The limitations and potential design risks when applying empirically-derived coal pillar strength equations to real-life mine stability problems

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THE LIMITATIONS AND POTENTIAL DESIGN RISKS WHEN APPLYING EMPIRICALLY-DERIVED COAL PILLAR STRENGTH EQUATIONS TO REAL-LIFE MINE STABILITY PROBLEMS

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ABSTRACT: Determining coal pillar strength equations from databases of stable and/or failed case-histories is more than 50 years old and has been applied in different countries by different researchers in a range of mining situations. Whilst common wisdom sensibly limits the use of the resultant pillar strength equations and methods to design scenarios that are consistent with the founding database, there are a number of examples whereby failures have occurred as a direct result of applying empirical design methods to coal pillar design problems that are inconsistent with the founding database.

The paper explores the reasons as to why empirically-derived coal pillar strength equations tend to be problem-specific, and so should perhaps be considered as providing no more than a pillar strength “index”. These include the non-consideration of overburden horizontal stress within the mine stability problem, an inadequate definition of super-critical overburden behaviour as it applies to standing coal pillars and the non-consideration of overburden displacement and coal pillar strain limits, all of which combine to potentially complicate and so confuse the back-analysis of coal pillar strength from failed cases.

A modified coal pillar design representation and model is presented based on coal pillars acting to reinforce a horizontally-stressed overburden, rather than suspend an otherwise unstable self-loaded overburden or section thereof, the latter having been at the core of historical empirical studies into coal pillar strength and stability.

INTRODUCTION

The inspiration for this paper is founded in three statements from two eminent persons in the field of coal pillar strength research, Jim Galvin and Essie Esterhuizen, as follows:

“Both Salamon and Munro and UNSW based the derivation of their pillar strength formulae on a criteria that the diameter of a panel of pillars, W, had to at least equal the depth of mining, H. This was thought to result in full tributary loading. It is now known that there are some mining environments included in both the South African and Australian databases in which mining span must exceed depth by a considerable margin in order to achieve full deadweight loading. Hence, it is logical to conclude that these data points may have contributed to pillar strength being overestimated by Salamon and Munro and UNSW (underline added by authors). Normally, this should be of no consequence because it is reflected in the probability of design success associated with any given safety factor.” Galvin 2006

“Empirical models, based on the analysis of large numbers of case histories, have found wide acceptance as a tool for engineering design. The application of empirical models is

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limited by the restriction that they should not be used beyond the limits of the empirical base from which they were developed.” Esterhuizen 2014

“Pillar design criteria based on field experience have met with mixed success” – Galvin 2016

This paper addresses three inevitable but currently unresolved questions that follow from these statements:

(i) How significant might the overestimate of pillar strength be when the varying contribution of the overburden to the stability or instability of mine workings supported with coal pillars is ignored when back-analysing failed cases?

(ii) How important and what are the various “limits” that need to be considered when determining whether an empirical method can be used with confidence or not?

(iii) Based on (i) and (ii), in hindsight is it reasonable for empirically-derived pillar strength equations to use units (e.g. psi or MPa)?

A CONCEPTUAL CAUSE AND EFFECT MODEL FOR OVERBURDEN STABILITY/INSTABILITY

If the influence of the overburden above collapsed mine workings supported by coal pillars is to be quantified, a conceptual model is required that incorporates all of the primary controls. Such a model was first outlined in Frith and Reed 2017 which is developed further herein to produce a Ground Reaction Curve (GRC) representation that incorporates the associated principles.

A series of simple thought-experiments relating to super-critical extractions, as stated by Galvin 2006 as W/H > 1, can demonstrate the direct influence of key geotechnical parameters on overburden stability or instability.

Figure 1 represents a massive sandstone with no vertical joints or horizontal stress. Under this scenario, it is obvious that the overburden will remain stable across a wide extraction span, with the associated GRC rapidly reducing to zero stress (i.e. a self-supporting condition).

Figure 1: Thought-experiment and ground curve: massive overburden with no vertical joints or horizontal stress

Figure 2 is identical to Figure 1, but contains laminated material. Under this scenario, the overburden would initially “sag” downwards and eventually exceed a “critical” level of movement marking the onset of instability to full overburden collapse to the surface (i.e. Tributary Area Loading in coal pillar design terminology).
Figure 2: Thought-experiment and ground curve: laminated overburden with no vertical joints or horizontal stress

Figure 3 contains the overburden representations of Figures 1 and 2, but introduces vertical joints and horizontal stress. Vertical jointing is omnipresent in coal measures strata sequences and is characterised by zero cohesion and a friction angle that varies according to surface conditions along the joint. Therefore, vertical shear resistance cannot develop along the joint without a normal confining stress, which is horizontal in this case. Therefore irrespective of overburden lithology, without the presence of horizontal stress the presence of vertical jointing will inevitably result in a GRC as shown in Figure 4, namely an unstable overburden with zero stiffness from the outset.

Figure 3: Thought-experiment representations: massive and laminated overburdens including vertical joints and horizontal stress

Figure 4: GRC- vertical joints present without horizontal stress
Once overburden horizontal stress is included, the influence of overburden lithology and vertical shear resistance along vertical joints can be combined, resulting in a range of possible GRC outcomes as generally illustrated in Figure 5.

![Figure 5: Varying influence of overburden lithology, vertical joints and horizontal stress on GRC's](image)

For any given span between either barriers or solid coal, overburden stability or instability is directly influenced by the presence or absence of massive strata units, and the horizontal stress generating a stabilising influence along vertical joints. In combination, these two geotechnical parameters logically give rise to two distinctly different mechanisms associated with overburden instability and eventual collapse:

- delamination and/or associated sag whilst ever vertical joints remain horizontally “clamped”, or
- a “plug” type collapse due to vertical joints becoming unstable from insufficient horizontal confinement.

The first point of developing this conceptual model is to justify the concept that overburden conditions dictate the importance of the coal pillars in maintaining stable mine workings, not the other way round.

**MEASUREMENT DATA THAT SUPPORTS THE BASIS OF THE CONCEPTUAL OVERBURDEN MODEL**

At the 36th International Conference on Ground Control in Mining, (ICGCM), concern was raised that without field-data substantiating the magnitude of the overburden stress drop before collapse was initiated in a GRC (as per Figure 5), there was no way of quantifying the extent by which the nature of the overburden may have influenced back-analysed coal pillar strengths from failed cases. It was also strongly suggested that the overburden GRC may commonly approximate to that shown in Figure 4, hence there was no significant disconnect between back-analysed and actual coal pillar strengths.

These statements are hypothetically correct and even the fundamental work of Esterhuizen et al. 2010 provides only limited assistance in addressing them as the study was undertaken without field data validating the numerically produced GRC’s (see Figure 6), the statement being made that “it is difficult to measure the ground response curve in actual underground excavations because of the significant loads that would have to be applied to balance the original ground pressure”. This again is correct, but it doesn't alter the need for field data to validate GRCs if their value in the design of underground mines using coal pillars is to be maximised.
Figure 6: Ground response curves at the centre of a 300 m wide panel in weak and strong overburden strata at 150 m and 450 m depth of cover (Esterhuizen et al. 2010)

A literature search has been undertaken to identify surface subsidence data from above coal pillar systems that have allowed overburden collapses. Fortunately, such subsidence data exists from the Lake Macquarie area of NSW in Australia relating to partial extraction layouts, and despite pillar system failure relating to floor rather than pillar failure, as it is the GRC of the overburden that is of specific interest, this makes no material difference.

Ditton and Sutherland 2013 describe a significant unexpected subsidence exceedance related to a completed Duncan Method of partial extraction workings in the Fassifern Seam with a soft claystone floor at the Tasman Mine. The exceedance was within the 3 North Panel and was limited to an area whereby the standard five heading development layout was extended to six headings over a panel length of four pillars (i.e. approximately 180 m) as shown in Figure 7.

Figure 7: Modified Duncan panels (2b-North, 3 North and 4 South) to west of transition zone and cover contours (Ditton and Sutherland 2013)
Figure 8 shows the variation in vertical subsidence across the exceedance area of six headings and the adjacent area of five headings, Figure 9 containing a time-dependent plot of $S_{\text{max}}$ above the six heading area as estimated from Figure 8. Based on these two figures and what is known about the Tasman geotechnical environment (including from McTyer and Sutherland 2011), the following comments are made:

(i) Immediately post-mining, the development of $S_{\text{max}}$ follows a trend of a high rate that decelerates to a longer-term condition, in this case very slow creep at an average rate of 3 mm/month.

(ii) Based on extrapolation, once $S_{\text{max}}$ reached 150 mm to 200 mm, an obvious change of state occurred via a substantial increase in settlement rate (to around 50 mm/month) followed by a deceleration back to a second longer-term condition with $S_{\text{max}} > 450$ mm (NB questions-marks have been included in Figure 9 as reading frequencies do not allow the exact nature of the transition to be reliably identified).

(iii) The floor of the mine workings was soft and heaved following mining (Figure 10), coal pillars remaining relatively intact.

(iv) The overburden included the Teralba Conglomerate in the order of 20 m thick.

(v) The subsidence exceedance was restricted to the six headings area with an extraction width between solid coal of 248 m, as compared to the five heading area at a width of 203 m as shown in Figure 8.

(vi) Both five and six heading areas were at a cover depth in the order of 130 m (see Figure 8) and so using the selection criterion used by Salamon and Munro as well as UNSW, both were under full tributary area loading to surface and presumably had identical pillar loadings.

(vii) The increased subsidence did not extend into adjacent five heading areas, indicating that the “event” was controlled by the excavation geometry and overburden stability, rather than pillar stability.

(viii) With a seam outcrop around three sides of the mine shown in Figure 11, tectonic horizontal stress levels were low, as discussed by McTyer and Sutherland 2011.

The conclusion reached is that the increased subsidence in the six heading area was likely to have been caused by the onset of “plug” type overburden instability within the Teralba Conglomerate once a critical or threshold level of overburden movement had been reached (around 150 mm) due to on-going overburden creep with time due to floor instability.
Figure 8: Delayed subsidence above 3 North in level 1 area (Ditton and Sutherland 2013)

Figure 9: Time dependent variation in $S_{\text{max}}$ within 3 North subsidence exceedance area

Figure 10: Moderate floor heave in 3-North panel (outbye)

Figure 11: North-south section across the Tasman mine lease showing the Fassifern seam outcrop around the sugarloaf range (H:V = 20:1) - Fassifern Seam is shown in black (McTyer and Sutherland 2011)
Four similar examples to that described for the 3 North Panel at Tasman Mine have been found in the published literature.

Figure 12: An example of the rate of development and magnitude of vertical surface displacement due to bearing capacity failure of the floor in partial extraction workings at a depth of 160 m (Galvin 2016)

Figure 13: Surface settlements from Newvale colliery (Shirley and Fagg 2017)

Figure 14: Subsidence vs time plot for 5NE panel, Newvale 2 colliery (Vasundhara et al 1998)
Figure 15: Remnant mine layout, NE panels, Newvale 2 colliery (Vasundhara et al 1998)

Figure 16: Some of the known rapid floor heave and subsidence events in the great northern seam at Awaba colliery (Seedsman 2008)

Figure 12 is taken from Galvin 2016 and Figure 13 from Shirley and Fagg 2017 relating to the section of the Newvale Mine associated with the well-publicised lowering of the lake foreshore in Chain Valley Bay in the late 1980’s/early 1990’s. Figure 14 contains measured surface settlements vs time above the 5NE Panel at Newvale 2 Colliery (Vasundhara et al 1998) with Figure 15 showing the remnant mining layout in the NE Panels. Figure 16 is taken from Seedsman 2008 whereby he back-analysed what were described as “rapid floor heave and
subsidence events” at Awaba Colliery, noting that some of these events occurred at depths as low as 60 m with coal pillars on 20 m centres having pillar Factor of Safety (FoS) values in excess of 3.

All of the listed case histories have a number of common characteristics that are of particular relevance herein:

(i) The partially extracted areas are all super-critical in that W/H values are >> 1. The partial extraction areas shown in Figures 12 and 15 are in the order of 600 m x 600 m with cover depths in the order of 160 m to 180 m, resulting in W/H values in the order of 3 to 4.

(ii) Following the completion of partial extraction, initial subsidence levels were low with longer-term trends consisting of very low rates of creep with time (where sufficient measurements were taken to allow time-dependent trends to be reliably identified).

(iii) At subsidence values of 150 mm and greater, the rate of subsidence with time rapidly increased with longer-term subsidence levels approaching 1 m.

(iv) Longer-term settlement rates commonly returned to low values with no evidence of further sudden increases, even several years later.

(v) In Great Northern Seam workings, the presence of thick, massive conglomerate units in the overburden as well as soft tuffaceous floor material, can be reliably inferred.

Figure 17 (Mills and Edwards 1997) succinctly summarised some 29 remnant pillar case histories incorporating soft floor measures in the Lake Macquarie area, whereby measured surface subsidence magnitudes clearly polarise into two distinctly different categories, namely “pillars intact” for $S_{max}/T < 0.075$ and “pillars failed” with $S_{max}/T$ varying as a direct function of pillar w/h. A gradual transition between the two conditions via increasing surface subsidence over time is also identified in four of the case histories. With the stated seam thickness involved being 2.2m to 2.5 m, provides for an upper $S_{max}$ value for “pillars intact” (or overburden stable in more general terms) in the order of 165 mm to 187.5 mm.

![Figure 17: Subsidence as function of pillar width to height ratio for soft floor failures (Mills and Edwards 1997)](image)

Using these specific case histories and relevant geotechnical characteristics, a technical discussion on mechanistic causation can be developed.
The majority of the investigative work that accompanied these delayed and unexpected surface settlement events above partial extraction areas, focused on the failure and compression of soft floor material beneath remnant coal pillars. This is fully understandable given the nature of the floor material and commonly observed floor heave in the workings.

The technical issue that received almost no attention was determining the cause of the rapid increase in the rate of subsidence months after the completion of mining, this being a common feature of the case histories.

Seedsman 2008 makes the statement that “massive conglomerates may span and delay evidence of imminent over-loading of pillars – temporarily stiff loading system”. However when the mined-out areas have widths and lengths in the order of 600 m at cover depths < 200 m, conventional subsidence thinking would inevitably eliminate the possibility that even thick massive conglomerates could span across such areas, this being consistent with the periodic weighting classification for longwalls (Frith and McKavanagh 2000) whereby a 30 m thick conglomerate can only span across an extraction width of 200 m (see Figure 18), certainly not 600 m. Clearly there is a major problem or disconnect using overburden caving behaviour from total extraction panels such as longwalls, to estimate overburden spanning ability when substantial coal pillars are left in place.

![Figure 18: Near-seam, massive strata weighting classification (Frith and McKavanagh 2000)](image)

The suggested solution to this conundrum, which is as per that stated by Van de Merwe 2006 and addressed in Frith and Reed 2017 in relation to the non-collapsed area at Coalbrook, is found in two aspects of bord and pillar workings and/or partial pillar extraction that are absent from longwall extraction once full caving has been established, namely:

(i) the contribution of the remnant coal pillars to overburden stability, and

(ii) the stabilising influence of horizontal stress within the overburden.

In other words, the GRC for the overburden must be being altered by remnant coal pillars, this being consistent with the idea that coal pillars “reinforce” rather than “suspend” the overburden, as was discussed in Frith and Reed 2017.
As illustrated in Figure 5, it is postulated that the onset of super-critical overburden conditions to surface is dictated by the overburden exceeding a critical level of subsidence, which based on data published by Mills and O’Grady 1998 and Ditton and Frith 2003 was suggested as being in the order of 200 mm by Frith and Reed 2017. Surface extensometry data published by Salamon et al 1972 further indicates the onset of rapid subsidence for values exceeding 150 mm to 200 mm (see Figure 19). The close correlation with measured subsidence magnitudes at the onset of rapid subsidence in the previously described partial extraction cases from the Lake Macquarie area of NSW, is also noted.

Re-defining the role of coal pillars as reinforcing rather than suspending the overburden, was discussed in length by Frith and Reed 2017, a general arrangement for the pillar design problem including a more detailed overburden representation containing thick massive strata units, vertical joints and in situ horizontal stresses, being shown in Figure 20. It is noted and accepted in this representation, that the in situ vertical stresses acting on the production pillars cannot be re-distributed out to any flanking barrier pillars by the action of the overburden, as this would require said pillars to vertically expand or extend due to mining. Therefore, it is only the in situ vertical stress that is released by the formation of mining excavations that can be re-distributed, either in full or more likely, in part.
The controlling influence of overburden horizontal stress on surface subsidence was recognised by Mills 2012, who concluded that “sag” subsidence increases in the presence of high horizontal stress, based on subsidence data from the Newcastle Coalfield in NSW. The explanation for this phenomenon is beyond the scope of this paper, but inevitably leads into the significance of high horizontal stress in roadway roof control as being the driver for uncontrolled buckling of the roof strata, the control and limiting of which is a reinforcing rather than suspension roof support design problem.

If overburden instability to surface (i.e. the “vertical shear slip” line within the GRC in Figure 5 occurs as a distinct change due to vertical joints becoming unstable at subsidence values of 150 mm and greater, then as discussed in Frith and Reed 2017 any coal pillars that subsequently collapse as a direct consequence will have inevitably exceeded their peak strength well prior to this occurring. This is illustrated schematically in Figure 21 and is consistent with the quotation from Galvin 2006, the question then being whether the magnitude and design significance of coal pillar strength over-estimates can be quantified or not?

**HOW SIGNIFICANT CAN COAL PILLAR STRENGTH OVER-ESTIMATES ACTUALLY BE?**

A general equation for the reinforcement of a mine roadway roof was provided in UNSW 2010 and has been slightly modified as follows:

\[
\text{FoS} = f(P_{\text{roof}}, P_{\text{support}})/(\text{applied load}) \tag{1}
\]

where:
- FoS = a measure of stability;
- \( P_{\text{roof}} \) = contribution to stability from the roof strata itself (e.g. Coal Mine Roof Rating);
- \( P_{\text{support}} \) = contribution to stability from installed roof support (e.g. PRSUP);
- applied load = horizontal stress in the case of roadway roof reinforcement.

This basic equation manifests in the statistically significant empirical relationships published by Colwell and Frith 2009 and 2012 relating to primary roof support design in normal width and wider coal mine roadways respectively. It is also the foundation of the AMCRRR Method as published by Colwell and Frith 2010.

Equation 1 can be modified for coal pillar design as follows:

\[
\text{FoS} = f(P_{\text{overburden}}, P_{\text{pillar}})/(\text{applied load}) \tag{2}
\]

where:
- FoS = a measure of stability;
P_{overburden} = stability contribution from the overburden (linked to both the structural competence of the overburden and horizontal stresses acting as outlined previously);

P_{pillar} = stability contribution from coal pillars left in place;

applied load = either horizontal stress or vertical stress based on the problem being reinforcement of suspension respectively (NB P_{overburden} = 0 represents the special case of full-tributary area loading to surface with the overburden being critically unstable).

If the model for overburden and coal pillar stability (Figure 20) is accepted along with both the generic GRC concept (Figure 5) and Equation 2, it logically follows that the accuracy of back-analysed coal pillar strengths from failed cases must improve as the stabilising influence of horizontal stress and/or massive strata within the overburden decreases, the overburden GRC then tending towards that shown in Figure 4 with no stabilising contribution from the overburden from the outset.

Two obvious scenarios whereby the stabilising influence of horizontal stress is likely to be minimised or reduced are:

1. Highwall Mining (HWM) from an open cut highwall, this entire issue being at the centre of a recently published pillar strength equation specifically for Australian HWM pillars (Mo et al 2017), and

2. Decreasing cover depth more generally whereby surface topography effects, the depth of weathering and reducing strata stiffness should increasingly act to reduce horizontal stress magnitudes in the overburden.

The significant mismatch between underground mining failed cases and those from HWM, in Australia at least, is obvious in Figure 22 (Hill 2005). This representation of failed pillar cases resulted in a strong response (Galvin 2006) arguing that as pillar w/h was included in both axes, it was mechanistically incorrect or “ill-advisable” to represent failed cases in this manner. Unfortunately, the more obvious question went either unnoticed or unaddressed at that time, namely why is the stability of HWM pillars so different to those from the underground mining environment?

![Figure 22: Database of pillar collapses – width to height ratio vs. FoS (Hill 2005)](image)

Various arguments have been made by others concerning the weakening influence of minor geological structures on the strength of low w/h ratio pillars due to the absence of pillar confinement, but this would surely equally apply to both HWM and underground coal pillars.
Figure 22 does not support such a hypothesis, particularly given that the number of underground failed cases is greater than those from HWM, such that the effect should be more, rather than less, obvious in the underground failed cases if it were present in low w/h ratio pillars. Nonetheless, UNSW undertook a back-analysis of the HWM failed cases shown in Figure 22 and developed a HWM-specific strength equation (Equation 3 from Canbulat et al 2016) with the equation itself included in Mo et al 2017:

$$\sigma_p = 4.66(0.56 + 0.44 \frac{w}{h}) \text{ or } 2.61 + 2.05 \frac{w}{h}$$

(3)

However Equation 3 for HWM pillars results in the illogical situation whereby the strength of a long strip pillar (as given by Equation 3) is less than for a square pillar of the same width and height as given by the Salamon and Munro 1967 equation for w/h < 5 as an example (Equation 4).

$$\sigma_p = 7.176(\frac{w^{0.46}}{h^{0.66}})$$

(4)

However, it is intriguing to consider that Equation 3 is very similar in magnitude to the Bieniawski 1968 equation that was derived from the in situ testing of coal pillars in South Africa as given by Equation 5.

$$\sigma_p = 2.76 + 1.52 \frac{w}{h}$$

(5)

The suggestion that coal pillar design in underground mining is a reinforcing problem whereby the stabilising contribution of the overburden needs to be given due consideration, is seemingly strengthened by the fact that Australian HWM coal pillars, where the stabilising influence of overburden horizontal stress is inevitably lower than in underground mining, return lower inferred pillar strengths as compared to pillars in underground mining.

In terms of the stabilising influence of horizontal stress being reduced by ever-decreasing cover depth, it is judged that both the US and Australian collapsed pillar databases are too small to provide any meaningful insights. However, the South African collapsed pillar database in its entirety (i.e. including as many failed cases have been able to identified) is sufficiently large and does show intriguing trends as will now be detailed.

Figure 23: FoS vs depth for cases used by Salamon and Munro 1967
Figure 23 shows the 27 collapsed cases that were used by Salamon and Munro 1967 whereby the FoS using the Salamon and Munro 1967 strength equation (Equation 4) is plotted against cover depth. The collapsed cases centre around an FoS in the order of 1 with no obvious significant trend of increasing FoS with reducing cover depth.

Figure 24 contains those collapsed cases used by Salamon and Munro 1967 and the additional 17 cases considered by Bernard Madden between 1967 and 1988 (Madden 1991). Again the cases centre around 1, but there is a hint of increasing SF with decreasing cover depth at less than 50 m.

Figure 25 includes all of the known collapsed cases from South Africa, with both the Salamon and Munro and Madden data points being differentiated from the other cases. The clear and obvious trend for maximum FoS value to incrementally increase with decreasing cover depth below 100 m being obvious. This is not dissimilar to that shown in Figure 22 for Australian HWM cases, the point being that the South African cases in Figure 25 are all from underground mines. Therefore, perhaps it is not HWM that is the driver for reduced coal pillar strength in HWM, but something far more fundamental?

![Figure 24: FoS vs depth for failed cases used by Salamon and Munro 1967 and Madden 1991](image1)

![Figure 25: FoS vs depth for failed cases used by Salamon and Munro 1967 and Madden 1991 Along with other South African failed cases](image2)
An explanation for the apparent conundrum of these very high FoS collapsed cases from South Africa was linked to the time-dependent spalling or scaling of pillars, such that pillar collapse must have eventually occurred when the FoS reduced to a suitably low level as compared to the as-formed pillars. Van der Merwe 1993 examined this issue for Vaal Basin collapsed cases and determined that the rate of pillar scaling was a direct function of mining height. Salamon et al 1998 developed the idea that pillar scaling was driven by the swelling of montmorillonite clays within the coal seam, this basic model then being utilised by Canbulat 2010 in his treatment of the time to failure problem (Figure 26).

![Figure 26: Design safety factor vs time interval (Canbulat 2010)](image)

Unfortunately the originators of this hypothesis only ever put forward the idea of swelling clays driving pillar scaling as a possible mechanism to explain high Safety Factor (SF) collapsed cases, making the following clarification:

“No direct evidence appears to exist to substantiate the proposed model of pillar scaling. Thus, it is not possible to prove convincingly the validity or otherwise of the approach” (Salamon et al 1998).

They also state that

“It is important that the cause of abnormal collapses be investigated and explained as soon as possible. Such study is likely to find that anomalous behaviour is due to more than one cause. Van der Merwe’s observations imply that pillar scaling could be a reason for some of the premature failures. This deduction and the promising performance of the model proposed here provide a powerful basis for recommending that further study should be initiated to clarify the role of scaling or spalling in pillar mechanics”.

In other words, the work of Salamon et al 1998 was no more than an initial attempt at explaining failed cases with anomalously high FoS values.

One possibility that was not considered, but would be well supported by the overburden reinforcing model for coal pillars outlined herein, is that the high FoS values of failed cases were erroneous in the first instance due to the strength equation that was used substantially overestimating actual coal pillar strength due to the fundamental assumptions used as part of its derivation. When this possibility is combined with the stabilising contribution of the overburden decreasing with decreasing cover depth, the occurrence of pillar scaling over time makes good sense, such scaling being related to under-designed coal pillars that are being compressed over time above yield and towards their ultimate strength, until overburden instability and inevitably pillar collapse eventually occurs.
The suggestion that pillar scaling over time could be due to coal pillars being under-designed to start with is hardly controversial. However, if high pillar FoS values were accepted as correct due to reliance being placed on the coal pillar strength equation that was used in their derivation, then searching for an alternate explanation that was independent of coal pillar strength would be a logical path to follow.

OVERALL SUMMARY

A set of technical arguments backed-up with various field data have been presented to support the hypothesis that bord and pillar—type coal pillar design in underground coal mining is generally one of the coal pillars reinforcing the overburden, such that they combine with the overburden to stabilise the mine workings. The reinforcing representation put forward is comparable with that which is well established in coal mine roadway roof control and contains the same basic input parameters, including the significant influence of horizontal stress magnitudes.

If it is assumed (for the sake of illustration only) that the full-tributary area loading model is correct and is applied within a GRC representation (as shown in Figure 27), then for collapsed pillar cases one must conclude that the actual peak pillar strength is inevitably less than full-tributary area pillar loading, otherwise the two curves would have intersected and system stability would have been returned. In other words, the assumption of full-tributary area loading when back-analysing collapsed pillar cases must result in pillar strength equations that over-estimate the true strength of the pillars by some amount, even in those situations whereby there is no contribution to system stability from the overburden. The pertinent question therefore is the potential magnitude and significance of over-estimated or optimistic coal pillar strengths being returned due to this irresolvable and undefined error, this being the main subject of on-going work.

![Figure 27: Schematic illustration of pillar strength over-estimate even if full-tributary area loading is appropriate in a collapsed case](image)

The reinforcing model logically suggests that pillar strength equations derived from the back-analysis of failed pillar cases under the assumption of full-tributary area loading, in reality more likely provide a measure of the combined stabilising influence of both coal pillars and the overburden. The result of this is that under specific conditions whereby the stabilising influence of horizontal stress within the overburden is either low or indeed absent, highly optimistic mine layouts can inadvertently and unknowingly be developed and implemented if those same pillar strength equations are applied without this realisation.

The design risks associated with determining pillar strengths from back-analysed case histories, particularly from single or only a small number of cases, are potentially substantial if one
accepts this conclusion, the worst-case consequence of which is perhaps best summarised in the following statement in relation to the Crandall Canyon disaster:

“In a December 3, 2007 submission to MSHA, a consultant explained that the “coal strength was calibrated from three mining stages in the south panel of Section 36. The coal strength was incrementally increased from 900 psi to 1640 psi until modelling results were consistent with actual conditions. The average cover depth in this calibration panel was about 1,700 ft. We were told that all the pillars during retreat mining were stable and only limited yielding occurred at some pillar ribs.” – taken from US Senate 2008.

Therefore, perhaps it might be prudent for coal pillar strength equations that are determined from case histories to never be given units (such as MPa or psi), even if the associated statistical correlations are compelling. Treating them as “index” parameters that are linked to a particular design method, or re-naming them as an “estimate of the combined stabilising influence of coal pillars and the overburden” for example, may assist in ensuring that such equations are not used out of context.

Based on the content and conclusions of this paper, the quotation from Esterhuizen 2014 in regards to only using empirically design methods within the limits of their supporting database, has great substance, but leaves one further key question unanswered – what are those limits and how are they defined? Given the critical importance of this to the mine designer, the developers of the various bord and pillar-type coal pillar design methods may wish to consider this question in more detail according to the known specific characteristics of the supporting case histories.

REFERENCES


