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COAL PILLAR DESIGN WHEN CONSIDERED A REINFORCEMENT PROBLEM RATHER THAN A SUSPENSION PROBLEM

Russell Frith[1], Guy Reed

ABSTRACT: Current coal pillar design is the epitome of suspension design. In principle, this is seemingly no different from early roadway roof support design. However, for the most part, roadway roof stabilisation has progressed to reinforcement, whereby the roof strata is assisted in supporting itself. Suspension and reinforcement are fundamentally different and, importantly, lead to substantially different requirements in terms of roof support hardware characteristics and their application. This paper presents a prototype coal pillar and overburden system representation where reinforcement, rather than suspension, of the overburden is the stabilising mechanism via the action of *in situ* horizontal stresses within the overburden, the suspension problem potentially being an exception rather than the rule, as is also the case in roadway roof stability. Established principles relating to roadway roof reinforcement can potentially be applied to coal pillar design under this representation. The merit of this assertion is evaluated according to documented failed pillar cases in a range of mining applications and industries found in a series of published databases. Based on the various findings, a series of coal pillar system design considerations and suggestions for bord and pillar type mine workings are provided. This potentially allows a more flexible and informed approach to coal pillar sizing within workable mining layouts, as compared with common industry practices of a single design Factor of Safety (FoS) under defined overburden dead-loading to the exclusion of other potentially relevant overburden stabilising influences.

INTRODUCTION

The simplest model for coal pillar loading consists of an unstable overburden to the surface, known as Tributary Area Theory (TAT), overburden stability then being entirely controlled by the load-bearing ability of the coal pillars formed in the workings (Figure 1). For bord and pillar type mining design purposes, the TAT model to the surface has been and can be modified (by the application of either pressure-arch concepts or by considering the sub- or super-critical nature of the overburden at the surface) to modify pillar loading magnitudes, it is still generally true to state that the stability of coal pillars is evaluated via a defined unstable section of overburden imparting dead loads onto the coal pillars beneath. The level of confidence in the design remaining stable is then determined according to the design Factor of Safety (FoS) over and above the assumed coal pillar strength(s).

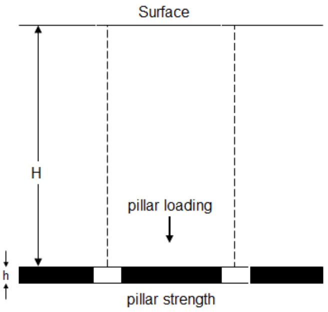

Figure 1: Tributary Area Theory (TAT) loading arrangement for coal pillars

Since the Coalbrook disaster in 1960, the basic model of full TAT to surface has been applied in empirical studies attempting to define the strength of coal pillars by back-analysing failed cases (e.g. Salamon and Munro 1967). Figure 2 shows how pillar loading can be modified

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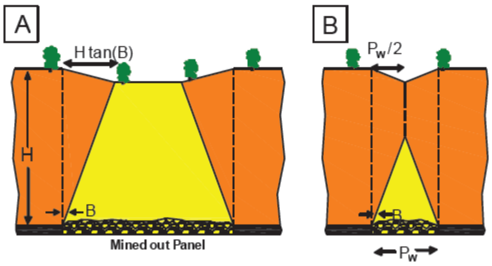
according to panel width to cover depth considerations (*W*/*H* ratio) as part of what may be termed as partial TAT [Mark *et al* 2010]. In both cases, vertical dead-loading of the overburden onto the coal pillars is the key pillar design assumption.



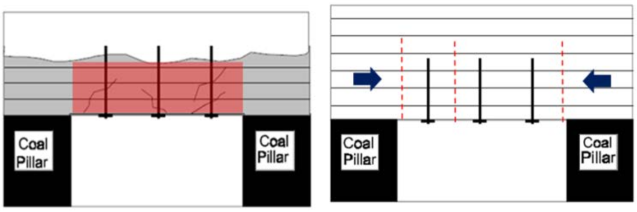
(a) Super-critical panel (b) Sub-critical panel

Figure 2: Abutment angle concept used to estimate loads in ARMPS [Mark *et al* 2010]

Van Der Merwe 2006 makes the following statement in relation to what occurred in the immediate aftermath of Coalbrook: *"The attention was focused on pillar strength research, very little attention initially being paid to overburden strength. This is not an unreasonable approach: if the pillars are strong enough to support the overburden, it doesn't matter how weak the overburden is—failure cannot occur. This is especially true if the [TAT] is used to determine pillar load because TAT predicts the maximum load on the pillar".*

The fact that this statement was made as recently as 2006, over 40 years after Coalbrook, is taken to be evidence that the TAT pillar loading model has persisted, whether it be full TAT to the surface or a modified/partial version.

At the 35th ICGCM, Reed, McTyer, and Frith 2016 posed a question, asking whether it was possible for coal pillar research to follow what had already occurred in roadway roof control research. Roadway roof control was initially founded on the belief that roadway roof support needed to be designed to hold in place an otherwise critically unstable roof mass, using suspension roof support [Figure 3(a)]. However, this was eventually superseded by the prevailing concept that roadway roof stability could be far more efficient and reliable by retaining some or all of the self-supporting ability of the roof strata via reinforcement using roof bolting and longer cables and tendons (Figure 3(b)). The reinforcing approach considers the competence of the roof mass (as given by the Coal Mine Roof Rating or CMRR for example), the horizontal stresses acting across the roof, the width of the roadway and the installed roof support in formulating design outcomes. The roadway roof stability design problem was forever changed from the simple and often far too simplistic assumption of "dead-load" suspension when the problem became one of roof reinforcement. Frith and Colwell 2011 outline details of the various problems and potential risks of continuing to apply a dead-load suspension approach to roadway roof support design in reinforcing design situations.



(a) suspension arrangement (b) reinforcing arrangement

Figure 3: Schematic illustrations of suspension and reinforcing problem representations for roadway roof control

This paper debates the application of full or modified TAT dead-load pillar loading to bord and pillar coal pillar design nearly 60 years after Coalbrook. Figure 1 shows the suspension arrangement for coal pillars. The similarity with Figure 3(a) for roadway roof support is evident; the only difference being that the unstable strata mass is held in place by roof bolts anchored into stable overlying strata, as compared to a coal pillar being founded on the floor of the roadway.

In stark contrast, Figure 4 outlines a suggested reinforcing problem representation for coal pillars similar to that shown in Figure 3(b) for the roof of a mine roadway. In the reinforcing coal pillar design representation, the horizontal stress acting within the overburden, the competence of the overburden in terms of its self-supporting ability across the panel, and the panel width are all brought into the problem representation. These are directly analogous to the horizontal stress in the roof of a roadway, the competence of the roof strata (e.g. the CMRR), and the roadway width, respectively. Each is a primary variable in the reinforcing roadway roof stability problem.

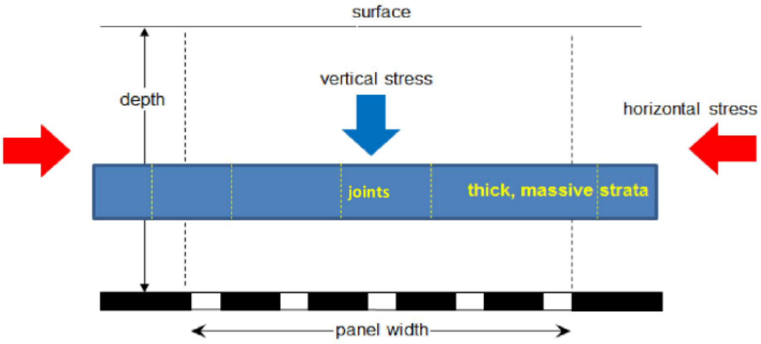


Figure 4: Schematic illustration of a reinforcing problem representation for coal pillar design

This then leads to the fundamental question as to whether, albeit with many years of hindsight, the mechanics of coal pillar design are comparable to that of reinforcing roadway roof support. Do coal pillars control the overburden through reinforcement rather than suspension? Do pillars work to allow the overburden to stabilise itself, rather than simply support the overburden?

The paper seeks to demonstrate that the overburden reinforcement scenario is the more likely answer in many instances with some specific exceptions and offers views on the implications on bord and pillar layout design involving coal pillars.

JUSTIFICATION FOR A REINFORCING APPROACH TO COAL PILLAR DESIGN

In addressing whether the coal pillar design problem is one of suspension or reinforcement, it must be determined which becomes unstable first: the overburden to surface or the pillar? This question is derived by considering suspension design for roadway roof support where by definition, the installed roof support must remain load-bearing well after the roof strata has failed and become critically unstable, a roof collapse being solely dictated by the structural state and associated load-bearing capacity of the installed roof support.

The earlier quotation from Van Der Merwe 2006 implies that as long as the overburden becomes critically unstable before a correctly designed coal pillar reaches its maximum load-bearing capacity, it does not matter how weak the overburden is at face value this makes perfect sense, but leaves one critical issue unanswered: “Will in fact the overburden become critically unstable before the coal pillar goes post-peak”?

If the answer to the question is generally “no”, it must logically be concluded that the manner by which the suspension approach to pillar design as outlined in Figures 1 and/or 2, whereby an unstable amount of overburden is controlled by coal pillars prior to their peak strength being reached, is a worst, a flawed and at best, a limiting view. Therefore, how and why the overburden becomes critically unstable relative to the coal pillar becoming unstable becomes of significant interest.

Useful thought-experiments

Before presenting detailed technical arguments, it is useful to consider a number of basic "thought-experiments" whereby the significance of the horizontal stress in the overburden can be justified as a problem variable, both conceptually and numerically.

The Ground Reaction Curve (GRC) concept (Figure 5) was originally developed in the early 1960's to assist tunnellers ensure that permanent, and often, stiff permanent tunnel linings were not damaged by excessive ground strains. This has since been applied by others to coal mining problems, such as tailgate standing support design and longwall shield design.

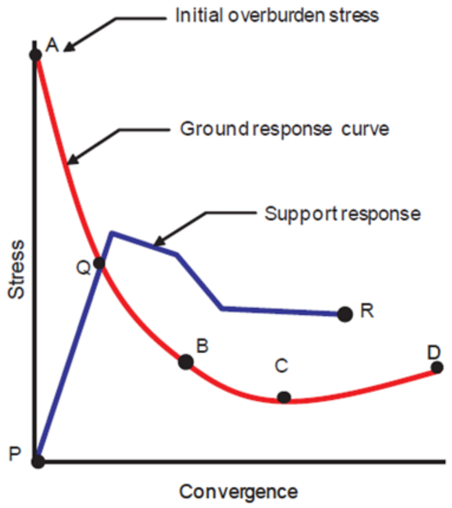


Figure 5: Generic Ground Reaction Curve (GRC) representation

Figure 5 shows that a significant element of a GRC is the installation of ground support following excavation; however in this instance it is only the ground curve that is of interest. The ground curve (ABCD contains both a section of negative slope (ABC) whereby the strata is losing its natural stability due to increasing vertical movement and a section of positive slope (CD) whereby natural stability is effectively lost with self-weight or dead-loading then dominating the stability problem.

A series of simple thought-experiments relating to super-critical extractions (i.e. W/H > 1) will now be used to demonstrate the direct influence of key geotechnical parameters on initial overburden caveability. Figure 6 presents a simple situation whereby the overburden consists solely of massive sandstone to the surface with no vertical joints. Under this scenario, it is self-evident that the overburden will retain its stability across the extraction span with the ground curve rapidly reducing to zero stress (i.e. self-supporting) following extraction.

Figure 7 is geometrically the same as Figure 6 but the overburden now solely consists of laminated material, albeit still with no vertical joints. Under this scenario, the overburden initially flexes via vertical downwards movement, but eventually exceeds some undefined "critical" level of overburden movement which marks the onset of mass instability back to full overburden collapse (under tributary area loading in coal pillar design terminology).

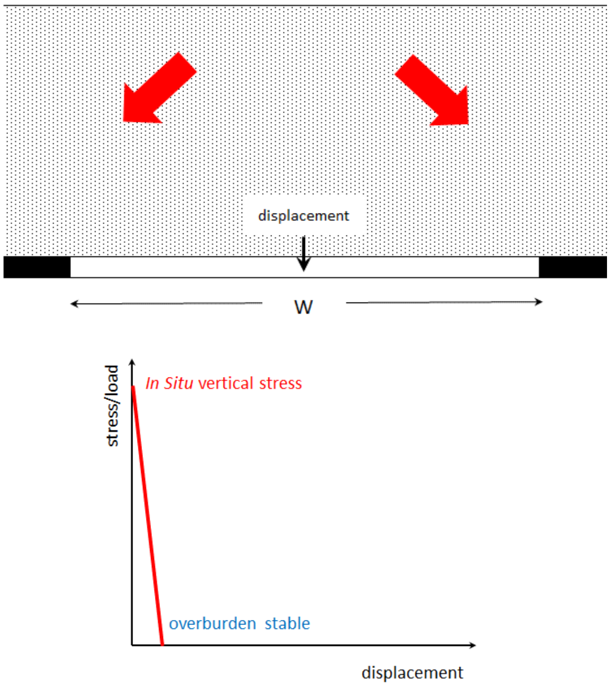


Figure 6: Thought-experiment and ground curve: massive overburden with no vertical joints

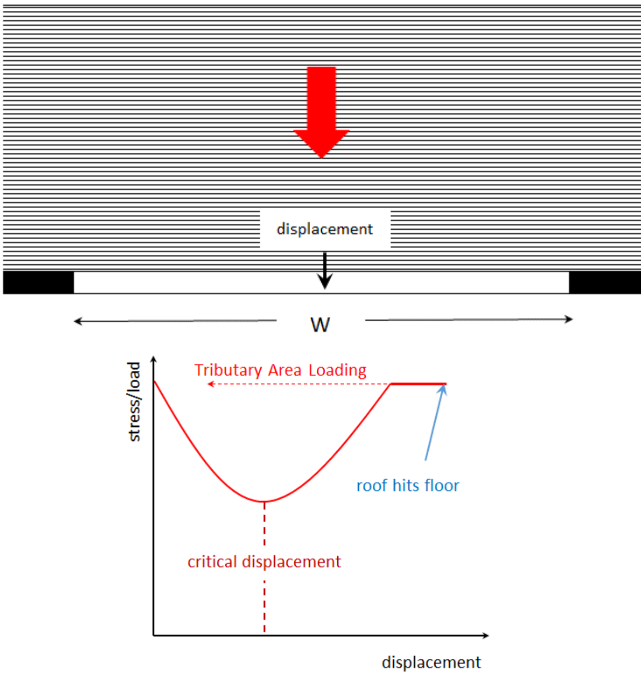


Figure 7: Thought-experiment and ground curve: Laminated overburden with no vertical joints

Figure 8 contains the massive and laminated overburden representations used in Figures 6 and 7, but introduces both vertical joints and horizontal stress.

Vertical jointing is almost always present in coal measures strata sequences (although spacings, orientations and persistence vary) and is typically characterised by zero cohesion and a friction angle that varies according to surface conditions along the joint. Under such joint conditions, no vertical shear resistance can be developed along the joint without the influence of a normal confining stress (horizontal stress in this case). Therefore irrespective of the overburden type, without the presence of horizontal stress vertical jointing results in a ground curve as shown in Figure 9, namely the overburden is an unstable detached block from the outset.

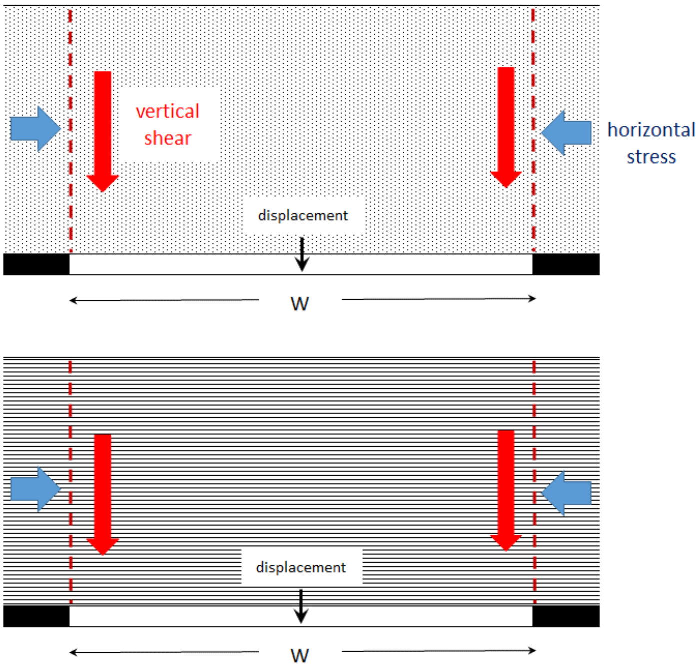


Figure 8: Thought-experiment representations: Massive and laminated overburdens including vertical joints and horizontal stress

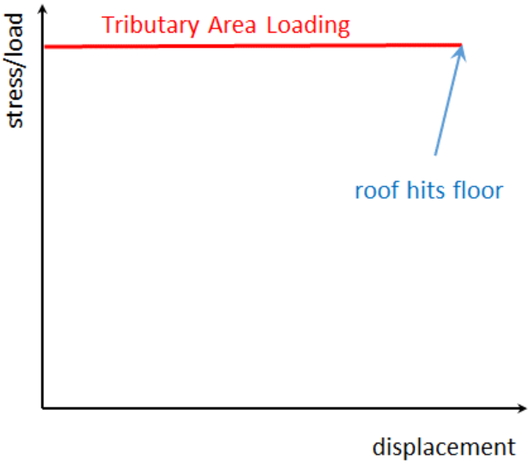


Figure 9: Ground curve: Vertical joints present without horizontal stress

Once horizontal stress is included into the representation, it allows the varying influence of overburden lithology and vertical shear along vertical joints to be combined, resulting in a range of possible ground curve outcomes as generally illustrated in Figure 10. To provide context as to what may be a significant level of horizontal stress in this regard, assuming a joint friction angle of 45° only 2.5 MPa of horizontal stress is required for limit equilibrium in terms of shear slip along vertical joints at the extremities of a 200 m wide extraction span. This is a relatively low level of horizontal stress in general coal mining terms.

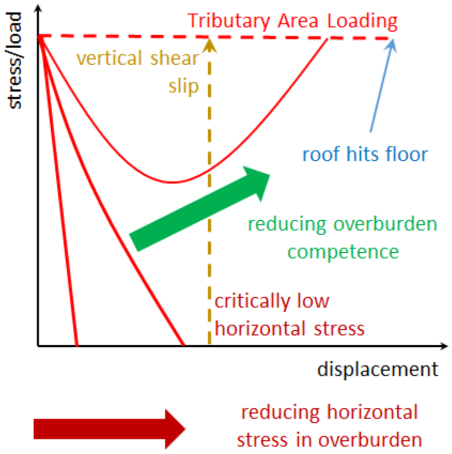


Figure 10: Varying influence of overburden lithology, vertical joints and horizontal stress on GRC's

In general terms, for any given extraction span, initial caveability is directly influenced by both the structural competence of the overburden in terms of the presence or absence of massive strata units etc. and also the level of horizontal stress acting within the overburden which defines the level of stabilising influence along vertical joints. The important point to make is that in combination they can result in two distinctly different caving mechanisms, namely:

- delamination and incremental overburden collapse whilst ever vertical joints do not undergo vertical shear slip, as opposed to;
- a "plug" type collapse of otherwise intact overburden material due to vertical shear slip along vertical joints.

The point of these thought-experiments and simple calculations is to justify that it is almost certainly overburden condition above coal pillars, which dictate their importance in maintaining the overall stability of mine workings. More to the point, the full TAT representation of Figure 1 is clearly only one possible pillar loading and overburden condition scenario and as will be now further argued, it is potentially quite uncommon for the peak-strength of the coal pillar solely controlling whether a pillar collapse (low *w/h*) or pillar creep (higher *w/h*) occurs or not.

Which generally fails first–overburden or coal pillars?

The starting point for an assessment of which is more likely to fail first - overburden or coal pillar- is again found in the (GRC) concept (Figure 5). The GRC concept was originally developed around the same time as the Coalbrook disaster to assist tunnellers to ensure that permanent, and often, stiff permanent tunnel linings were not damaged by excessive ground strains. Others have since applied this to coal mining problems, such as tailgate standing support design and longwall shield design.

Figure 5 implies that a significant element of GRC is in the installation timing of different types of ground support following excavation in that:

1. They should be installed before the surrounding strata becomes critically unstable. In reality, the surrounding strata becoming critically unstable is the onset of the suspension design problem, this being where the ground curve starts to rise with ever-increasing strata displacement.
2. They should be installed sufficiently early so that the ground and support loading curves coincide at some point. This is the point that overall equilibrium or stability is achieved.

It is suggested that applying the GRC concept to coal pillar design is a perfect analogy to attempting to protect a permanent tunnel lining from excessive ground strains. The reinforcement design problem for a permanent civil excavation for example is about controlling ground movements within acceptable limits, particularly if a key supporting structure could be overloaded as a direct result of being installed too early. However, two major differences are apparent when applying the GRC concept to coal pillars rather than excavation support, namely:

3. The pillars are already installed at the time of excavation (i.e. their installation cannot be delayed).
4. They are inevitably pre-loaded to a pre-determined level by the action of the in situ vertical stress, therefore their maximum elastic straining ability post-mining is inevitably reduced as cover depth increases (all other factors being equal).

Defining the initiation point for overburden instability

Considering the issue of the overburden first, the relevant question is how much vertical movement is required for the overburden to become critically unstable to surface at a super-critical panel width? (See Scenario A in Figure 2). For the purpose of demonstration, a panel width range between 150 and 200 m will be considered, these generally resulting in a super-critical mining geometry at relatively shallow (<150 m depth) bord and pillar mining ($W/H>1$).

Two sources of guidance will be used in addressing this question: (a) surface subsidence data with respect to the transition from sub-critical to super-critical surface behaviour (as illustrated in Figure 2), and (b) overburden extensometry data relating to measured overburden movements following the extraction of longwall panels in the same panel width range.

Figure 11 shows the standard S_{max}/T vs W/H representation for a series of varying width longwall panels in the Newcastle Coalfield, the cover depth ranging between 70 and 150 m [Ditton and Frith 2003]. This is also a common bord and pillar mining cover depth range. The data indicates that the onset of full overburden instability and associated collapse at the surface commences at an S_{max}/T value of around 0.1, the mid-point of the transition to super-critical being 0.25 to 0.3, and full collapse at surface at a value in the order of 0.5. For an assumed mining height of 2 m, these represent vertical overburden movements at the surface of 200, 600, and 1000 mm respectively. In other words, overburden collapse at the surface does not typically commence under this scenario before 200 mm of vertical movement and is only reliably complete by 1000 mm. It is accepted that these values change according to varying extraction height and may also be influenced by overburden characteristics and goaf bulking behind a longwall. However, they are a useful starting point for this discussion.

Also of interest is the amount of vertical movement in the immediate overburden above the mine workings that is required to initiate overburden collapse across the full panel width, this section of strata directly interacting with the coal pillars that are left in place.

Figure 12 shows overburden movement isopachs in vertical section behind a longwall face as a function of both distance into the overburden above the working horizon and distance behind the face [Mills and O’Grady 1998]. While the figures themselves are not particularly clear, statements from the paper are worth re-quoting herein.

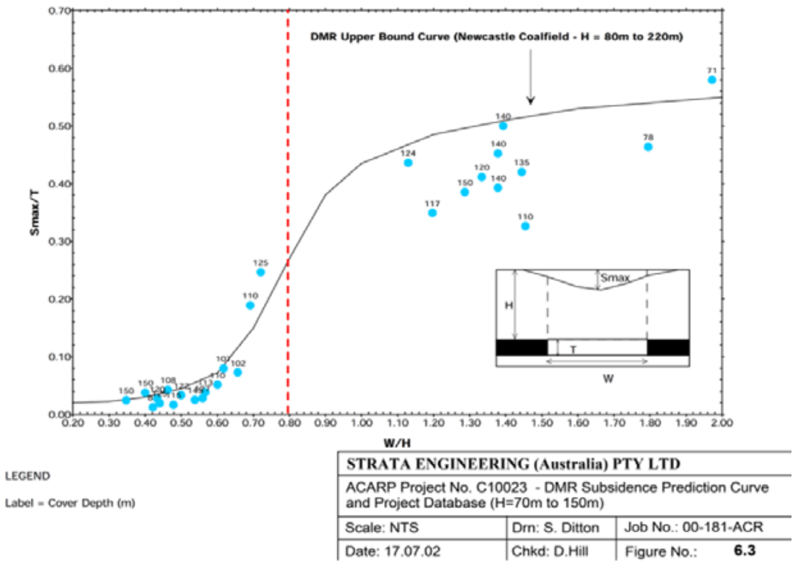
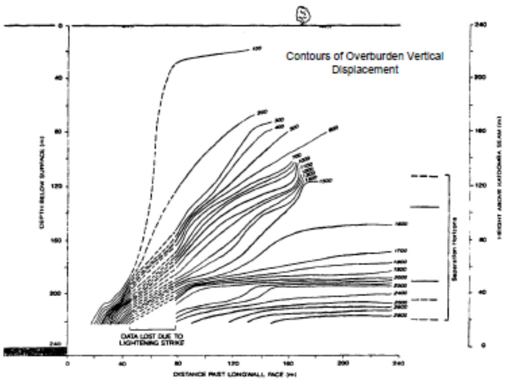
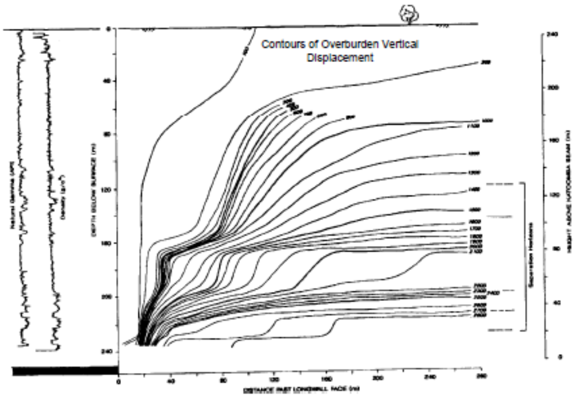


Figure 11: Measured S_{max} values analysed according to extraction height (*T*), panel width (*W*) and cover depth (*H*) for depths ranging from 70 to 150 m [Ditton and Frith 2003]



(a) LW4 at 150 m width



(b) LW5 at 200 m width

Figure 12: Surface extensometry data, LW's 4 and 5, Clarence colliery [Mills and O'Grady 1998]

The following is in relation to Figure 12(a) for a 150-m-wide longwall panel: "the 200 mm contour represents the line below which, downward movements accelerate rapidly. The transition between relatively small displacements (<200 mm) and much larger displacements occurs within a relatively narrow zone."

Regarding Figure 12(b), Mills and O'Grady (1998) state that for a 200 m wide longwall panel: "immediately below the 200 mm contour, the rate of ground separation increases rapidly as indicated by the close spacing of the 500 mm and 1 m contours".

In both instances, Mills and O'Grady (1998) are seemingly stating that the onset of rapid overburden movement following longwall extraction occurs at an overburden displacement magnitude in the order of 200 mm.

Independent and fundamentally different data sets relating to instability at the surface and within the overburden following longwall extraction, may cause minimum overburden movements prior to the onset of full overburden collapse in the order of 200 mm for panel widths in the range 150 to 200 m. This is the first requirement in determining whether the coal pillar or the overburden fails first when coal pillars are left in place between stable barriers.

Condition of coal pillar at peak loading

In terms of the coal pillar, the relevant consideration is the vertical compression at the point that it reaches its maximum or peak load-bearing ability, this being commonly termed as "pillar strength". Figure 13 provides stress-strain curves relating to the laboratory testing of coal samples according to varying *w/h* ratio [Das 1986]. From this data, it is estimated that for a *w/h* range of 1 to approximately 5, the vertical strain at peak-loading varies from 1% to 2%. Extrapolating this to a coal pillar scale means that for a 2 m high pillar, the total vertical compression at peak loading varies between 20 and 40 mm. However, as discussed by Galvin, caution needs to be used when applying laboratory test data to *in situ* pillar behaviour; therefore, some form of *in situ* coal pillar testing data would be valuable to provide real-world insight into this issue

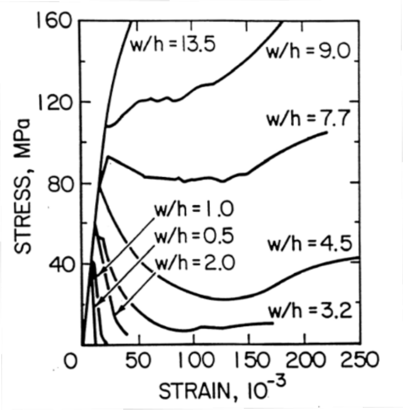


Figure 13: Stress-strain behaviour of coal for varying width to height (*w/h*) ratio [Das 1986]

Figures 14 and 15 contain stress-strain data for larger coal "pillars" tested *in situ* as opposed to laboratory specimens [Van Heerden 1975]. In the two cases for two different *w/h* ratios, the compressive strain at peak-loading is <1% (i.e. 10×10^{-3}). In the case of a 2 m high coal pillar this equates to <20 mm of vertical compression at its maximum strength.

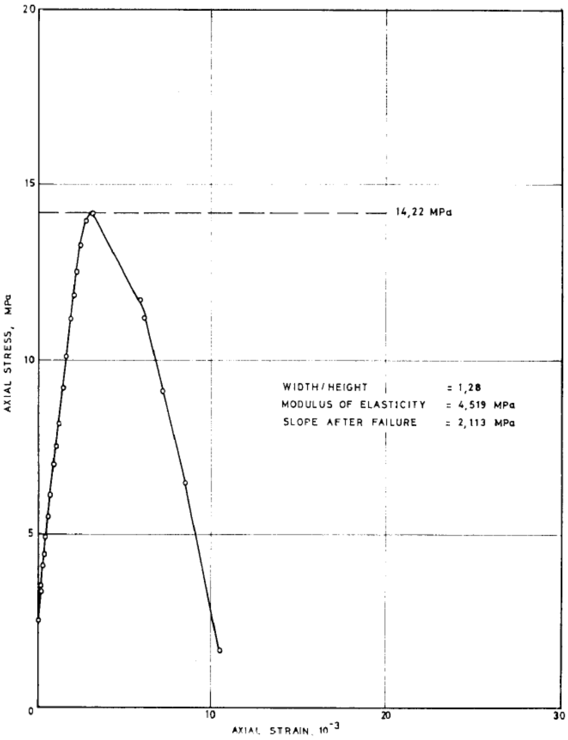


Figure 14: Stress-strain behaviour for in situ coal pillar testing [Van Heerden 1975]

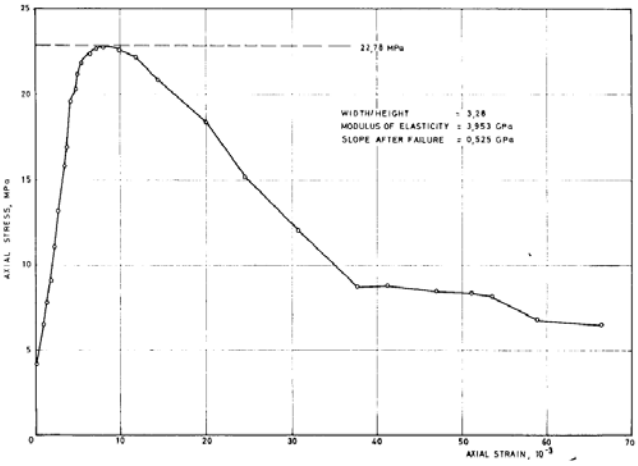


Figure 15: Stress-strain behaviour for in situ coal pillar testing [Van Heerden 1975]

Figure 16 relates to a different method of *in situ* coal pillar testing. In this test, an approximately 1.8 m-high coal pillar is incrementally reduced in size and the applied pillar load and vertical compression responses are measured [Skelly *et al* 1975]. Recognising that the coal pillar is pre-stressed before it is reduced in size due to the in situ pre-mining vertical stress, an additional 2.54 mm of compression is recorded when taking the pillar from its in situ loading under the action of vertical stress 16.5 MPa of (2,400 psi), to its measured peak load of around 2900 psi (20 MPa). This equates to 2.54 mm of pillar compression for a 3.5 MPa (500 psi increase in average pillar stress. Extrapolating this value to the complete elastic stress-strain range of the pillar from 0 to 20 MPa, results in total vertical compression of the pillar at peak loading of only 14.7 mm for the 1.8 m high pillar in the test case. For a 2 m-high pillar, this would increase to 16 mm, all other factors being equal.

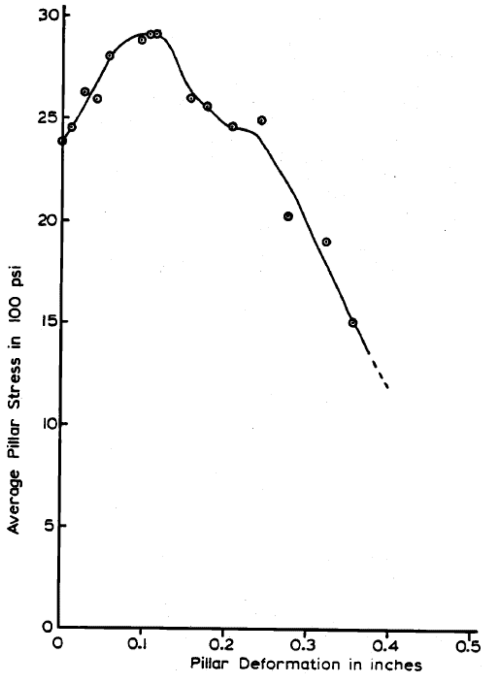


Figure 16: Stress-deformation curve for test pillar "a" [Skelly *et al* 1975]

In situ coal pillar testing data from both South Africa and the USA indicate that for a 2 m high coal pillar, vertical pillar compression at peak-loading or maximum strength would be in the order of 20 mm. This is of similar magnitude as that inferred from the Das 1986 lab-testing data of 20 to 40 mm, according to a varying *w/h* ratio of between 1 and up to 5.

So which fails first—overburden or coal pillar?

Even making an allowance for the elastic compression of an immediate stone roof and floor above and below coal pillars, the preceding general analysis of overburden movements above total extraction panels and vertical strains in coal at peak-strength, leads to the inevitable conclusion that it is more likely than not that coal pillars will exceed their peak strength (and so "fail") before the overburden becomes in a critically unstable state to the surface.

This general conclusion is well justified in the various reports relating to Coalbrook in that (a) surface subsidence cracks above the area of the mine that was eventually to collapse so catastrophically, were identified days before the major event (NB subsidence cracks at surface generally require hundreds of millimetres of vertical subsidence before they appear, not tens of mm), (b) various coal pillars were observed to be spalling and splitting well prior to the main collapse (which is inconsistent with the retention of an elastic pre-peak pillar state leading up to the collapse) and (c) micro-seismic events were heard and measured as part of the main collapse, a common source of micro-seismic and indeed seismic events being stress-driven shear slip along pre-existing planes of weakness (such as the vertical joints in Figure 8), rather than the compressive failure of soft material as in a coal pillar.

One case example on its own obviously does not prove that all failed pillar cases in the various coal industry databases conform to this same scenario. Weaker and less stiff roof and/or floor measures, thick soft clay bands within the coal seam, very low horizontal stress environments in mountainous terrain or in proximity to highwalls and/or the presence of mid-angled structures in the overburden above a collapsed area, would all tend to change the conditions at the point of overburden collapse towards one whereby the coal pillar may be the controlling influence, as analysed previously. However, the various observations leading up to the Coalbrook collapse certainly support the idea that the overburden failing before the coal pillar can be eliminated as a universal truth. If nothing else, this means that any coal pillar strength equations that have been empirically-derived from databases of failed pillar cases, will only reasonably reflect the intact strength of coal pillars if all or the majority of the failed cases occurred as a direct and immediate consequence of the coal pillars first exceeding their intact strength, the Coalbrook collapse now being strongly argued to not fit this description.

This finding, in particular as it relates to Coalbrook, is seemingly quite profound and raises a question-mark as to the reliability of almost 60 years of coal pillar strength research that has utilised failed pillar cases in back-calculating intact coal pillar strengths at failure and so developing coal pillar strength equations. However, it is only based on one technical argument, namely that coal pillars can reach their peak-loading condition well before the overburden has displaced sufficiently to become critically unstable. Therefore, further supporting evidence has been sought.

Other real-world examples worth considering further

Three significant case history examples have been identified that either (1) seemingly further back the assertion that the rigid application of full TAT loading to surface (Figure 1) when back-analysing failed pillar cases contains limitations that may only manifest when the resultant pillar strength equations are used in practice, and/or (2) indicate that a key piece of the design problem has been overlooked and that we may do well to now include it. Figure 17 shows the combined Australian and South African databases of failed coal pillars, including a series of Highwall Mining (HWM) pillar failures that were back-analysed using the previously-developed pillar strength equations of the University of New South Wales Pillar Design Procedure (UNSW PDP) [Hill 2005]. The area of interest (marked by a red ellipse) contains a number of HWM pillar failures with UNSW PDP FoS values ranging from 1.7 to as high as 2.4, these all being greater than, significantly so in most cases, the range of FoS values for the failed non-HWM cases that define the majority of the two databases.

It could perhaps be argued that these HWM pillar failures are due to low pillar *w/h* ratios having reduced pillar strengths as compared to the predicted strengths, due to the influence of localised geological structures. In fact, this influence is commonly argued by others, although at first glance it isn't immediately obvious from Figure 17, as there are a number of non-HWM failed cases with similarly low *w/h* ratios (which would have also been square/rectangular underground pillars rather than continuous HWM pillars) that do not generally mirror those of HWM. Perhaps the HWM pillar failures that stand out from the general underground mining examples have a different causation entirely.

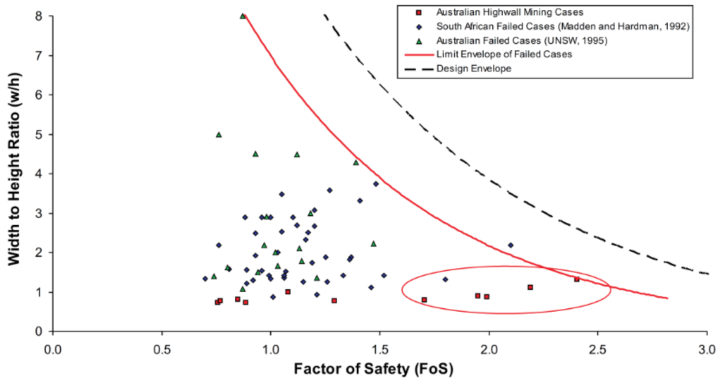


Figure 17: Database of pillar collapses–width to height ratio vs. FoS [Hill 2005]

Forming coal pillars next to an open cut highwall represents a specific and not particularly common scenario, whereby the self-supporting ability and stiffness of the overburden above the pillars is inevitably reduced due to the presence of a zero friction vertical discontinuity in the overburden with no horizontal stress acting across it, namely the highwall. If, as previously argued via the various thought-experiments and calculations, the overburden needs to overcome the stabilising influence of horizontal stress acting across vertical joints before it enters a critically unstable state, then being located adjacent to an open cut highwall is an obvious situation where this influence would logically be reduced as compared to further into an underground mine. In other words, the HWM situation may more closely resemble that of Figure 1, as compared to that of underground mining. Therefore, if the UNSW PDP pillar strength equations as used by Hill 2005 contain a limitation that is linked back to their derivation, its presence and significance should logically show up in any case examples that significantly deviate from the majority within the founding database. To have five failed examples in the FoS range of 1.7 to 2.4 in such a small database as that of Australian HWM, strongly suggests that the coal pillar strength equations used in determining the FoS values in Figure 17, are substantially overstating coal pillar strength. In this regard, it is interesting to note that UNSW are currently undertaking a joint project with CSIRO to re-evaluate their pillar strength equations for low-width HWM pillars, presumably as a direct result of the Australian and other failed HWM examples.

The other notable aspect of Figure 17 is that, for *w*/*h* values >4 to 4.5, there is only one outlier collapsed failed case at a *w*/*h* of almost 8, which, according to Colwell 2010, is more likely to be a floor failure than a core pillar collapse based on his personal knowledge of the case history. As such, its relevance in terms of the discussion on whether the pillar or overburden fails first is judged to be minimal, as without definitive knowledge on the type of instability involved it cannot be included. The same trend is also evident in the ARMPS failed pillar database (Figure 18), where, in terms of core pillar failures there are no examples with *w*/*h* values >3 [NIOSH]. This leads the discussion into pillar squeezes or creeps and what the relevant case histories might be able to tell us about the general validity of pillar strength equations at higher *w*/*h* ratios.

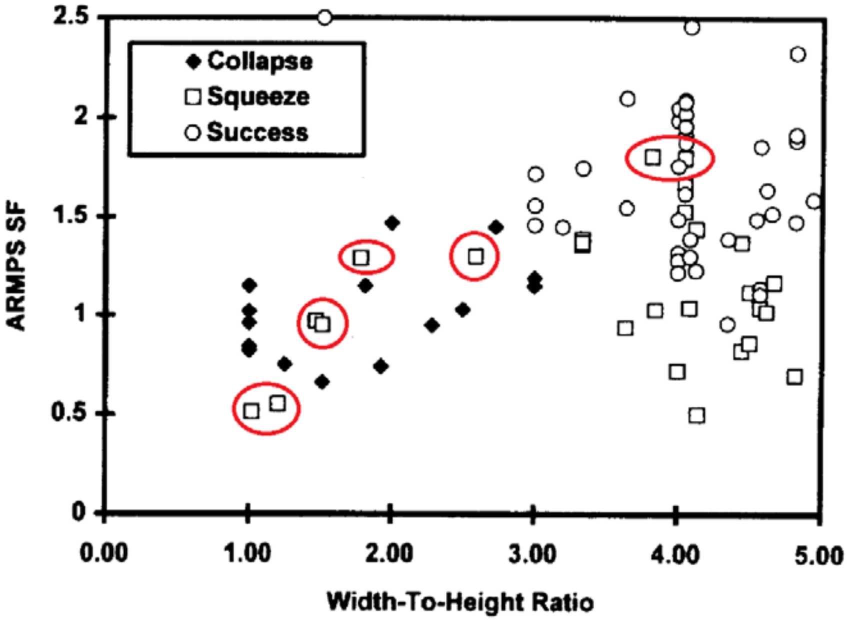


Figure 18: ARMPS SF vs pillar *w*/*h* ratio for pillar collapses and other case histories [NIOSH]

Ditton and Frith 2003 analysed the relationship between surface settlements above longwall chain pillars (under Double Goaf (DG) loading with extraction panels on both sides) that could not be explained by the superimposition of the two individual subsidence troughs on either side of the chain pillar The resulting levels of surface lowering were plotted against the FoS of the chain pillar under DG loading as determined using the UNSW PDP pillar strength equation for *w*/*h* values >5. A relationship between the two parameters was found as shown in Figure 19.

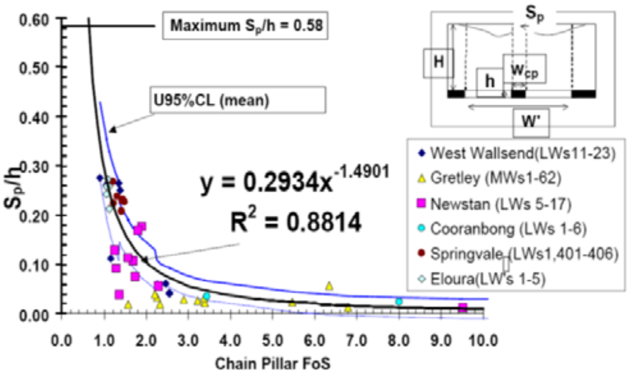


Figure 19. Surface lowering above a chain pillar under DG loading v chain pillar FoS using UNSW PDP strength equations [Ditton and Frith 2003]

This pillar loading scenario is probably quite unique in that due to the presence of extracted longwall panels on either side of the chain pillars, any stabilising influence of horizontal stress within the overburden should have been substantially reduced as compared to standing coal pillars in a bord and pillar type layout. Despite the extreme extraction geometry on either side of the pillars as compared to mine roadways, this scenario may in fact be more consistent with that of full TAT pillar loading and so provide further interesting insights. Surface lowering in above a chain pillar with longwall goaf on both sides is inevitably also influenced by the compression of the roof and floor strata, as well as that of the chain pillar itself. However, as the chain pillar controls the vertical stresses that are being applied to both the roof and floor strata, and as the coal has a Young's Modulus that is generally substantially lower than that of stone, it is perhaps not unreasonable to examine the problem, at least in the initial instance, using this data set.

What is most interesting is that the general relationship in Figure 19 indicates that the magnitude of surface lowering starts to exponentially increase for chain pillar FoS values below the range of 2 to 2.5. The chain pillars in this database are all of a high *w/h* ratio as a result of Australian longwall mining practice, therefore coal pillar collapse via failure of the pillar core cannot be attributed as the cause. Therefore, for the onset of what appears to be non-elastic chain pillar compression effects at FoS values in the range of 2 to 2.5, one can infer that the pillar strength equations being used may be significantly overstating the intact or elastic peak-strength of the coal pillar. This is essentially no different from what has been concluded in relation to the Australian HWM cases in Figure 17.

Having analysed two different Australian databases that contain what appear to be anomalous pillar stability outcomes with respect to either pillar strength, there is perhaps a credible argument that the pillar strength equations used in both examples tend to over-estimate the true intact strength of coal pillars across a wide range of w/h ratios.

Where all of this ultimately leads to is the statement that mine layout design for bord and pillar type mining may benefit by dispensing with the idea that the overburden can be stabilised at a prescribed level of design confidence by simply assigning an FoS (or SF) to the coal pillars in isolation from the natural stability of the overburden. Furthermore, if coal pillars do indeed commonly exceed their peak strength well before the overburden becomes critically unstable, their role in preventing overburden collapse cannot be linked to their peak strength, nor therefore by definition, the traditional pillar design FoS of pillar strength/pillar load. In other words, coal pillar FoS under vertical loading may be no more than a useful surrogate for some other, more relevant consideration.

This leads to the inevitable question as to how else can coal pillars act to stabilise the overburden above either bord and pillar or partial extraction mine layouts, whereby retaining overburden stability during and post-mining is almost always the critical layout design requirement? The only credible possibility is that of overburden "reinforcement" with the coal pillars assisting the overburden support itself; in the same way that reinforcing roof support acts to assist the roof strata above a mine roadway to support itself. This however is another topic for another time.

Another quick look at Coalbrook

Returning to Coalbrook, it is interesting to re-consider the sequence of events leading up to the disaster as outlined by Van Der Merwe 2006. Two comments, in particular, are intriguing:

1. The main collapse on January 21, 1960, was preceded by a smaller collapse on December 28, 1959, in an experimental area where top coaling had been undertaken.
2. Mine management concluded, incorrectly as it turned out, that “the weight had come off” following the first two collapses on January 21, based on the occurrence of surface subsidence. They therefore assumed that the remaining areas were safe.

If one applies the full TAT pillar loading model shown in Figure 1 it is difficult to understand how su**c**h a large area of inadequately sized coal pillars (as evidence by their eventual collapse) could stand over years without incident, yet a pillar collapse in one, small area of only 6 hectares, triggered at least three major collapses in rapid succession totalling over 324 hectares, less than 1 month later. However, if one applies the overburden reinforcement model shown in Figure 4, the focus becomes one of overburden and coal pillars working in tandem to retain horizontal stress within the overburden. With this model in mind, the events at Coalbrook can be explained quite differently.

The smaller pillar collapse in December 1959 within the trial area of top coaling, would have inevitably caused a substantial reduction in horizontal stress within the overburden above nearby surrounding mine workings that were still standing. Similar to high magnitude guttering or cutter roof in the roof of a mine roadway, with the stabilising contribution of horizontal stress being lost above part of the overall pillar system remote from any barriers, the stability of the entire overburden would have inevitably been put at risk. As it turned out, a series of major collapses occurred not long afterwards.

It is interesting to dwell on the coal pillar strength research that occurred in South Africa following Coalbrook. The most intriguing issue are the numerous changes made to coal pillar strength equations as other collapsed cases have been considered from different coalfields. Currently this process is still ongoing, with new formulae being developed in response to new pillar failures. It is still continuing in Australia today with the UNSW highwall mining pillar strength formula [Mo *et al* 2017]. Therefore, it could perhaps be argued that the process has now got to a point where selecting the appropriate pillar strength equation for design purposes is as much engineering judgement as assigning representative values to any other geotechnical parameter. This is hardly acceptable in a mine design discipline that carries the safety and business consequences associated with coal pillar failures.

With this in mind, it is instructive to further reflect on the coal pillar strengths equation developed after Coalbrook. Equation 1 is based on the in situ testing of large coal specimens with no direct link to failed cases and/or the assumption of full TAT [Bieniawski 1968] and it provides lower pillar strength values as compared with the statistically-derived Equation 2 and those of the UNSW PDP which use the assumption of full TAT as per Figure 1. However Equation 3 is the recently published strength equation for highwall mining coal pillars [Mo *et al* 2017], highwall mining being one scenario whereby the stabilising influence of horizontal stress on the overburden can logically be minimised, which is very close numerically to that of Equation 1.

$$\sigma_p = 2.76 + 1.52\, w/h \tag{1}$$

$$\sigma_p = 7.176\,(w^{0.46}/h^{0.66}) \tag{2}$$

$$\sigma_p = 4.66\,(0.56 + 0.44\, w/h) \text{ or } 2.61 + 2.05\, w/h \tag{3}$$

The conundrum that emanates from Equations (2) and (3) is that they suggest that a square pillar with a w/h of say 2 [Equation 2] is actually stronger than a long strip pillar as used in highwall mining [Equation 3]. This does not make logical sense, and so raises a very significant question regarding pillar strength determination and assignment during design for industry to address. In hindsight, perhaps coal pillar strength research should have ceased with the Bieniawski equation from 1968 [Equation 1] based on the in situ testing of coal, rather than becoming an on-going statistical battle to develop new and supposedly "improved" pillar strength equations from failed cases databases, that in reality may provide no more than a slightly better answer to what may commonly be the wrong problem and at times, can be misleading.

While this did not occur in 1968 for obvious and understandable reasons, industry might be wise to focus more intently on other relevant pillar design, or more correctly, "overburden stability" design parameters, as outlined herein and in Reed, McTyer, and Frith 2016.

The final question Van Der Merwe 2006 poses relates to why a section of similarly sized coal pillars at Coalbrook that were directly adjoined to the large collapsed area did not similarly collapse (Figure 20). He offers that the only possible reason is that as the span across the pillars was reduced as compared to the main collapse area; the collapse did not propagate into this area. However, he also makes the following statement: "*the fact that those pillars did not also fail cannot be explained by either the pillar safety factors or the presence of the dolerite sill based on current understanding. Clearly, a better understanding of the overburden stability is required. Had the overburden failed, then the pillars could not have survived, but current knowledge does not offer a method to evaluate the role of the overburden. For the time being, this question cannot be answered*".

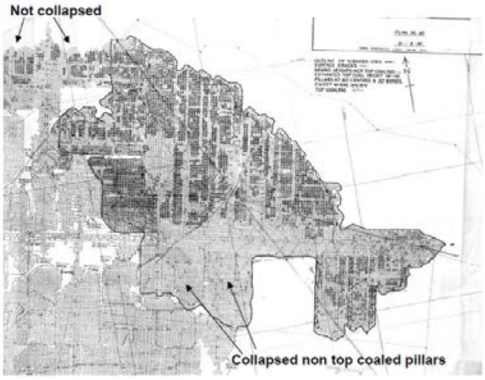


Figure 20: Details of the collapsed and non-collapsed areas at Coalbrook [Van Der Merwe 2006]

If the coal pillars in this un-collapsed area were of insufficient strength to prevent a collapse and the panel width was super-critical, even with the overburden containing a thick dolerite sill, and therefore was critically unstable to surface without the assistance of the coal pillars, only one credible possibility is seemingly left to explain why the area remained stable despite the absence of a barrier pillar between the collapsed area. Namely, the interaction between the coal pillars and the overburden maintained levels of horizontal stress within the overburden that provided a significant and critical contribution to overburden stability in addition to that of the coal pillars themselves, thereby preventing the overburden collapse.

In this regard, it is interesting to consider whether the alignment of the major horizontal stress may have coincided with the minimum span or width across the mined-out un-collapsed area. When reviewing the role of horizontal stress in South African coal mining, Frith 2002 found that the most predominant alignment of the major horizontal stress was closer to NS than EW based on observations and measurements at a number of underground mines.

Referring again to Figure 20, an alignment of the major horizontal stress east of north would closely align with the minimum span across the stable mined-out area. This combination logically represents the most stable possible overburden condition, as higher amounts of horizontal stress would need to be dissipated before the overburden could collapse via vertical shear at the extremities of the span.

Accepting the comments and judgements of Van Der Merwe 2006 as being essentially correct, this one small area that remained stable both during and after the Coalbrook collapse, conclusively proves that bord and pillar coal pillar stability problems cannot and should not be uniquely defined by full or even partial TAT representations, one exception to the rule potentially being sufficient to disprove the rule.

Decades later, it seems that the 1960 Coalbrook disaster may still provide us with valuable lessons if we are prepared to view the problem through a different lens.

Implications to mine planning, layout design, and future research

The final section of this paper considers, in general terms, the implications to future mine layout design as a result of these findings. Is there any benefit in undertaking research in order to overcome any of the limitations that are now seemingly inherent, to a varying extent, in our current bord and pillar type pillar design approaches?

The short-term answer to this question is probably “no”. Major coal mining research institutions around the world that would have the resources to do the work are now largely absent from industry. It is also the case that the statistical approach to determining coal pillar strength equations has fortuitously, if perhaps unknowingly, compensated to some degree for some of the limitations by providing statistically-derived recommendations on what FoS or SF to apply in certain mining circumstances, irrespective of how accurate or inaccurate the coal pillar strength equations that evolved from the database may happen to be.

Nonetheless, should the nature of the pillar-loading scenario differ substantially from the majority of failed cases within a database (as per the Australian HWM and longwall chain pillar compression examples herein), the mine designer needs to be aware of this to ensure that the overall layout design contains suitable measures to compensate for any threats to mine or surface stability resulting from pillar strength equations over-estimating the true intact peak strength of the coal pillars. This frames the layout design problem as one of engineering adequate overburden rather than solely coal pillar stability and considers the coal pillars as one of several component in that problem.

Given that the paper has concluded that overburden reinforcement may be generally more appropriate for coal pillar design in non-caving mining scenarios such as bord and pillar and partial extraction, some historical context is required to explain why this may not have been realised much earlier:

1. In the aftermath of the Coalbrook tragedy, the need to develop credible pillar design methodologies to prevent a recurrence would have been enormous, both technically and politically. Spending many years undertaking research studies to generate all of the various geotechnical insights that the industry is incredibly fortunate to have today, would have been prohibitive and unimaginable. There was a need to provide a reliable solution relatively quickly. In that context, the researchers at that time and since should be recognised and congratulated for their achievements both now and into the future.
2. At the time of Coalbrook in 1960, the impact of horizontal stress in coal mine strata control was barely recognised, let alone proven and accepted. In fact, a Safety in Mines Research Advisory Committee research project came about in the early 2000’s as the role of horizontal stress in South African coal mine roadway roof control was still subject to industry debate at that time.
3. The insights in this paper have only come about as a result of nearly 60 years of international coal mine research and publications based on documented mining experiences—none of which were available in 1960.

The development of coal mine strata control knowledge and principles has been an on-going work-in-progress internationally for well over a century, but was undoubtedly accelerated after 1960 as a direct consequence of the Coalbrook disaster. Inevitably, as more mining experience-based research work is conducted and published, more engineers and scientists are exposed to real-world problems, rather than laboratory or computer-based simulations.

From time to time, significant realisations will inevitably emerge that challenge our views. This may be one such time. As a fraternity the question we need to consider is are we prepared to embrace a changing understanding of a problem and steer the ongoing search for improved knowledge in different directions as a direct consequence? Or conversely, do we prefer to stoically defend previous understandings, despite credible arguments that may render them incomplete, on the basis that it is perhaps more important to preserve the integrity of the past than look to the future with a new vision?

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