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DEVELOPMENT OF A METHOD FOR LONGWALL TOP COAL CAVEABILITY ASSESSMENT

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ABSTRACT: Prediction and assessment of caveability for Longwall Top Coal Caving (LTCC) operations remains problematic. Whilst operating effectively in China for some years and having recently been introduced into Australia, there remains limited information and methods for predicting optimal coal recovery and productivity under Australian conditions. This paper describes the development of a novel approach to LTCC assessment. This involved the development of a coal failure and breakage model and then simulation of the LTCC process using a hybrid FLAC/PFC model. In order to establish key parameters for coal fracture, a Synthetic Rock Mass (SRM) modelling process was used to examine a range of variables such as particle size, clumping logic, contact strength, and fracture energy and how they relate to the strength, stiffness and dilation behaviour of the coal. This was processed was calibrated using triaxial test data. Simulation of the LTCC process used a Particle Flow Code (PFC) model of coal behaviour based on the SRM results embedded within a FLAC model to allow simulation of both far field and near field effects. This allows the influence of depth, mining induced stresses, goaf behaviour, weak and strong overlying strata, to be superimposed on the near field caving response. The main outputs from this modelling process include a measure of caveability or recovery and draw profile; and the effect of operating controls upon them.

INTRODUCTION

BHP Billiton Mitsubishi Alliance (BMA) is currently in the process of implementing the Longwall Top Coal Caving (LTCC) mining method at Broadmeadow Mine (BRM). As part of studies on various aspects of the proposed operation, BMA commissioned MineCraft Consulting Pty Ltd (MineCraft) and PDR Engineers Pty Ltd (PDR) to develop a caving and materials handling model for input into their productivity assessments. The project had two broad aims, namely:

- To develop a generic modelling tool for LTCC extraction that provides an ability to assess potential mining reserves and production capacity for current and future projects;
- Undertake an analysis of the proposed Broadmeadow operation as a starting point for model development and productivity assessment, thereby providing the opportunity for further calibration and ongoing improvement.

LTCC extraction is heavily dependent on the behaviour of the top coal itself followed by the manner in which the caving sequence is managed. Distinct Element (DEM) analysis was identified as a one of the few methods in which to address caving behaviour via simulation of rock failure and breakage, then the subsequent gravity flow of broken material. These methods however are highly computationally intensive, which require the problem to be separated into two parts, namely:

- Coal Failure and Breakage Model– which is designed to simulate the caving process over the selected range of mining conditions and cover depths; with a corresponding estimate of the volume and size of material delivered to the rear AFC;
- Materials Handling Model– which is designed to simulate the rear door sequencing process over a selected range of door opening times; with a corresponding estimate of throughput.

The project was aimed at addressing several key feature of LTCC extraction. In particular, a suitable combination of cutting height and support geometry is required to maintain face stability whilst achieving the desired caving behaviour. It is commonly accepted that caveability depends on several factors including coal strength characteristics and cleating, mining induced stresses, cut height and seam

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thickness as well the influence of the overlying strata. Moreover, the sequence and timing of rear door caving operations will also affect the development of the drawzone.

One major question is how much the drawzone will influence face stability, associated support load and ultimately coal recovery. In order to establish the size of the cave zone, a means to assess the level of fracturing within the coal seam is needed. This paper describes the development of the coal breakage and failure model and key results arising from the analyses.

CHALLENGES FOR CAVE MODELLING

Cave prediction and modelling present one of the most challenging areas of analysis in geomechanics today. At the heart of these predictions is the ability to capture the right failure mechanisms and to estimate the rock mass properties that govern this behaviour. Failure of rock masses at low confining stress, as is the case for LTCC, is a complex process in which the role of both joints and cleat as well as the strength of the coal blocks itself plays a role.

Tensile cracking leads to a unique failure process (slabbing) that is inconsistent with conventional shear based failure criteria. In this case rock mass strength is controlled by damage initiation mechanisms that are relatively insensitive to confinement and by fracture propagation (extension) mechanisms that dominate at low confinement. For brittle rock, the strength envelope can be represented by a multiphase linear failure envelope illustrated in Figure 1.

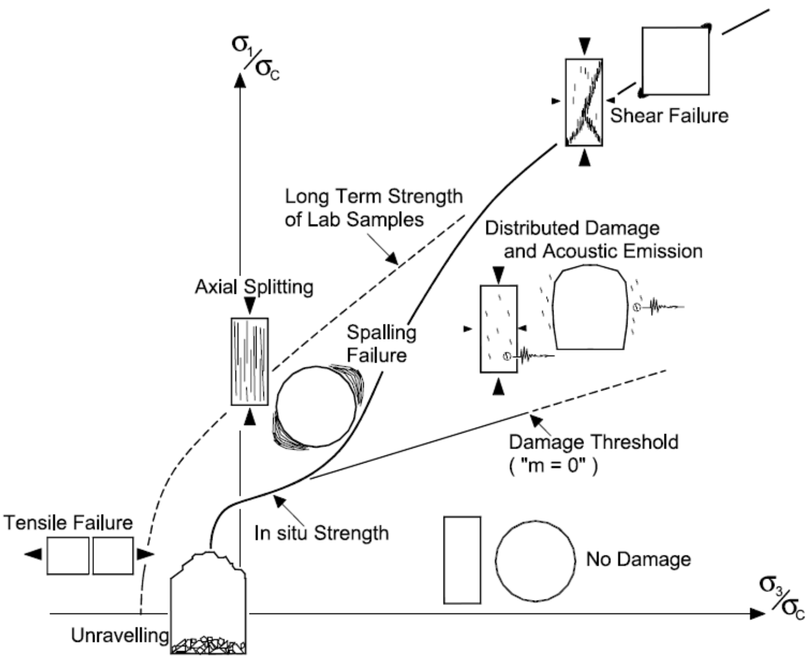

Figure 1 - Schematic failure envelope for brittle failure (Diederichs, 2003)

The most important aspect of this representation of failure behaviour is that different failure mechanisms reflect different estimates of rock mass properties. These properties depend on the stress path leading to failure and the role the discontinuities might play in the failure process.

The process of LTCC extraction can involve several failure mechanisms involving gravity driven failure such as unravelling or tensile failure at the cave boundary, axial splitting due to abutment loading above the longwall supports and shearing at seam contacts and along bedding in the overlying strata. This requires models that can capture these processes. The use of DEM analysis is one of the few methods that can be used to simulate rock failure and breakage under conditions of differing stress paths (or loading conditions). The basic concept of DEM is to model the rock mass as an assemblage of particles, which are bonded together. Joints or cleats can also be inserted into the assemblage to form preferred weakness planes. The general concept is shown in Figure 2 (Itasca, 2012).

It can be appreciated that a Bonded Particle Model (BPM) is a powerful technique in which any possible rock failure scenario might be simulated. However such an approach with its ability to model the relative movements of particles, or blocks of particles will suffer from the ability to reliably calibrate performance under a range of different loading scenarios.

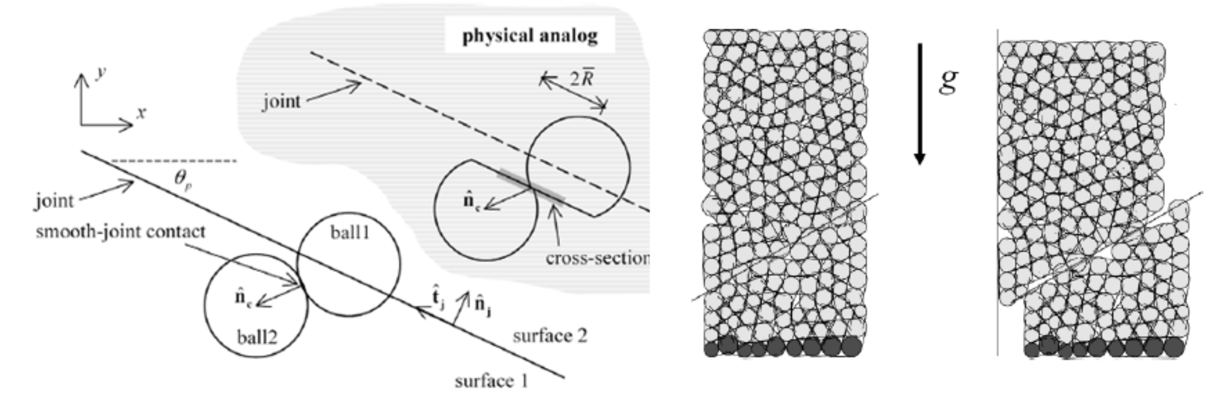

Figure 2 - Schematic bonded particle model with smooth joints

COAL BREAKAGE AND FAILURE MODEL

Effect of scale

In order to build a framework for LTCC extraction an important consideration is to recognize the scale effect present, i.e. to capture the effects of fractures, joints or cleats on the geomechanical properties of the coal when transitioning from small samples to larger field scales. Figure 3 shows the transition from intact coal to a typical cleated coal seam. It can be see that the influence and variation of cleating needs to be considered in assessing the seam's mechanical properties. If laboratory testing is undertaken, core samples from the seam may exhibit a different cleat distribution from that of the entire seam.

The problem of size dependency on the strength and stiffness of rock is a well-known problem and is present in most all rock masses that contain joints and fractures. In general the strength of rock reduces with increasing sample size due to the greater number of fracture per unit volume that is present. For coal, this problem was addressed via a detailed experimental study of the strength and deformation behaviour of coal in the mid 90's, sponsored by BHP Australia Coal, in order to establish the relationship between coal type, strength and scale. An experimental program was conducted to measure the change in coal properties by triaxial testing of 61 mm, 101 mm, 146 mm and 300 mm diameter coal samples (Medhurst and Brown, 1998).

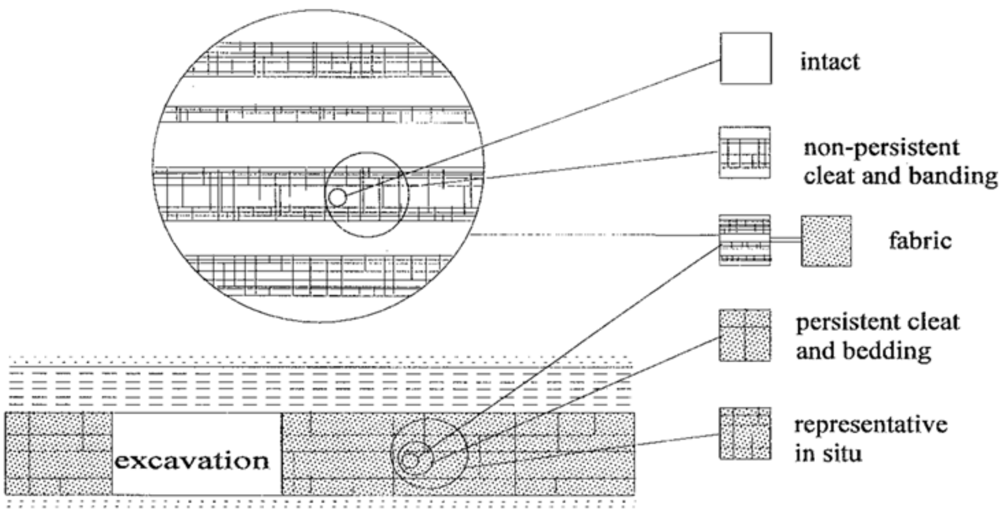

Figure 3 - Idealised diagram showing the appearance of coal at different scales

Figure 4 shows the effect of sample size on the peak strength of coal at various confining pressures. The important point to note is that the mechanical properties reach a constant minimum value. This limit is known as the Representative Element Volume (REV) and is thought to be at the point where the density of fractures within a given volume of rock becomes constant. This particular aspect of rock behaviour allows the properties of rock to be predicted masses from laboratory measurements of rock samples.

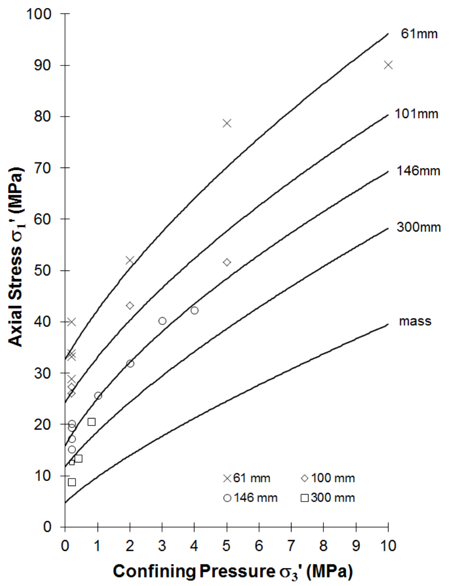

Figure 4 - Influence of sample size on peak strength of coal

The ability to predict the strength of coal seams becomes viable provided some measure of cleat density can be undertaken and matched against laboratory and field performance. Underground pillar strength tests were undertaken some years ago in South Africa suggesting that the REV for coal was about 1 to 2 m^3. Further work undertaken in the Bowen and Sydney Basins based on experiences for highwall mining pillar design has allowed the experimental work outlined above to be extended across a range of Australian coal seam condition (Medhurst, 1999). This work provides the foundation in which the coal breakage and failure model is developed.

Synthetic rock mass model

The Synthetic Rock Mass (SRM) approach was developed to determine the main factors influencing the rock mass behaviour in block cave mines such as caveability, fragmentation, gravity flow and draw control (Mas Ivars, *et al.*, 2011). The process involves the generation and testing of synthetic rock mass samples by combining the bonded particle models of rock and discrete fracture network modelling. Figure 5 shows the SRM components.

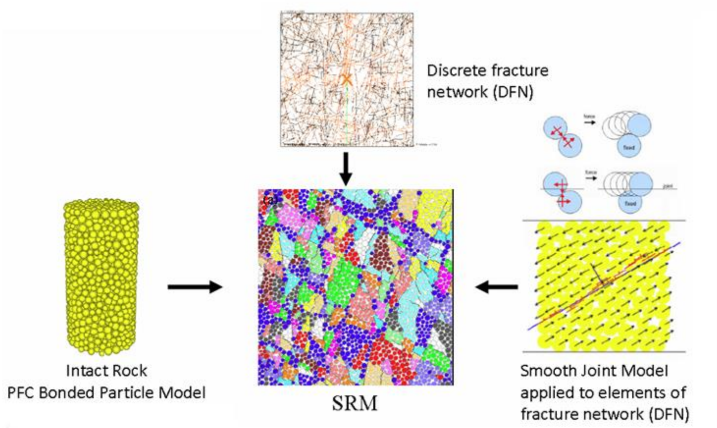

Figure 5 - Development of synthetic rock mass model

Using these concepts SRM models can be generated that represent samples of the rock mass at small scale up to large scale. This process therefore allows the development of a coal failure and breakage model based on simulation of the experimental triaxial test data. In particular, the experimental study revealed some fundamental aspects of coal behaviour that are important to caving. Figure 6 shows volumetric/axial strain measurements from triaxial testing of the 101, 146 and 300 mm diameter samples at various levels of confinement. The results show that when confining stress is low, coal fails along cleats resulting in expansion or dilation of the coal. When confining stress is high, cleating has minimal influence on the coal response and shearing across cleats is the dominant failure mechanism and the volume change of coal is small.

The experimental data shows how the coal will behave at the cave front. Under low confining stress, cleating has a dominant role and results in a weakening effect on the coal (this effect is similar to rib spall). Further into the coal mass, confining stresses are higher and shearing is more predominant. The caving model needs to be able to mimic the expansionary effect of coal at low confining stress, whilst adequately reflecting the effect of scale on strength.

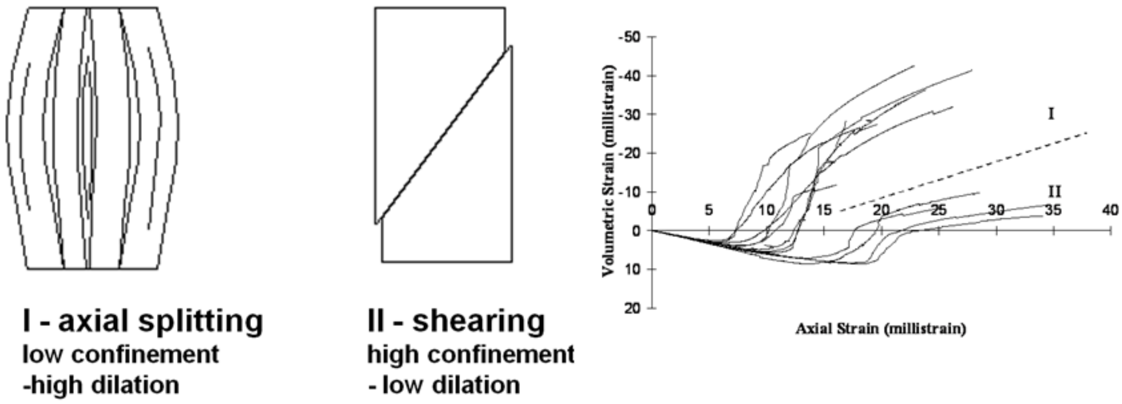

Figure 6 - Mechanisms of coal failure

Figure 7 shows the SRM workflow used in the project. The SRM consists of the Bonded Particle Model (BPM) and the fracture network represented by a smooth joint contact model. The BPM represents the intact or matrix of the SRM and is calibrated against laboratory test data. The joints and cleats are then inserted into the numerical model using smooth joints and the assigned its relevant properties. The BPM and fracture network can then be created at any scale and tested against the available data.

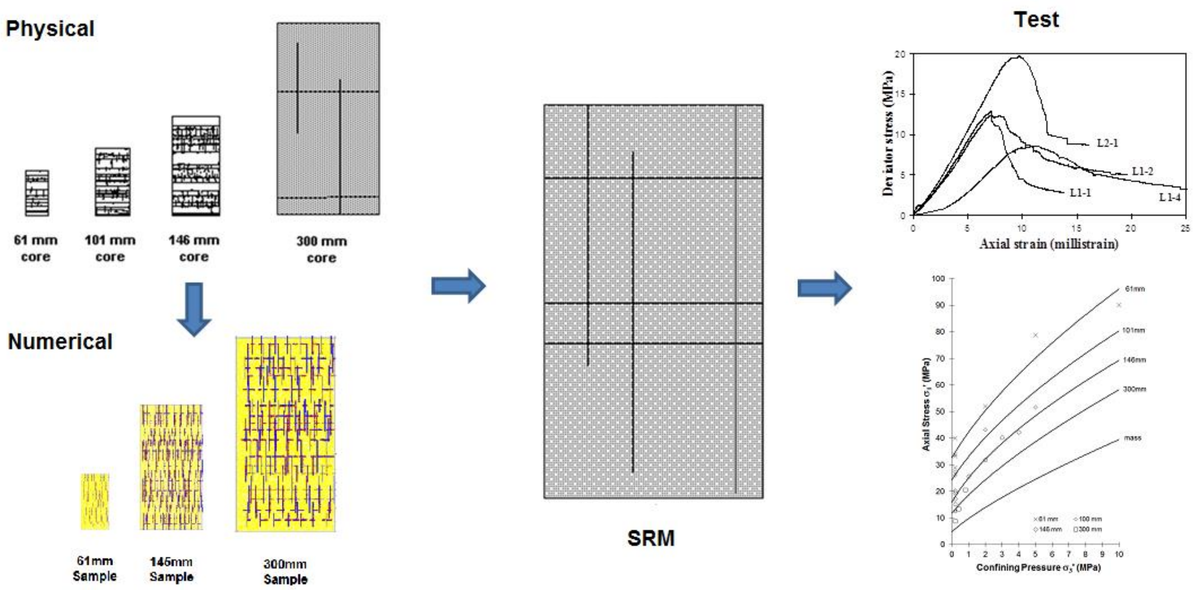

Figure 7 - SRM workflow for characterisation of coal seam properties

LONGWALL TOP COAL CAVING MODEL

Mechanics of caving

The process of cave development requires an understanding of what is required to carry a rock mass from peak to residual strength (i.e. post-peak behaviour). To be able to predict caving, the modelling process requires the prediction of four distinct zones:

- Elastic zone: where rock mass behaviour and properties are undisturbed;
- Seismogenic zone: where discontinuity damage (discontinuities going from peak to residual strength) and the initiation of new fractures develops;
- Yielded zone: the rock mass is fractured and has lost some or all of its cohesive strength and provides minimal support to the overlying rock mass;
- Mobilized zone: the rock mass has caved and may be recoverable with continued draw.

In the case of LTCC extraction, all of these factors need to be considered. One of the key geotechnical risks is potential for the cave line developing over the canopy resulting in poor face stability and uncontrolled caving. Fragmentation is another important factor which has to be evaluated together with the ability to maintain a consistent top coal caving sequence. The model must therefore be able to investigate the inter-relationship between roof stability, fragmentation and dilution under variable overlying strata conditions.

In an effort to simulate the LTCC process, the model must be able to adequately capture the transition from intact to completely broken material. The preceding discussion outlines several key challenges to develop these models including adequately addressing the geometry of the problem; representation of differing strata conditions; modelling the fracture process and finally, simulating the longwall retreat and draw sequence. At the core of this problem is the need to capture the mechanical behaviour of the coal under various stages of loading and its impact on its failure behaviour. For this reason a coupled model is required. In the near field, a detailed particle based model of the coal caving process is developed. Surrounding this model is a continuum FLAC model, which captures the necessary far field influences such as cover depth, different overlying strata and abutment stresses. Figure 8 shows the modelling architecture used for the development of the FLAC-PFC hybrid model. It consists in a PFC2D inclusion embedded in a rectangular FLAC grid with a fine mesh resolution. This inner FLAC grid is itself then embedded in a coarser FLAC grid.

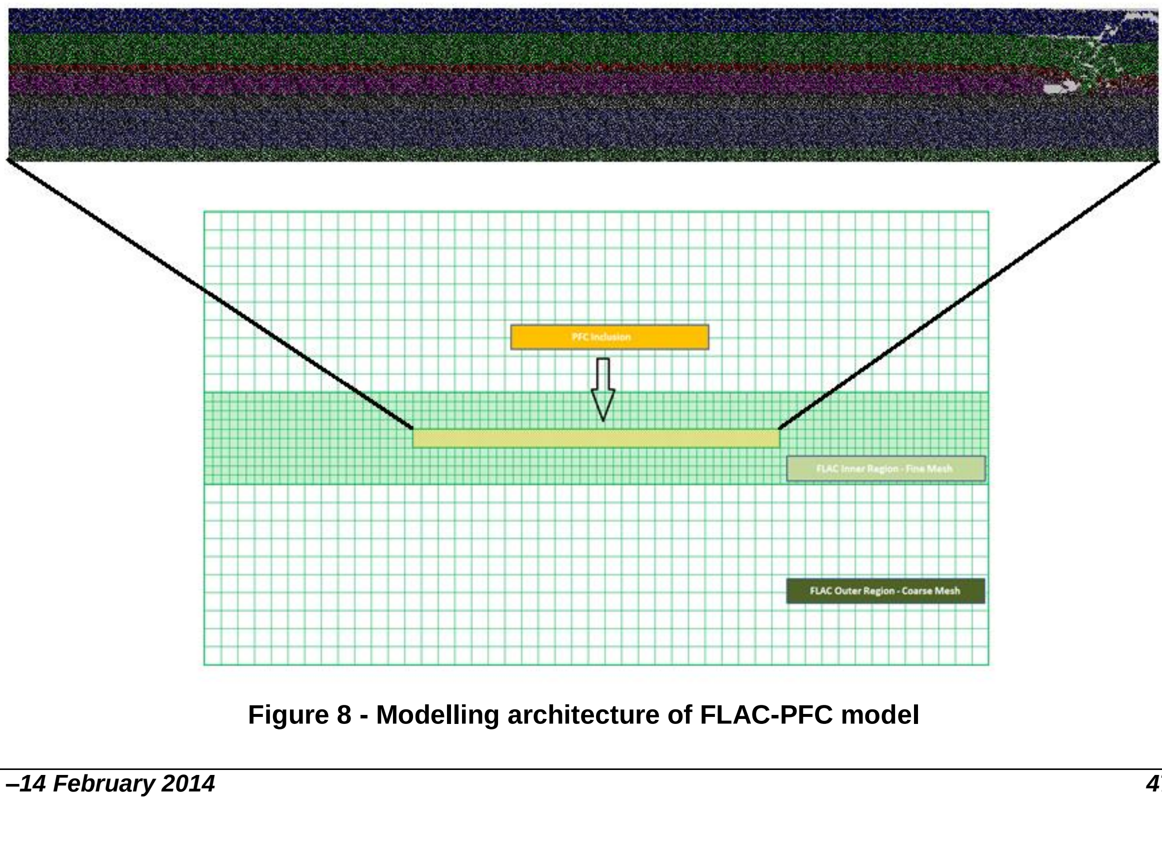

Figure 8 - Modelling architecture of FLAC-PFC model

Caving analysis

Modelling was completed for a range of conditions including depths set at 150 m, 250 m and 350 m with the coal strength being defined as 'low' or 'high' and the overburden material strength being represented as either 'weak' or 'strong'. A weak overburden represents the case where predominantly siltstones are present and the strong case where heavier sandstones predominate. Of particular interest in this study were:

- The particle size distribution of coal and overburden material;
- Recovery rates of the top coal when using the LTCC process.

Figure 9 shows a snapshot of the caving behaviour for a siltstone roof at 350 m depth. In this case the caving is regular, reflecting a frequent periodic cycle often noted in LTCC operations. In general the model shows that the coal caves regularly and moves readily down the rear of the shield, typically with a significant movement of coal when the support moves forward. It is notable that occasionally a fracture forms just ahead of the face line as a result of the draw sequence. For modelling purposes the draw sequence was set to "draw to dilution" to enable an estimate of recovery and to help determine the effects of LTCC extraction at "full" recovery.

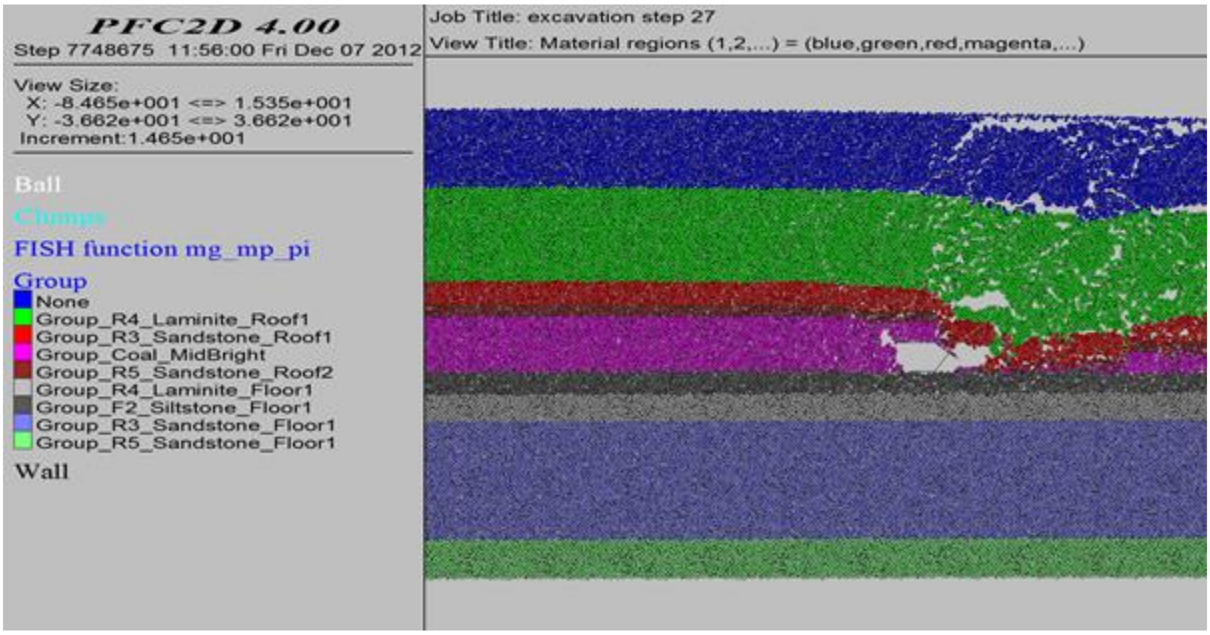

Figure 9 - Caving behaviour under siltstone roof at 350 m depth

Another aspect of caving response is the periodic behaviour of both support loading and coal recovery. A close examination of the models shows how, depending on the fracture pattern, some shears are associated with large recoveries as the support moves forward, and others less so, since a significant proportion of the top coal has been recovered on the previous shear. This is a common observation on LTCC faces, and from the results of the modelling, suggests this becomes pronounced under a scenario of drawing to dilution.

The FLAC-PFC caving model was developed to allow for the detection and extraction of materials entering into a cluster detection window as depicted by the square at the rear of the longwall in Figure 10. Any particle or clusters with a particle contained in, or touching the boundaries of the window were then removed from the model. This sequential removal material is referred to as a 'draw' within the modelling environment. The number of draws taken was set by considering the amount of top coal which would become available after each longwall advance. The width of the top coal rectangle was set to be the same as the distance covered by each longwall advance and the height as the difference between the seam thickness and cut height. In doing so, algorithms were developed to measure the number of particles, size and type entering the detection window.

The ability to report the finer fraction of top coal particle size distribution was limited to the minimum particle radius (Rmin in the caving model was 150 mm for computational purposes). Nevertheless the model provided an ability to determine the maximum size of particles as well as to estimate the percentage of particles detected that would be less than the minimum detected particle size. A typical result at 250 m depth for example indicated a maximum particle size of around 2 m and approximately 73% of caved coal would be less than the about of 450 mm and 84% would be less than 700 mm. It is important to note that model results represent primary breakage of top coal from the overlying seam and do not include secondary breakage effects that may occur in the goaf zone or on the rear AFC.

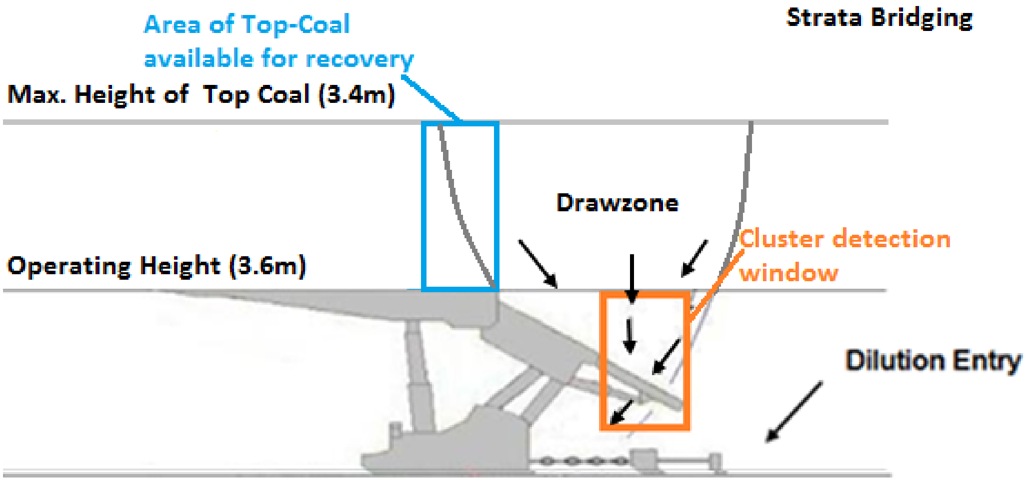

Figure 10 - Model setup for top coal recovery

A typical cumulative recovery profile arising from the analysis is shown in Figure 11. For example, the expected range of top coal recovery at 250 m depth based on a strategy of drawing to dilution is between 65% and 81% depending upon the roof conditions and coal parameters used.

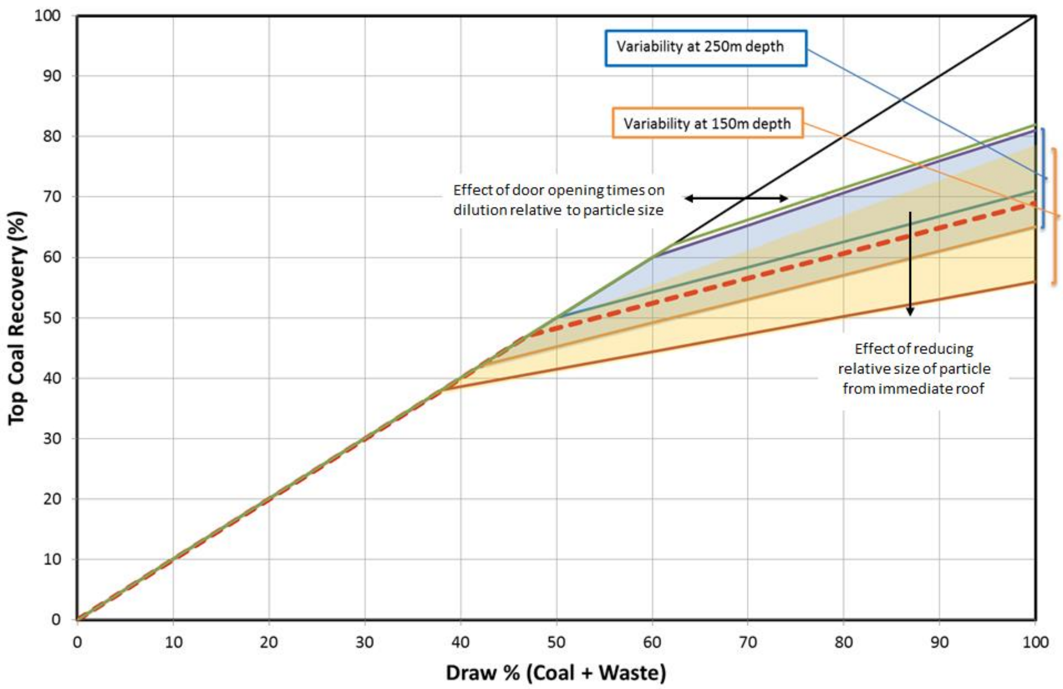

Figure 11 - Top coal recovery profile

The 45 degree line is the upper limit of coal recovery and represents the idealised case where 100% of the material that is drawn from the rear AFC is coal. The effect of increasing door opening times may increase recovery, but potentially also increase dilution. If the goaf material from the immediate roof has a relatively small particle size, then it is more likely to migrate through the caved coal and report to the rear AFC, thereby reducing recovery and increasing dilution.

CONCLUSIONS

The development of the caving models has provided a range of outcomes including several theoretical aspects concerning the behaviour of coal and modelling of the fracture process; the failure mechanics and what influences any given outcome; and from this an ability to understand what is governing the caving process and what factors can affect it. From this perspective the key outcomes obtained from the caving models were as follows:

- The coal properties are of primary importance in caveability and top coal recovery estimates. For a given depth and overburden condition, up to a 16% range in coal recovery may be present depending upon the *in situ* roof conditions and coal properties.
- Increased particle sizes for both the coal and overburden are expected at the shallower depths as is the variability of recovery of top coal. Periodic events are expected to be more frequent at shallower depth;
- Caving conditions are expected to improve with increased cover depth, as the cover loads increase the level and extent of fracturing. Particle sizes are expected to be finer, and the top coal recoveries higher and more consistent than in shallower parts of the mine;
- The modelling process was directed towards "drawing to dilution" as is commonly practiced in LTCC operations. Examination of caving behaviour under this scenario revealed that the well-known periodicity experienced in LTCC operations is a function of this draw strategy. This affects both support loading and coal recovery. A close examination of the models shows how, depending on the fracture pattern, some shears are associated with large recoveries as the support moves forward and others less so, since a significant proportion of the top coal has been recovered on the previous shear;
- In some instances drawing to dilution can result in what has been termed "overdraw", which can result in excessive face loading and cavity development under weak strata conditions or creation of goaf voids under strong strata conditions leading to caving in large blocks;
- There is obviously a trade-off between the percentage draw and coal recovery and the risks associated with overdraw under maximum coal recovery. The balance of these risks is difficult to estimate other than that based on the recovery trend.

ACKNOWLEDGEMENTS

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REFERENCES

Diederichs, M.S. 2003. Rock fracture and collapse under low confinement conditions. *Rock Mech. Rock Engng*. 36 (5), 339–381.

Itasca Consulting Group Inc., 2012. PFC user manual.

Mas Ivars, D., Pierce, M.E., Darcel, C., Reyes-Montes, J., Potyondy, D., Paul Young, R. and Cundall, P. 2011. The synthetic rock mass approach for jointed rock mass modelling, *Int. J. Rock Mech. Min. Sci.*, Vol. 48, pp219-244.

Medhurst, T.P. 1999. Highwall mining: practical estimates of coal seam strength and the design of slender pillars. Trans. Instn Min. Metall. (Sect. A: Min. industry), Vol. 108, A161-71.

Medhurst, T.P. and Brown, E.T., 1998. A study of the mechanical behaviour of coal for pillar design. *Int. J. Rock Mech. Min. Sci.*, Vol. 35, pp1087-1105.