including the necessary significant overburden fracturing via the development of a caving angle, can realistically develop within such a layout. It is simply one method of demonstrating that for sub-critical panel geometries, it is seemingly mechanistically improbable for the overburden to drive low FoS pillars between larger barriers to failure, the panel geometries of known failed cases supporting this assertion.

**COMMENTS ON DESIGN FACTOR OF SAFETY**

The current use of pillar FoS or SF is based largely on a statistical assessment of failed cases, the idea being to ensure that the design value used is sufficiently conservative so that the various unknowns or vagaries of the design problem do not in practice, combine to cause a pillar system failure whereas the analysis indicated otherwise. As a basis for further discussion, this paper suggests another possible interpretation of Factor of Safety based on the concepts presented herein, which are all based around the interplay between coal pillar stiffness and overburden stiffness rather than simply pillar strength/load.

With the exception of the failed HWM cases in Figure 4, all of the collapsed cases in both Figure 4 and Figure 5 are associated with FoS or SF values <1.5. There are no collapsed cases above this, yet the UNSW Pillar Design Procedure (PDP) extrapolates beyond this to determine Probability of Failure (PoF) values for FoS values that are well above 1.5.

The question being raised in this paper is whether there is in fact a mechanic reason as to why the collapsed cases truncate at a maximum FoS of around 1.5, such that there is then perhaps a reason to argue that for values >1.5 the potential for pillar collapse is effectively eliminated for mechanistic reasons. If this were shown to be the case, it would necessitate a complete re-consideration of the statistical evaluation of failed cases for design FoS guidance above 1.5. The practical significance of such a change in approach would be quite considerable.

If one accepts that a specific role of coal pillars is to limit overburden movements to maximise the level of overburden stiffness that is retained (thus assisting overall system stability), then a different interpretation of FoS in the failed cases is forthcoming. If one assumes that the strength formula provides for a reasonable approximation of the maximum loading-bearing capacity of the pillar, a design FoS of 1.5 would approximately represent the pillar being loaded at or close to its elastic limit (i.e. Hooke's Point). For FoS values above 1.5, the pillar would be in an elastic state, whereas below 1.5 it would enter a non-elastic state with an ever-decreasing stiffness towards its maximum strength.
In other words, for FoS values above 1.5, the coal pillar is most likely to remain in an elastic state whereas for values below it is far less likely. In terms of overburden stiffness being maximised by minimising overburden settlements, the difference between a FoS of 1.4 as compared to 1.6 would be highly significant when considered in this manner.

The work has not been done to prove this hypothesis. However it is interesting to consider that there may be a mechanistic explanation for collapsed cases almost always having pillar FoS values <1.5, rather than simply assuming that it is all based on design uncertainty and therefore applying statistical methods to address the problem of determining acceptable design FoS values to prevent future collapses.

**SUMMARY**

This paper has outlined various technical arguments for the use of a mechanistic and far more holistic approach to coal pillar system design, whereby the independent influences of w/h ratio, W/H ratio and the presence (or absence) of thick massive strata units within the overburden are considered in conjunction with pillar FoS. The objective of combining these various parameters is to provide far more robust design outcomes where more than just the strength of the coal pillar is acting to promote system stability. The potential mining advantage of doing this is in being able to design more efficient mining layouts that recover more of the available coal reserves.

The ability to combine the stabilising influences of occasional high w/h pillars within a mining layout and sub-critical working panels according to both geometry (W/H) and/or spanning strata units within the overburden, may allow for the development of stable mining layouts that would have previously been discarded on the basis of the smaller production pillars within the system having insufficient FoS or SF under full tributary area loading. This is of particular relevance to thick seam bord and pillar workings in deeper cover whereby mine design utilising only FoS under full tributary area loading is highly restrictive.

In a more general sense, shifting the focus of coal pillar design from a simple load balance to one of maximising the stiffness of the pillar system and the consequent minimisation of overburden movements as an aid to global stability, is analogous to the change from roof suspension to roof reinforcement that transformed the way that mine roadway roofs are stabilised with rock bolts. This is in an intriguing possibility to consider and one that will be the subject of a future research.

At a time when mining economics are at best marginal, the ability to remove unnecessary design conservatism without negatively impacting those catastrophic risks that relate to global mine stability, should be of interest to all mine operators and are an important topic for discussion amongst the geotechnical fraternity.

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