Incorporating mine seismicity and coal burst considerations into a strata failure management plan for coal mine roadways

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INCORPORATING MINE SEISMICITY AND COAL BURST CONSIDERATIONS INTO A STRATA FAILURE MANAGEMENT PLAN FOR COAL MINE ROADWAYS

Ross Seedsman

ABSTRACT: For coal mines the term bump should refer to a seismic event that is generated at some distance from the excavation and a burst should refer to a sudden uncontrolled fall of ground. There may be additional seismic noise generated at the excavation boundary directly associated with the fall of ground. The seismic sources for bumps are most likely to be the immediate or delayed failure of thick rock units in the overburden. For Australian coal mines, the sudden collapse of ribs should be considered to be either a strain burst in the context of the hard rock mining knowledge base or a gravity-driven kinematic failure (slump). As the depth of cover increases there is a greater thickness of failed coal at the excavation boundary and hence more material is available to be dislodged as a strain burst if the installed ground support is inadequate. Depending on the orientation of the roadway with respect to small-scale faults it is possible for wedges of coal to be defined, and these may be dislodged by a seismic bump. The dimensions of such wedges may be in excess of the maximum practical tendon length.

INTRODUCTION

The 2016 Work Health and Safety (Mines and Petroleum Sites) Regulation requires all mines to manage the health and safety associated with mining-induced seismic activity. There is a specific requirement for the principal hazard management plan for strata failure to include considerations of induced seismic activity. It is well known that mining-induced seismicity is associated with rock bursts in metal mines. There was little appreciation of the seismic hazard in Australian underground coal mines until the double fatality at Austar coal mine in 2014 which has been identified as a pressure burst (NSW Mine Safety Investigation Unit, 2015). The investigation report provided general guidance as to where a pressure burst hazard may be encountered – depths greater than 300 m, the presence of structures such as faults and dykes, changes in joint orientation, and the presence of massive roof or floor strata – and then infers a number of specific actions that should be adopted by mine management. Many of these actions would substantially slow the mine development and may make mining uneconomic.

This paper reviews the knowledge of coal bursts in the context of rock bursts in metalliferous mines and kinematic failure of vertical rock walls. It seeks to provide more clarity into how specific hazards can be identified and in particular the advantages and limitations of rib bolts and rib mesh support to limit the impact of the sudden onset of potential falls of ground.

MINING SYSTEMS

Much of the recent knowledge on mine seismicity and rock bursts comes from the metalliferous mining sector with perhaps the key publications being Kaiser et al (1996) and Kaiser and Cai (2013). Whilst the physics will be the same in the two mining sectors, there are substantial differences between the mining systems used in hard rock and those used in underground coal mining. These differences may require changes in the way the mine seismicity and burst hazards in coal mines are understood and managed.

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Coal mines

In Australian coal mines the development roadways are excavated using continuous miners or occasionally road headers. Drill and blast is rarely used, and then typically only for excavation through igneous dykes. The roadway excavations are rectangular in shape and typically 5.0 m - 5.5 m wide and 2.5 m - 3.5 m high. To extract additional coal longwall mining systems are used. Longwall extraction is conducted in sub-horizontal seams with the extraction voids currently ranging from 160 m to 410 m wide. Successful longwalling requires the immediate roof to cave, although the delayed caving of thick units (thickly bedded coarse sandstones or conglomerates) while not ideal is acceptable in some circumstances. A key requirement for high-production Australian longwalls is the lack of faults with throws more than the seam thickness; there are often small-displacement faults within the longwall extraction panels. To access suitable longwall reserves, development roadways may need to traverse larger throw faults and also fault zones with negligible net displacement.

The overall geotechnical environment for coal mining is dominated by the transverse isotropy introduced by the laterally persistent bedding discontinuities in the sedimentary rock mass. Uniaxial compressive strengths can range between 10 MPa and 100 MPa; the coal itself can range in strength from 6 MPa to 25 MPa. In Australia the maximum depth of mining is currently in the order of 600 m. Depending on rock and coal strength, the onset of brittle failure can occur at depths as low as 100 m. Figure 1 extends the excavation behaviour matrix first introduced by Hoek et al (1995) to highlight how the orthogonal joints and laterally persistent bedding produce an equivalent to a highly fractured rock mass. Note that kinematically unstable blocks (shown with the open arrows in Figure 1) can be readily defined by non-vertical discontinuities, bedding, and the excavation boundary and these will be present at all stress levels. Because such blocks will relax into the excavation they will not be exposed to elevated stress failures. The smaller zones of overstressing in the coal seam are ultimately related to the different stress field present in the coal seam ahead of mining compared to that in the roof and floor stone (Seedsman, 2004).

In Australian coal mines the roof and ribs are secured with bolts and mesh, typically installed off the continuous miners within about 2 m to 3 m the face. Bolt lengths can vary between 1.5 m and 2.4 m for the roof and typically between 1.2 m and 1.5 m in the ribs. Typically there are 6 to 8 bolts per metre in the roof, and 2 to 3 bolts per metre in the ribs. Longer flexible strands are often installed in the roof albeit with a substantial time penalty; longer strands into the ribs are not used. Mesh is in the form of welded mesh panels. By contrast, in the USA ribs are rarely supported; for example Hoelle (2009) summarises bumps in Eastern Kentucky, and although the seam was 3 m to 4 m high, rib support was not used (Hoelle, 2016).
In Australian coal mine terminology (NSW Mine Safety Investigation Unit, 2015), bursts are referred to as either:

- **Pressure bump, or a bounce:** A pressure bump is a dynamic release of energy within the rock mass in a coal mine, often due to intact rock failure or failure/displacement along a geological structure, that generates an audible signal; ground vibration; and potential for displacement of existing loose or fractured material into mine openings.

- **Pressure burst:** A pressure burst is a pressure bump that actually causes consequent dynamic coal/rock failure in the vicinity of the mine opening, resulting in high velocity expulsion of this broken/failed material into the mine opening. The energy levels, and hence velocities involved here can cause significant damage to, or destruction of conventionally installed ground support elements such as bolts and mesh.

A limitation with these two definitions is that the pressure burst definition requires high velocity expulsion which would have to be inferred from the geometry of the muck pile after the event. The possibility of gravity collapse without ejection is not covered. In US mines the terminology is different: Hoelle (2009) uses the term bump to describe events where coal is dislodged, with major bumps being defined as when mining had to be stopped, a significant quantity of coal was displaced, equipment damaged, and ventilation disrupted. A minor bump consisted of noise, small quantities of coal displaced, ground bounce, but no major large coal moved or equipment damaged.

**Metal mines**

By contrast the mining systems used in hard rock mines utilise drill and blast excavation techniques in roadways with an arched roof. Rock strengths are higher as are the maximum mining depths. The nature of metalliferous deposits is such that mining is often conducted in close proximity to major faults. Ground support typically utilises split sets, bolts, and fibrecrete.

A general assumption adopted to the geotechnical environment for hard rock mines is that the rock mass can be considered to be isotropic with no particular discontinuity set being dominant. This is one of the key assumptions that underlies the use of the Generalised Hoek Brown strength criterion and the Geological Strength Index (Hoek and Brown, 1997), and one that also allows the subsequent use of plasticity in the various numerical codes. These options are not as useful in transversely isotropic rock masses such as coal measures as the transverse isotropy alters not only the rock mass strength but also the way by which the stresses are redirected around excavations.

Rock bursts are defined as sudden ejection of rock associated with seismicity. Kaiser and Cai (2013) distinguish between strain bursts, pillar bursts, and fault-slip bursts. Strain bursts are defined as sudden and violent failure of rocks near an excavation boundary with the bulking and energy for the seismic activity being co-located. Strain bursts are induced close to the excavation boundary and are further categorised as:

- **Mining-induced strain bursts** - seismicity generated by the rock breakage at the locus of the bursting.
- **Seismically-triggered strain bursts** – seismicity generated remote from the excavation boundary.
- **Seismically-triggered, dynamically loaded strain bursts** – there is an additional permanent deformation applied to the excavation.

A simple criterion used to assess the likelihood of strain bursts is the spalling criterion, which is the ratio of the deviatoric stress to the uniaxial compressive strength. Values of between 0.6 and 0.8 are often used to identify the potential for strain bursts.
Terminology

In the following discussion the term bump will be used to refer to the seismic activity, and burst will refer to a sudden fall of ground with no reference to the velocity or violence of the movement. In fact it would be preferred that the use of the term “burst” was abandoned as it conjures up dynamic behaviours that may be misleading. There is no doubt that high velocity ejection is associated with outbursts and also some strain bursts, but the key concept should be the energy at the time of impact with a person. The principle of momentum conservation requires that for the same dynamic event a larger mass must be ejected with a lower velocity although the energy release will be the same. By analogy to excavation trench collapses, it is considered that there is enough gravitational potential energy in a coal rib to cause death or injury to persons or damage to equipment as a result of a slump.

In the absence of engineering controls (ground support), sudden falls of ground can result from strain bursts, pillar bursts, and fault slip bursts as well as from gas outbursts and kinematic failures (Figure 2). This paper will concentrate on the concepts of strain bursts in coal mine roadways and also on kinematic failures, extending the work of Seedsman (2006) to highlight the possibility of a kinematically acceptable block that may move without any stored or added strain energy but simply as a result of gravitational potential energy. It is argued that fault-slip bursts are relatively rare in Australian coal mines because of the general lack of faults in longwall mines such that it is unlikely that large expanses of extraction can remobilise faults that cut across roadways. It is recognised that pillar bursts are possible in thin fenders of coal that may be formed as a longwall approaches a pre-driven roadway. There can be pillar bursts (or longwall face bursts) as a result of extreme weighting events (Mark, 2014).

![Figure 2: Mechanisms for sudden falls of unsupported ground: yellow arrows show possible seismic input, blue arrows show possible seismic emissions](image)

Strata failure management plans seek to prevent falls of ground through the use of ground support which in an Australian coal mine is typically in the form of bolts and mesh. It is possible that this support is inadequate in the face of a seismic event – if so this is referred to as seismic shakedown.
SEISMIC SOURCES

Seismicity in coal mines has been extensively studied (Kelly and Gale, 1999) however large magnitude seismic events have not been a characteristic of longwall mining in Australia. There are reports of a ML4.5 earthquake in the coal mining area around Wollongong (ANSIR, 2000) and there is hearsay that ML3.0 events have been recorded in the Cessnock district of NSW. The 2007 collapse at Crandall Canyon was associated with a 3.9 ML event (MSHA, 2008). Swanson et al (2008) refer to experience in western US coal mines where seismic events of 2 ML and 3 ML can occur without any noticeable impact to mining operations or even an awareness that such events have occurred. They report two case studies where floor heave and rib spall were associated with 1.9 ML and 2.9 ML events and in both cases the damage was localised to areas of steeply dipping faults with no evidence of fresh macroscopic slip movement on the fault planes.

Of greater interest in the context of managing the impacts of seismic activity is how such activity is felt underground. Compared to the state-of-the-art in deep metal mines which have sophisticated seismic monitoring and a design process based on peak ground velocities, there is little information on seismicity in Australian coal mines. This is partly due to the generally lower seismic activity and possibly partly due to the lack of reported damage or impact to the coal mine roadways. In lieu of such information, Table 1 is focussed on suggesting an intensity scale by combining qualitative descriptions presented by ACG (2008) with the Mercalli scale as downloaded from Wikipedia. By reference to Table 1, the author has experienced intensity IV and V events in some of the longwall mines in both NSW and Queensland and was on the surface for one VI event. For the USA mines, Hoelle (2016) recalls bumps being mostly intensity V and one event with intensity VI; he recalled lots of sloughing from the (unsupported) ribs.

Table 1: A suggested correlation between mine observations and the Mercalli intensity scale

<table>
<thead>
<tr>
<th>Qualitative Description – underground metal mines (ACG 2008)</th>
<th>Mercalli – Earthquake effects on the surface</th>
<th>Mercalli Perceived shaking</th>
<th>Mercalli Peak Ground Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground shaking felt close to the event. Felt as good thumps or rumbles. May be felt remotely from the source event (more than 100 metres away). Often detectable by a microseismic monitoring system.</td>
<td>IV – Felt indoors, dishes, windows, doors disturbed. Walls make cracking sound. Standing motor cars rocked noticeably</td>
<td>Light</td>
<td>0.039g</td>
</tr>
<tr>
<td>Often felt by many workers throughout the mine. Should be detectable by a seismic monitoring system. Significant ground shaking felt close to the event.</td>
<td>V – Felt by nearly everyone, Some dishes or windows broken, Unstable objects overturned.</td>
<td>Moderate</td>
<td>0.092g</td>
</tr>
<tr>
<td>Vibration felt and heard throughout the mine. Bump may be felt on surface (hundreds of metres away), but may audible on surface. Vibrations felt on surface similar to those generated by a development round.</td>
<td>VI - Felt by all, Some heavy furniture moved.</td>
<td>Strong</td>
<td>0.18g</td>
</tr>
<tr>
<td>Felt and heard very clearly on surface. Vibrations felt on surface similar to a large production blast. Events may be detected by regional seismological sensors located hundreds of kilometres away.</td>
<td>VII - Considerable damage to poorly built or badly design structures. Some chimneys broken. People loose balance</td>
<td>Very strong</td>
<td>0.34g</td>
</tr>
<tr>
<td>Vibration felt on surface is greater than large production blasts. National seismic stations can usually detect events of this size.</td>
<td>VIII - Fall of chimneys, factor stacks, monuments, walls. Heavy furniture overturned.</td>
<td>Severe</td>
<td>0.65g</td>
</tr>
</tbody>
</table>

The basic mechanisms proposed for rock bursts (Figure 3) may not apply to coal longwall mines because of the presence of jointing in the sedimentary sequence and the lack of large-scale faulting. Coal-mine microseismics studies have located events mainly in the roof with a few in the floor. Recent Australian coal industry research has sought to explain the seismicity by examining possible fracturing
events ahead of the longwall face in a two dimensional plane drawn along the centreline of a longwall extraction panel (Medhurst et al, 2014). This approach relies on seismic events generated by bedding-parallel shear and the onset of tensile fractures as progressive cantilevers fail (Figure 4). However, this approach does not consider the pre-mining presence of joints and cannot consider the possibility that the overburden rocks may span out of the plane of the cross-section and across the extraction panel.

It is suggested that a better model may be the failure of jointed rock beams that cannot span as the dimensions of the extraction panel increase. This mechanism can be considered in two dimensions if the analysis section is drawn parallel to the dominant joint set, which may or may not be parallel to the face line. Figure 5 shows the simplified model of how a voussoir beam fails in compression and it is noteworthy that in laboratory-scale physical models such failure initiated by crushing at mid-span at the top of the beam (Sterling 1980, Passaris et al 1993). Also shown in Figure 5 is a typical relationship between the span of a voussoir beam and the required thickness to span. Any research into the actual seismic energy that could be developed from the compressive failure of a 20 m to 30 m thick voussoir beam has not been located.
In summary, it is assessed that coal mine bumps are of low seismic magnitude and most are associated with the longwall caving mechanism and not the reactivation of faults. The intensity of the shaking felt underground suggests that horizontal accelerations of up to 0.2 g may be typical. It is speculated that if the failing voussoir beam is located very close to the coal seam, the subsequent collapse of the released joint blocks may be the soft loading system required for a pillar burst or a seismically triggered dynamically loaded strain burst. Such a mechanism could also be applied to the longwall face bursts discussed by Mark (2014).

**STRAIN BURSTS AND THE INNER SHELL OF COAL MINE ROADWAYS**

Seedsman (2014) has applied the concepts initially proposed Martin et al. (1999) to predict the depth of brittle failure around coal mine openings and incorporating the impact of transverse isotropy. To address the lack of a suitable failure criterion that incorporates both the brittle and spalling components for the inner shell (Kaiser et al., 2015), the depth of failure around coal mine roadways is considered to be the lesser of two rings identified in the Transversely Isotropic Brittle failure criterion (TIB) – a cohesion ring and a friction ring; reflecting the presence of jointing and cleating, the tensile strength is assumed to be zero. The cohesion ring is defined by a Mohr-Coulomb criterion with cohesion equal to UCS/6 and zero friction. For an empirically derived ratio of the Youngs Modulus to the independent shear modulus (E/G) of 15, the friction ring for stone is set at a $\sigma^1/\sigma^3$ ratio of 3.4 (equivalent to a friction angle = 33°). Buzzi et al. (2015) suggests a $\sigma^1/\sigma^3$ ratio of 38 may apply to high strength thermal coal (equivalent friction angle = 72°) which has been used in the following analysis with the same modulus ratio of 15.

**An example of predicting the thickness of the inner shell in a coal mine rib**

For Australian underground coal mines the horizontal stresses are typically 1.5 to 2.0 times the vertical stress in stone roofs, and in the order of 0.5 times the vertical in the coal seams (Seedsman, 2004). For a coal seam with a UCS of 16 MPa, an immediate stone roof of 60 MPa, and a mine operating at 550 m depth, this implies a spalling criterion of about 0.3-0.5 in the roof and about 0.9 in the coal.

Figures 6 and 7 present the following:

- a. Extent of failure in the inner shell with the colour contours showing strength factors less than unity for the cohesion component, truncated by a stress ratio of 15:1 in stone and 38:1 in coal. A typical roof and rib support pattern is anchored well beyond the indicated failure zones.
- b. The sensitivity of the maximum thickness of the inner shell in the coal ribs to the assumed value of the stress ratio at either mid-height or 0.5 m from roof or floor. Note that for lower values of the stress ratio the thickness of the inner shell is still less than about 1.25 m even for a value of 10.
- c. The shape of the inner shell is limited by the cohesion ring, in this case a UCS of 16 MPa. This thin geometry is a result of the assumption regarding transverse isotropy and differs from that obtained if isotropic parameters are used. It is noted that unsupported ribs at low depth of cover show the formation of slabs (Figure 7a) and for supported ribs with slightly higher coal strength fracturing can be seen near the roof line (Figure 7b) corresponding to the low strength factors.
- d. The concept of cohesion and frictional rings allows the development of a simple design chart that relates the maximum thickness of the inner shell in the coal ribs to the ratio of the UCS to the applied vertical stress. The chart shows the difference in shell thickness between the isotropic and transverse isotropic assumption. The frictional ring implies a maximum thickness of the inner shell regardless of the vertical stress if the UCS/vertical stress ratio (Coal Strength Index – CSI) is less than 6. This is in agreement with experience that even at depths in excess of 750 m coal ribs look and behave similarly to those at shallower depth. Note that
the maximum thickness value depends on the assumption of the frictional stress ratio (Figure 6b). Care needs to be taken not to extend the lines in Figure 6d to very low CSI values.

Photos of typical rib conditions (Figure 7) provide support to the TIB predictions. As depth increases, the first signs of damage can be seen near the roof and the floor (Figure 7a) which is where failure in the cohesion ring first develops. If there is no ground support slabs can form, as predicted by the frictional ring, and then either slide or topple from the sides (Figure 7b). At greater depths, where the CSI value is low, the ribs start to collapse close to the mining face and before support can be installed (Figure 7c).

The containment of strain bursts

Interpreting the TIB failure in terms of strain bursts, it is suggested that the reported “spitting” of coal at the development face is associated with the early development of the cohesion ring. As the failure expands into the frictional ring, the coal will bulk, possibly in the order of 1%–3%, or between 10 mm – 30 mm if the failure extends 1 m into the rib. Such bulking can be adequately restrained by a flexible mesh, and it is noted that bolts and particularly mesh are considered to be critical controls for rock bursts in metal mines. The practicalities of continuous miners do not allow meshing near the floor while at the development face. Spitting at floor level probably represents a lesser hazard.

![Possible bursting](attachment:image)

**Figure 6**: The transverse isotropic brittle (TIB) model for defining the inner shell about a coal mine roadway.
In summary, for a deep mine the coal ribs will undergo failure at the development face and before or very soon after when bolts and mesh can be installed. The weight of this failed coal that can potentially collapse is in the order of 3 tonnes/metre of roadway advance. Typically in Australian coal mines, bolts and mesh are routinely already used to manage the ribs and the bolt density used to adequately pin the mesh is well in excess of the dead-weight loading. In shallower mines rib deterioration is in the form of thin slabs (less than 200 mm thick). The question for coal mines then becomes whether the mesh and bolts are adequate if there is a subsequent seismic event, say associated with longwall caving. Kaiser and Cai (2013) consider that a seismic trigger does not increase the depth of failure; it requires additional imposed stain to increase the bulking and extend the depth such as would be associated with a pillar burst. Extending this further, it is possible that the imposed strain may interact with a slab geometry formed by the TIB failure and result in a buckling mechanism – a possible explanation for ejection in pillar bursts.

KINEMATIC FAILURES

Marginally-stable but kinematically-acceptable blocks that collapse under gravity may be formed either by the orientation of roadways to the joint bedding structure (Seedsman, 2006) or by the onset of deep TIB failure in the coal such that slabs are formed. This section examines if seismic loading can induce such collapse and also examines if anchoring behind such blocks can prevent collapse. The following kinematic analyses simplify the rib to be monolithic blocks while in reality the collapsing ground would be defined by a number of sub-parallel joint structures such that a very blocky rill pile may be formed after the collapse.

Depending on the spacing and relative orientation of the discontinuities these kinematic mechanisms may dominate. At depth the relative slow stiffness of the jointed ground, will prevent it being loaded by
the full overburden stress. This possibly introduces the additional hazard of the workforce failing to recognize better ribs as being a precursor to more adverse ground.

**Planar slides**

Consider a 0.5 m thick column of coal, either defined by joints parallel to the roadway, or by brittle failure developed within the inner shell. The base of the column is defined by a fracture surface dipping at 25° with an equivalent friction angle of 30°. The factor of safety of such a column is 1.24 without seismic loading, reducing to 1.0 with a seismic loading of 0.08g (Figure 8). By reference to Table 1, this corresponds to moderate shaking - category V. When supported with the pattern shown in Figure 6a very high factors of safety apply, in fact even 1 bolt per metre would be adequate.

![Figure 8: Stability of a supported or unsupported planar slide as a function of seismic coefficient](image1)

**Toppling**

The coal rib geometry being considered is not directly compatible with many of the rock toppling analyses codes. By way of an approximation, joints dipping at 88° into the rib and a 0.3 m thick slab have been assumed (Figure 9). This slab has a factor of safety of 15 without seismic loading reducing to unity at a seismic loading of 0.08g. Bolting serves to increase the thickness of the column and hence increase its aspect ratio. Once the aspect ratio is greater than height * tan (cross dip) toppling is not kinematically possible.

![Figure 9: Toppling of a near vertical slab as a function of the seismic coefficient](image2)
Wedges

Depending on the orientation of the joints sets, and especially if one of the sets has a moderate dip, large wedge hazards can exist in coal mine ribs. Consider a case where a coal mine roadway is driven through a complex strike-slip fault zone and finds itself at an angle to the strike of a shear surface. Experience is that shear surfaces in coal have friction angles of 15° to 20° and typically dip at about 40° to 45°. One possible 6 m deep wedge geometry, 12 m long and with a mass of 57 tonnes (Figure 10). For a 15° friction angle, the factor of safety of the wedge is 1.13, and at 20° friction the factor of safety is 1.32. Seismic loading reduces these factors to unity at 0.05g and 0.12g respectively, or shaking intensity V or VI (Table 1).

![Figure 10: Stability of a wedge as a function of the seismic coefficient](image)

Figure 10 overlays the support pattern in Figure 6a onto the wedge geometry in Figure 10. Recognising the likely presence of multiple bedding partings within the coal, only the middle and lower bolts would be effective in supporting the lower portions of the wedge and, depending on the location along the face of the wedge, these two bolts may not be long enough to adequately anchor in stable ground.

![Figure 11: Typical rib bolting pattern installed into the analysed wedge revealing insufficient length](image)

MANAGING THE SEISMIC HAZARD

By drawing analogies with kinematic rock slope stability, collapse of ribs could be generated by bumps corresponding to level IV and V intensity. Such collapses would be sudden, but would not have violent ejection. It is noted the gravitational potential energy that could be released by a fall of 1 m³ of coal from 2.5 m is 40 KJ which would impact at the floor level at 7 m/sec (25 km/hour). The general lack of awareness of bursts in Australian coal mines may be related to the standard practice of securing ribs with bolts and mesh. The association of coal bursts with small scale faults in US coal
mines (Swanson et al, 2008) may be explained by the presence of non-vertical surfaces defining wedges and the absence of rib support.

A key conclusion of this paper is that the general observations of coal mine bursts being associated with massive units, elevated depth, and faults may be explained by the driving seismic mechanism (the bumps) being associated with failure of massive voussoir beams, the increasing depth relates to the increasing thickness of failed coal at the excavation boundary, and the faults defining kinematically acceptable wedges and other blocks. The use of words such as ‘pressure’ and ‘violent’ are not necessary as the gravitational potential energy within the blocks is sufficient to cause the observed damage and the terms may be misleading when devising a management plan.

It would appear that the key hazard to be managed in a coal mine strata control plan is seismic shakedown of either the excavation damaged zone within the inner shell or kinematically acceptable wedges within fault zones. Importantly this paper suggests that the shakedown hazards can be managed with bolts and mesh, with the important proviso that the bolt length is sufficient to anchor behind wedges in joint zones.

Based on this paper, key questions to address when developing a management plan are:

- Is it a caving operation? If not, there is unlikely to be a seismic hazard. If yes, it is important to note that the caving may be associated with active coal extraction or the caving may be somewhat delayed. The distance to the caving is possibly not material as the bedded nature of the overburden can provide wave guides to allow distant transmission of seismic energy.
- Are there thick overburden units, the caving of which may be delayed such that large seismic events are induced?
- Can the proposed shaking intensity table (Table 1) be used?
- Is the combination of coal strength and depth of cover such that a thick excavation damage zone will be created? At this stage Figure 6d can be used to give some indication of the likely thickness of damaged ribs, recognising that more research is required into the characterisation of coal.
- What system will be used to ensure that rogue structures that may define wedges and other blocks are identified at the mining face?
- Are there adequate barriers to protect the face crews before the bolts and mesh can be installed?
- Are we sure that our bolts and mesh panels are adequate for both inner shell support and seismic shakedown? It would appear that the Australian standard of rib support using bolt and mesh is adequate and should be the minimum standard for all longwall and pillar extraction mines regardless of depth if there is a possibility of delayed caving of massive units.
- What is the maximum practical length of rib tendons?
- Do we need to consider rib side protection along the full length of the miner?
- How will we manage the rib hazard outbye of the continuous miner? Can we invoke low spatial and temporal exposure probability to reduce the assessed risk?

Finally it is stressed that more research is needed on the proposed perceived shaking scale and its associated accelerations, the quantification of seismic intensity related to the collapse of voussoir beams, and the TIB failure criterion for defining the inner shell and how it can transition to the outer shell. In addition some of the concepts of TIB failure may assist in understanding pillar bursts.

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