2018

Coal and Rock Bursts - Similarities and Differences When Considering the Sudden Collapse of the Sides of Excavations

Ross Seedsman
Ross Seedsman Geotechnics

Recommended Citation

Ross Seedsman, Coal and Rock Bursts - Similarities and Differences When Considering the Sudden Collapse of the Sides of Excavations, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2018 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019
https://ro.uow.edu.au/coal/700

COAL AND ROCK BURSTS – SIMILARITIES AND DIFFERENCES WHEN CONSIDERING THE SUDDEN COLLAPSE OF THE SIDES OF EXCAVATIONS

Ross Seedsman[1]

ABSTRACT: Using metalliferous terminology sudden collapses of the sides of coal mine roadways are likely to be strain bursts, plus the possibility of some kinematic failures or slumps. Brittle failure in coal induces vertical slabs parallel to the excavation boundary, which if unsupported, can topple or slide into the roadway. In Australian coalmines, the potential collapse of the ribs during strain bursting is controlled by the routine rib support that is installed off the continuous miners. Mine seismicity may be the trigger for additional brittle failure. The energy released by brittle failure can be absorbed by a bolted and meshed rib or may cause ejection. The association of the term "coal burst" with high velocity ejection of coal may be preventing the identification of sudden rib failures, which are the simple collapse under gravity of kinematically acceptable wedges that have dimensions greater than the length of the installed bolts. Vertical pillar deformations later in the mining cycle may generate additional brittle failure or load existing kinematically acceptable slabs or wedges causing them to collapse.

INTRODUCTION

Differing from typical metalliferous excavations, coalmine roadways are rectangular in shape and are formed in a transversely isotropic rock mass excavated using continuous miners. In Australian underground coal mines rib and roof bolting is conducted about 3 m from the active mining face behind the miner cutter head and coal gathering system; the mining method places the development workforce within 1.3 m of the ribs which are typically supported with mesh and short bolts. Subsequently, during either longwall mining or pillar extraction, the workforce can be within 2 m or 3 m of an active coalface that is not supported. Geological faults and other structures may need to be traversed to access "undisturbed" areas for coal extraction. By way of contrast, a typical metaliferous roadway is horseshoe shaped and excavated with drill and blast in rock masses that are assumed to be isotropic. The typical ground support consists of bolts and fibrecrete with mesh introduced when there are concerns with rock bursts. Mineralisation is often associated with large scale faulting.

The burst terminology is different between the two mining sectors. According to Canbulat, *et al* (2016) a pressure (or coal) bump is a form of dynamic release of energy within the rock (or coal) mass in a coal mine due to either 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. A pressure (or coal) burst is a pressure bump that actually causes consequent dynamic rock/coal failure in the vicinity of a mine opening, resulting in high velocity ejection of this broken/failed material into the mine opening. In metal terminology (Kaiser 2016) strain bursts are the result of a sudden bulking process associated with rock failure that may be triggered by a seismic event (itself possibly a fault slip) but are primarily the result of the tangential stress near an excavation exceeding the capacity of the unconfined or lightly confined rock mass due to excavation advance or nearby mining (the latter called a pillar burst). In the absence of support there may be ejection of the failed rock. Shakedown is the subsequent collapse of failed rock in response to a seismic event.

So in summary, a coal bump is a felt seismic event and a coal burst involves not only failure of the coal but also requires an unspecified high velocity ejection. In contrast a rock strain burst is defined as a failure process that may or may not be caused by a seismic event and the consequences of which may or may not be ejection depending on the installed support.

[1] *Ross Seedsman Geotechnics Pty Ltd. Email: sgplross@bigpond.com. Tel: +61 417 279 556*

These may appear to be subtle differences but they become important when designing possible control mechanisms.

BURST HAZARD

A simple empirically-derived relationship used in rock burst assessments (Kaiser et al, 1996) is the ratio of magnitude of the maximum stress at the excavation boundary relative to the laboratory uniaxial compressive strength (UCS) - referred to as SL_{UCS} with a value of 0.3 indicating the onset of a bursting hazard and 0.7 being the limit of the empirical data. The Q system (Barton et al, 1974) identifies a rockburst hazard by the reciprocal of this ratio with a mild burst at a SL_{UCS} of 0.2 and a heavy burst at 0.4; these were later changed to 0.33 and 0.5 (Grimstead and Barton, 1993). The Coal Strength Index (CSI, Seedsman, 2012) is the ratio of the coal UCS to the vertical stress and conversion to SL_{UCS} requires consideration of the shape of the opening, the stress field in coal, and transverse isotropy and may be approximated as equal to 5/CSI for the ribs. In Figure 1, it can be seen that a moderate burst hazard according to the definitions in hard rock is reached in coal mines at about 100 m depth and exceeds the metaliferous empirical relationship by 150 m depth. In the metaliferous sphere, rockbursts are subdivided into self-initiated strain bursts, seismically triggered strain bursts, and dynamically loaded strain bursts. As mentioned earlier these definitions are independent of possible ejection after failure. For coal, Iannacchione and Zelenk (1995) refer to three mechanisms – loss of confinement, seismic stress, and excessive pressure.

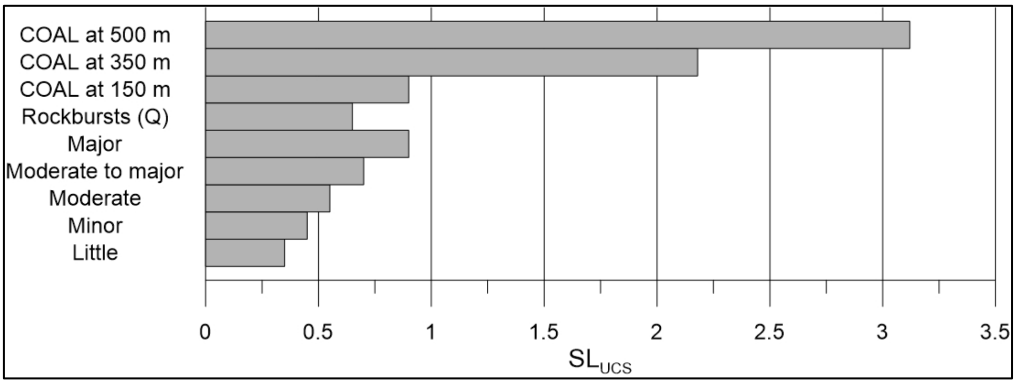


Figure1: SL_{UCS} as used for rock burst hazard identification compared with inferred values for coalmines

SEISMICITY

All failure in rock/coal masses can generate a seismic event of some magnitude. A self-initiated strain burst produces a seismic event just as mining-induced movements along a distant fault structure can produce a more energetic event such that when it arrives at an excavation boundary it initiates a strain burst.

Up until recently, support design practice in metal mines was based on estimating ejection velocities using case studies of presumed ejection velocities and the distance to seismic events. Ejection is considered possible if the Peak Particle Velocity (ppv) exceeds 1 m/s and it is common practice to assume a default design value of 3 m/s. For rock ejection the method advocated in Kaiser et al (1996) would require a Richter 2 event at 15 m from an excavation. In a major change in the design approach, Kaiser (2017) proposes that ejection velocities are simply related to the rapid onset of brittle failure. For example if 0.5 m thickness of rock undergoes rapid brittle failure in 0.1 seconds and then bulks by 20 % the resulting ejection velocity would be 1 m/s. In this model the mine seismicity may trigger the brittle failure but does not by itself accelerate the rock.

Microseismicity studies in Australian coalmines do not quote Richter magnitudes. The GeoScience Australia earthquake database includes Richter 2 and 3 events in the Appin and Cessnock areas; unless the events were very close to an excavation the likely impact according to rock burst knowledge would have been bulking but not ejection. Some appreciation of what can be felt in underground coal mine roadways can be gleaned from Table 1 which is derived from the Mercalli scale for earthquakes. Based on this scale the author has been exposed to events up to “Strong” (possibly accelerations of up to 0.18 g).

Table 1: Possible felt scale for coalmine bumps

Qualitative Description (ACG 2008)	Mercalli perceived shaking and seismic coefficient
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).	Light (IV) 0.014-0.039g
Often felt by many workers throughout the mine. Should be detectable by a seismic monitoring system.	Moderate (V) 0.039-0.092g
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.	Strong (VI) 0.092-0.18g
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.	Very strong (VII) 0.18-0.34g
Vibration felt on surface is greater than large production blasts. National seismic stations can usually detect events of this size.	Severe (VIII) 0.34-0.65g

DEFORMATION AND FAILURE OF COAL RIBS

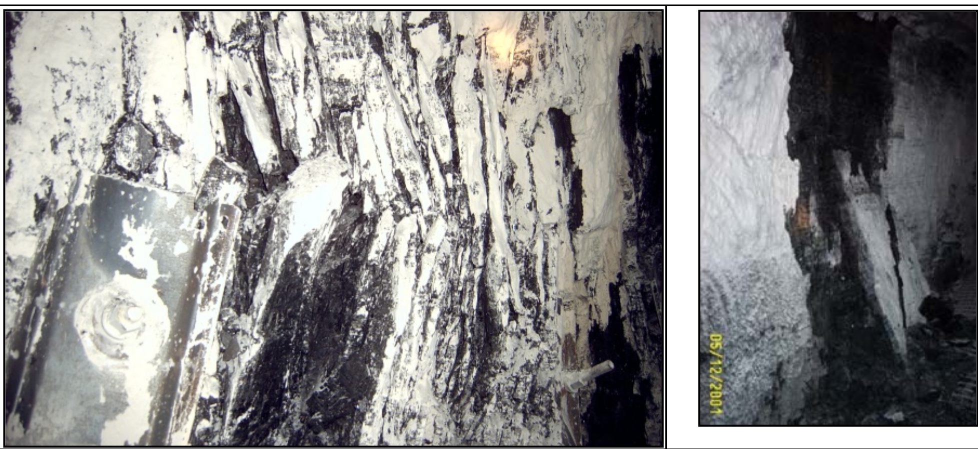
Rock burst literature proposes that the ejected rock has undergone brittle failure at the excavation boundary with the interpretation that seismic loading by itself does not increase the volume of failed material. Rock bursts are associated with brittle failure in hard rock and this section discusses the brittle failure in the ribs of coal mine roadways.

Observations

At shallow and moderate depths the sides of coal mine roadways are characterised by closely-spaced mining-induced fractures that strike parallel to the roadway direction (Figure 2); at greater depths the ribs may be so broken that the slabs are not readily discernible. The thickness of the slabs is typically less than about 10 cm. The mining-induced fractures exploit persistent joints in the coal when the roadway is driven sub-parallel. At other orientations, the mining-induced fractures are quite distinctive with a rough/stepped profile compared to smooth/planar profile for natural joints. The fact that the slabs have a vertical continuity indicates that intrinsic cleating of the coal is not a discontinuity in a geotechnical sense. In fact, the RQD of coal is typically 100 even though coal itself is typically strongly banded with alternating bright and dull layers.

Extensometry

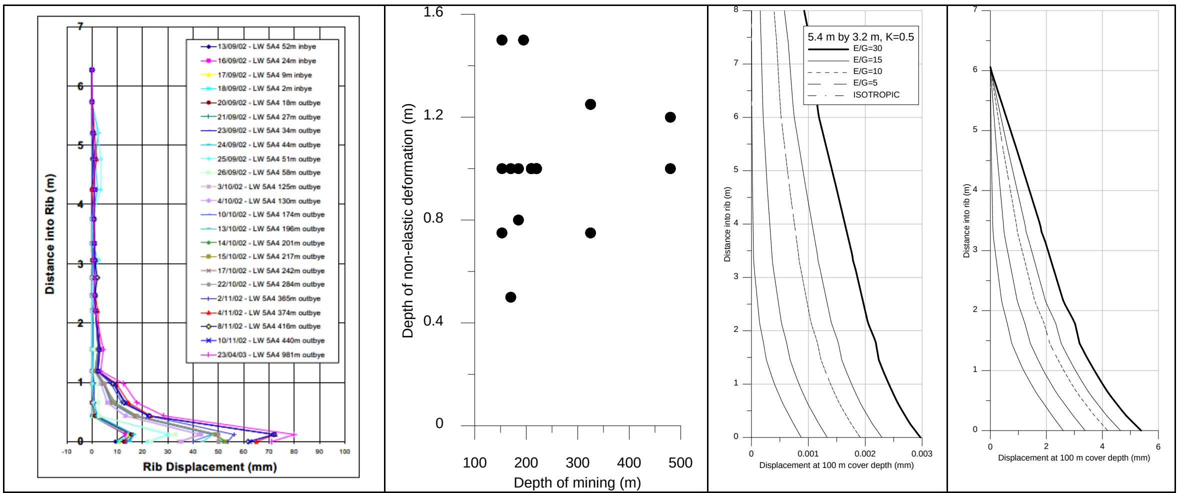
A typical extensometer plot for a coal rib in a development roadway at 480 m depth (Figure 3a) indicates that most of the movements are within 1 m of the excavation boundary. It is noteworthy that as the longwall retreated past the instrumentation the depth of movement increased from 0.5 m to 1.0 m and the horizontal movement at the boundary increased from 15 mm to 80 mm. If the non-elastic movements are assumed to be those in excess of 10 mm and recognising the resolution of the extensometer, Figure 3b suggests that the maximum depth of failure apparently does not increase with depth of cover between 140 m and 480 m depth.



(a) Thin slabs formed in a bolted and strapped coal seam rib at about 400 m depth of cover

(b) Slabs formed in the sides of an unbolted coal rib at about 65 m depth

Figure 2: Examples of coal ribs.



(a) A typical rib extensometer result at 480m depth showing initial rib deformation and the impact of the passing of longwall face (Colwell, 2004),

(b) Depth of non-elastic deformation in coal mine ribs does not increase with depth of cover (data from Colwell, 2004)

(c) Elastic deformations in the side of a coal mine roadway at 100 m depth for a range of independent shear modulus values

(d) Elastic deformations relative to 6 m depth.

Figure 3: Deformations in coal ribs

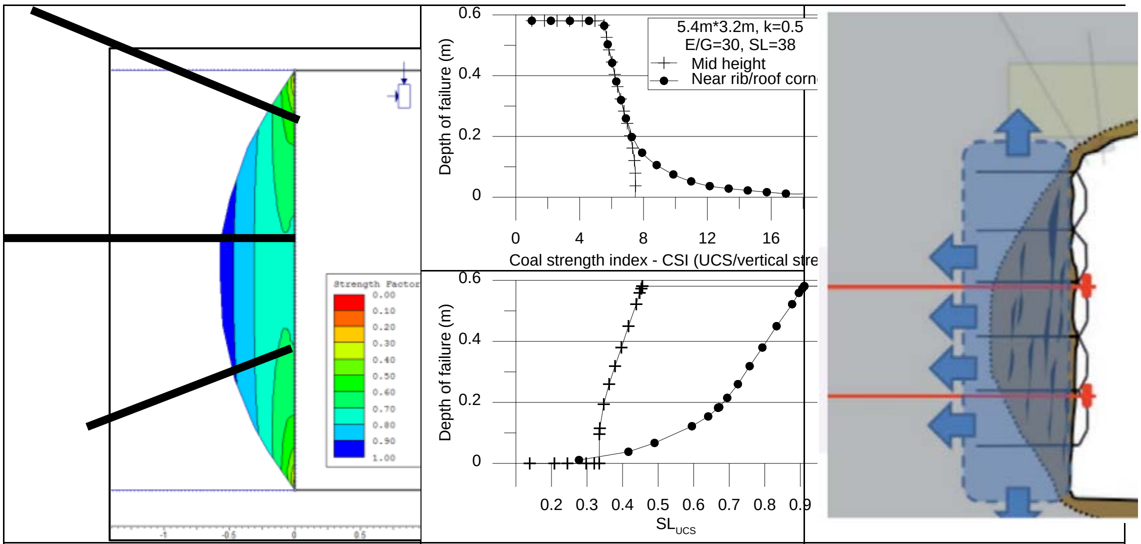
Elastic deformations

Figure 3c and 3d presents the result of a finite-element analysis of a rectangular roadway in a transversely isotropic homogeneous continuum with a horizontal to vertical stress ratio of 0.5 for a number of values of the ratio of Young's modulus to the Independent Shear Modulus (E/G) and normalised to a Young's modulus of 1 GPa. The elastic deformations increase with increasing values of the E/G ratio. In work on coalmine roofs, an E/G value of 30 has been used for moderately to thickly bedded units and 100 for thinly bedded units. For an extensometer with a 6 m length, the resolved elastic movements at the excavation boundary would be in the order of 2.5 mm for every 100 m depth of cover assuming a typical coal modulus of 2 GPa. Applying these results to the extensometer data in Figure 3a, the limit of elastic movement is 12 mm and hence non-elastic movements (failure) are located within about 0.5 m of the excavation boundary.

Brittle failure

Strain bursts in rock are caused by the sudden creation of a zone of stress-fractured rock (Kaiser, 2016) and this stress fracturing can be modelled using brittle rock concepts in what is referred to as the inner shell of an excavation. The UCS of coal varies from about 5 MPa for some high quality coking coals to about 40 MPa for dull thermal coals (Young's modulus/UCS ratio is typically in the range of 100 to 200). The possible independence of the depth of failure with respect to depth of cover (Figure 3b) suggests that a suitable failure criterion would invoke a stress ratio and not solely a deviatoric stress. The spalling limit component of the S-shaped failure criterion (Kaiser and Kim, 2008) is such a criterion. Laboratory testing of an Australian thermal coal has revealed evidence of a spalling limit value of 38 (Buzzi et al, 2014).

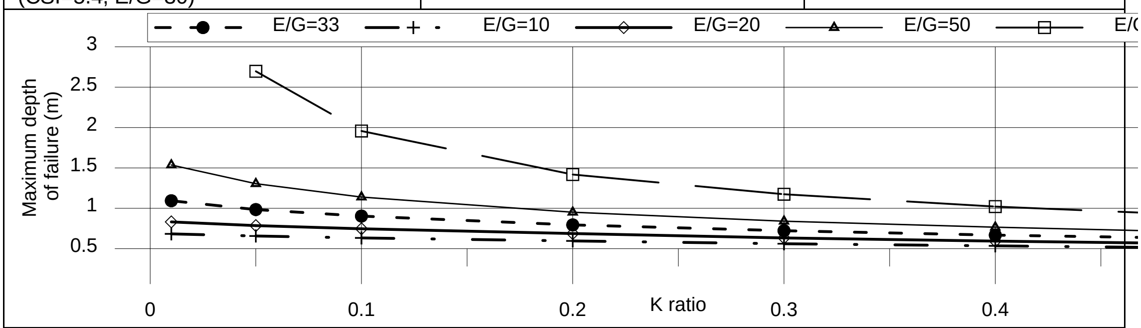
Simple boundary element analyses using the Transverse Isotropic Brittle failure (TIB) criterion (Seedsman, 2017) with an E/G ratio of 30 and a spalling limit of 38 produce a failure zone that appears somewhat similar to that developed in coal mine roadways – greater stress failure at top and bottom corners, and a vertical boundary at mid-height (compare Figure 4a with Figure 2). A spalling limit of 38 gives a depth of failure similar to that recorded in extensometry.



(a) Contours of the strength factor as defined by Examine2D with respect to damage initiation/cohesion assumption and limited by a spalling limit of 38 (CSI=5.4, E/G=30)

(b) Depth of rib failure as a function of CSI and SL_{UCS}

(c) The gabion concept for ground control in strain burst ground (Kaiser, 2016)



(d) impact of transverse isotropy and stress ratio on the depth of brittle failure in coal ribs

Figure 4: TIB analysis of coal ribs

Similar to the rock strength index (Seedsman, 2014), the depth of failure in coal ribs can be related to the CSI. Figure 4b shows that the depth of failure does not increase for CSI values less than about 5.5 as this is when brittle failure is determined by the spalling limit independent of the cohesive strength. Using the TIB failure criterion, the maximum depth of failure depends on the horizontal to vertical stress ratio (K) and also on the value of the E/G ratio (Figure 4d). The increase in the depth of failure at very low K values is of significance when considering the stress conditions under pillars in multiple seam mining (Seedsman, 2017).

These analyses are 2-dimensional plane-strain and represent the conditions likely to develop at about 10 m - 15 m from the mining face. Three-dimensional modelling of rectangular roadways in an isotropic continuum suggest that stresses at the time the rib bolts are installed in Australian mines will be about 70% of the plane strain values: hence the need for rib support to be installed off the continuous miners to address the possible formation and immediate collapse of the slabs induced by brittle failure.

SUMMARY

The concepts of brittle failure used to explain damage at the excavation boundary in high strength rock can be used to explain the onset and depth of mining-induced fractures in coal mine roadways once the impact of bedding is considered by assuming transverse isotropy. Based on this conclusion, the next sections of this paper seek to examine the collapse of ribs in coalmines, with particular reference to Australian underground coalmines.

GROUND SUPPORT

Kaiser and Cai (2014) discuss support for burst-prone ground in the context of sudden volume expansion during strain bursting. For strain bursting, support selection proceeds by estimating the depth of failure and the consequent bulking of the failed rock. The volume of the failed zone and the rock density is used to give the load demand on the support and the bulking provides the displacement demand. The displacement demand leads to selecting yielding support elements. Kaiser (2016) describes a gabion concept for large deformations utilising deep anchoring elements with good connections to a mesh/fibrecrete retention system for the material that will undergo brittle failure (Figure 4c). The idea behind this concept is that the gabion absorbs the energy released by strain bursting so that there is no kinetic energy left to cause ejection into the roadway. Kaiser (2017) proposes that the rate of brittle failure is possibly between 0.05 and 0.1 seconds and from this it is possible to determine a bulking velocity that can then be used in a calculation of energy that needs to be adsorbed by the gabion.

In Australian coalmines, the typical rib support that has evolved over the last three decades has similarities to the recently proposed gabion concept. It is suggested that the impetus for the typical Australian rib support has been the onset of brittle failure within the confined working area of the in-place miner-bolters. Bulking factors in coal ribs can be obtained from rib extensometry with values of 3% – 6% indicated in **Error! Reference source not found.**a for a light support pattern. It is speculated that the difficulties in achieving full encapsulation of rib bolts within the zone of brittle failure could be a positive result as it gives a displacement capacity that is required for any later bulking.

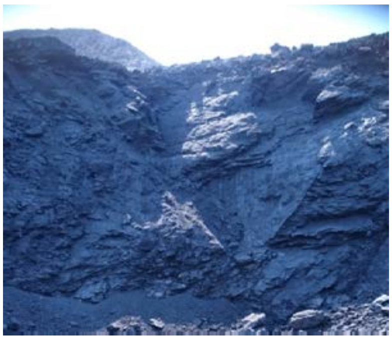
KINEMATICS AND SEISMIC SHAKEDOWN

The “burst” terminology used in coalmines presupposes violent ejection of coal from the sides of the excavation. Equally hazardous could be the simple collapse under gravity of large volumes of coal in mechanisms analogous to the collapse of excavation trenches in civil construction. Recent fatal collapses of ribs in Australian mines may be better explained by kinematics rather than bursting and it is for this reason that the title of this paper refers to sudden collapse. The kinematic hazard may not be as great a hazard in metalliferous mines due to non-persistence of joints, the use of drill and blast generating overbreak if joint blocks are present, and support installation that is not conducted in such confined spaces as on a continuous miner.

Undisturbed coal seams are typically characterised by two sets of persistent joints that are aligned orthogonal to bedding. For flat-lying seams, and hence sub-vertical joints, any planar slides or wedge hazards in the sides of underground roadways should be relatively small in size but they may become hazardous given the confined work places; the toppling hazard would always be present. A light bolting density should easily control these hazards in flat-lying unfaulted coal seams. Any collapse of unbolted ribs, such as in front of a continuous miner, would be seen as sudden and since there would be some shearing through the roughness of joint surfaces some noise and dust would be generated.

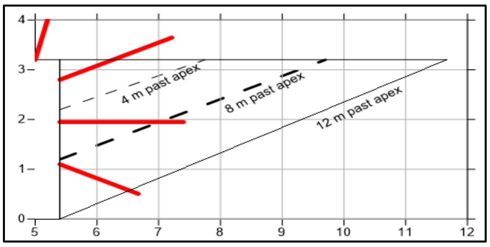
When traversing fault zones, or even isolated small-throw faults, there may be persistent non-vertical joints that define wedges or planar slides with dimensions such that standard bolt lengths do not provide anchorage in stable ground (Figures 5a,b,c). The physical constraints on the continuous miners used in Australia mean that rib bolts are typically limited to a maximum length of about 2 m. For planar slides, joint dipping at less than about 50° would start being of concern in terms of suitable anchorage being available for practical bolt lengths; for wedges the concern would extend to possibly less than 55°.

(a) Planar slide prior to bolting (n.b. standard rib bolt length would have been insufficient)

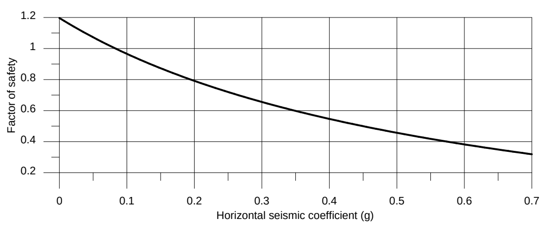


(b) Wedge geometry in a faulted block of coal in a surface mine

(c) Wedge defined by a joint dipping at 45°



(d) Wedge is wider than the rib bolts are long



(e) Decrease in stability of a wedge as a function of seismic loading

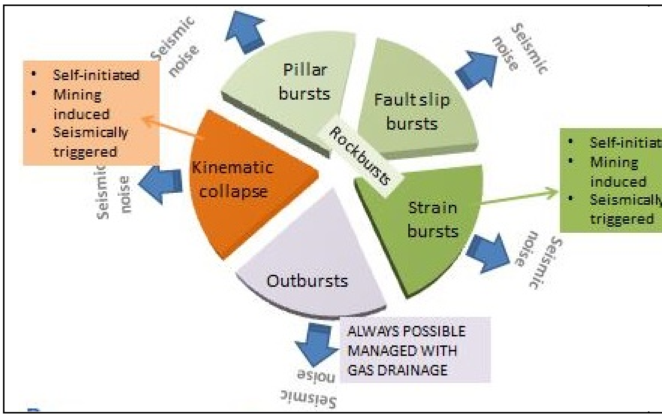
Figure 5: Kinematics of a coalmine rib

The application of kinematics to rib collapse may provide a framework to better appreciate seismic shakedown and seismically triggered strain bursts. In rock slope design, the impacts of seismic events are assessed by invoking an additional acceleration to that of gravity. Figure 5e shows how the factor of safety of a wedge decreases from 1.2 (often interpreted as “stable”) to less than unity with an acceleration of 0.1g which is only a moderate Mercalli event according to Table 1. Extending these concepts further, there is a need to recognise that such low accelerations may be sufficient to cause the collapse of a slab of coal formed by earlier brittle failure if it had not been supported.

SUMMARY AND CONCLUSIONS

It is suggested that similar brittle failure and bursting mechanisms are present in both coal and metal mines and that the selection of support elements can use the same engineering concepts. Coalmines are potentially exposed to an additional sudden collapse mechanism in the form of wedge, planar and topping failures of the type that are invoked in rock slope engineering (Figure 6). Just as for strain bursts, kinematic collapse may be self-initiated (low static factor of safety), mining-induced (additional displacements during subsequent mining applying an additional vertical loads), or seismically triggered. It is recommended that workplace safety considerations are formulated in the context of sudden collapse of ribs instead of reference to “bursting” which is often used to include a component of ejection. It is suggested that this approach would concentrate attention on the critical importance of developing ground control strategies and less on the emotional aspects on mine seismicity, high stresses, and high velocity ejection.

The routine installation of bolts and mesh installed from the continuous miners and hence close to the development face in Australian coalmines provides adequate management for strain bursts. Sudden failure of a coal rib may be encountered when the mining system is not compatible with the installation of bolts and mesh – for example longwall extraction – but the resulting hazards should be able to be managed with stand-off distances. In the restricted workspace of the miner-bolters used in Australia, kinematic failures represent a significant hazard, which in some situations may not be controlled with current support patterns.



Type	Sub-set	Energy source
Coal burst	Strain burst	Strain energy at boundary
	Fault slip burst	Tectonic strain
	Pillar burst	Overburden gravitational
Outburst		Gas
Kinematic collapse	Wedge, planar, topple	Seam level gravitational

Figure 6: Sudden rib movements can be induced by kinematic collapse, strainbursts and gas outbursts.

REFERENCES

Barton, N R, Lien, R and Lunde, J, 1974. *Engineering classification of rock masses for the design of tunnel support*. Rock Mechanics, 6(4), pp189-236.

Buzzi, O, Sieffert, Y, Mendes, J, Liu, X, Giacomini, A and Seedsman, R W, 2014. *Strength of an Australian coal under low confinement.* Rock Mechanics and Rock Engineering. 47(6), 2265-2270.

Canbulat, I, Zhang, C, Hebblewhite, B, Galvin, J, Suorineni, F, Shen, B, Gale, W, Thomas, R, Saydam, S and Hagan, P, 2016. Scoping of ACARP’s coal burst research – Project C25004. (ACARP Brisbane).

Colwell, M, 2004. Rib support design methodology for Australian collieries - Project C11027. (ACARP Brisbane).

Grimstad, E and Barton, N, 1993. *Updating of the Q-System for NMT,* in Proceedings of the International Symposium on Sprayed Concrete. - Modern Use of Wet Mix Sprayed Concrete for Underground Support, pp46-66 (Norwegian Concrete Association, Oslo).

Iannacchione, A T and Zelanko, B S, 1995. *Pillar mechanics of coal mine bursts: A control strategy*, in The Mining Industry on the Threshold of XXI Century; Proceedings of 16th World Mining Congress, 1995, Available from: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/pmocm.pdf [Accessed: 5 December 2017].

Kaiser, P K, 2016. *Ground support for constructability of deep underground excavations: Challenge of managing highly stress ground in civil and mining projects.* Sir Muir Wood Lecture, International Tunnelling and Underground Space Association.

Kaiser, P K, 2017. *Ground control in strain bursting ground – a critical review and path forward on design principles,* in RaSiM9, 9th International Symposium on rock bursts and seismicity in mining, pp146-158 (Editec S. A.: Santiago)

Kaiser, P K and Cai, M, 2014. *Design of rock support system under rockburst condition*. Journal Rock Mechanics and Geotechnical Engineering. 4(3), 215-227.

Kaiser, P K and Kim, B-H, 2008. *Rock mechanics challenges in underground construction and mining*, in SHIRMS 2008, pp1-16 (Australian Centre for Geomechanics:Perth).

Kaiser, P K, McCreath, D R, and Tannant, D D, 1996. Canadian Rock Burst Handbook. 314p (Geomechanics Research Centre, MIRARCO: Sudbury).

Seedsman, R W, 2004. *Failure modes and support of coal roof*, in Ground Support in Mining and Underground Construction, Proceedings 5th International Symposium on Ground Support, 2004, pp367-375 (A A Balkema Publishers: Leiden).

Seedsman, R W, 2012. *The development and application of a logical framework for specifying roof and rib support/reinforcement in Australian underground coal mines*, in 7th International Symposium on Rock Bolting and Rock Mechanics in Mining, pp153-162 (Verlag Gluckauf GmbH: Essen).

Seedsman, R W, 2014. *Practical strength criterion for coal mine roof support design in laminated soft rocks*. Transactions of the Institutions of Mining and Metallurgy: Section A, 122, 243-249.

Seedsman, R W, 2017. *The spalling limit in transversely isotropic materials, the prediction of the maximum height of failure and the design of long-tendon roof support systems*. Transactions of the Institutions of Mining and Metallurgy: Section A, DOI: 10.1080/14749009.2017.1325552.

Seedsman, R W, 2017. *Application of rock burst concepts to understanding the sudden collapse of ribs in coal mines*, in RaSiM9, 9th International Symposium on rock bursts and seismicity in mining, 15-17, 2017, pp297-303 (Editec S. A.: Santiago).