Numerical Study of Stability and Connectivity of Vertical Goaf Drainage Holes

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Abstract

During underground longwall coal extraction, overburden strata deformation may result in vertical goaf drainage holes, which are drilled in advance of mining for tail gate gas management, to fail. The performance of these vertical goaf

drainage holes is controlled by mine design parameters and local geomechanical properties. This paper investigates the use of advanced 3D finite element modelling and 2D discrete element modelling simulation techniques to understand the fundamentals of vertical goaf drainage hole failure mechanism due to strata shear at a currently operating gassy Australian mine site. Finite element modelling is used to investigate the location of high shear in the overburden strata at the vertical goaf gas drainage hole region during longwall mining and the discrete element modelling is used to examine connectivity from the goaf region to the goaf-gas drainage system.

Keywords: Goaf drainage; Goaf hole shearing; Longwall mining; Vertical holes;

Introduction

Underground longwall coal mining creates voids in the excavation region and the immediate roof strata may undergo separation and large scale vertical and horizontal displacements and consequently dynamic shearing, particularly around the strata boundaries. Vertical goaf drainage holes are installed to manage mining induced gas from the goaf region and must establish an unhindered connection from the goaf region to the goaf gas drainage system. Sheared bore holes or bore hole filled with broken debris that is connected to goaf-gas drainage system can block the flow of methane gas from the goaf, providing an un-safe working environment.

Goaf hole stability and failure analysis are topics of interest in resource industries (Daigle and Mills 2007; Davies et al. 2014; Dong et al. 2019; Dusseault et al. 2001; Su, 2017; Tian et al. 2015; Wang et al. 2014), and most studies are considered in a site specific cases (Dong et al. 2019; SCT 2015; Su 2017). The shear localization due to movement of rock strata can be one of the factors to contribute to the failure of vertical goaf gas drainage holes. The development of the shear zone in the ground strata causes the hole failures, typically, at fault locations (Dong et al. 2019). The change in *in-situ* stress field and large horizontal displacement trigger strata movement and this can cause the vertical hole failures in underground coal mining (SCT 2015; Wang et al. 2014). The detailed analysis on connectivity of goaf drainage holes to the goaf region is studied in (Balusu et al., 2004; Balusu and Tanguturi 2016; Balusu et al. 2019).

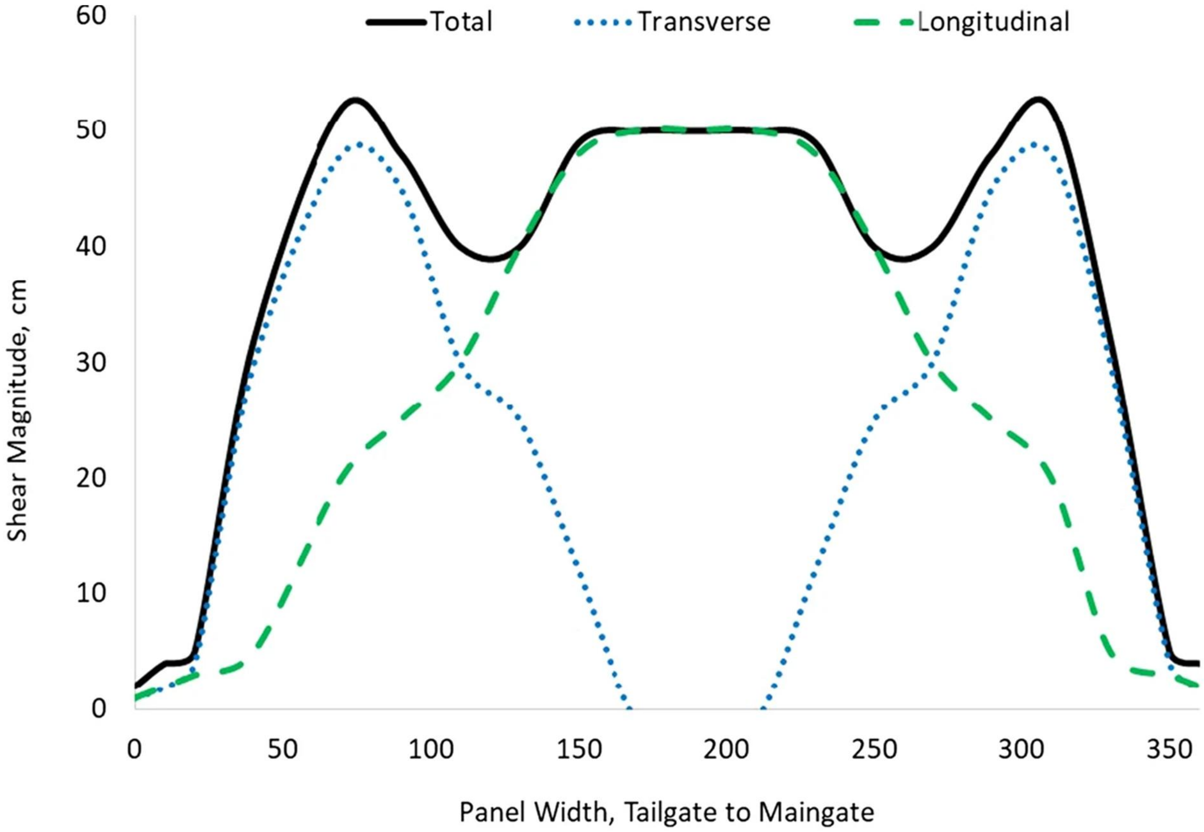


Fig. 1. The conceptual longitudinal, transverse and total shears at a vertical goad gas drainage hole during longwall excavation (unpublished work)

Goaf hole failure mechanism studies has been mostly conducted with 2D models and the effect on and of the longitudinal (mining direction) has been mostly overlooked. As a result, the true mechanism of strata movement and stress change on the longitudinal direction are discounted. The importance of longitudinal shear on vertical goaf gas drainage hole failure has been highlighted by a recent study (Adhikary et al. 2019) using 3D numerical models, Fig. 1. The conceptual transverse and longitudinal shear along with the resultant shear are explained as follows: "*The total shear started to increase as the distance from the void edge increases up to a certain distance then started to decrease, and again started to increase and becomes flattened around the centre of the panel. The longitudinal shear started to increase as the distance from the panel void edge increases and reaches maximum at the centre of the panel. Similarly, transverse shear increases up to a certain distance as the distance from the panel void edge increases then started to decrease towards the centre of the panel. Towards* *the centre of the panel, the longitudinal shear is dominant and towards the edge of the panel void, the transverse shear is dominant (unpublished work).*"

The CSIRO team conducted a numerical modelling study based on finite and discrete element simulation methods to understand the mechanical shear failure of vertical goaf gas drainage holes in an underground longwall mine based in Australia. The effect of displaced strata due to longwall mining on the integrity of vertical goaf drainage holes passing through the overburden strata and the connectivity of these holes to the mine goaf region have been investigated in this study. Mine specific parameters are used to develop a mine-scale numerical model to understand the operational failure of the vertical goaf drainage holes.

Model Development and Calibration

The CSIRO developed finite element code, COSFLOW has been used to study vertical goaf gas drainage hole failure mechanisms with emphasis on the connectivity of the hole with the goaf region. The development of fractures in the goaf region has been studied with the particle flow code (Itasca 2017). The description and feature of COSFLOW can be noted in (Adhikary & Dyskin, 1997; Guo et al. 2007) and its application on investigating various mining parameters with the calibrated model are highlighted in (Khanal et al. 2011, 2016, 2019) Fig. 2.

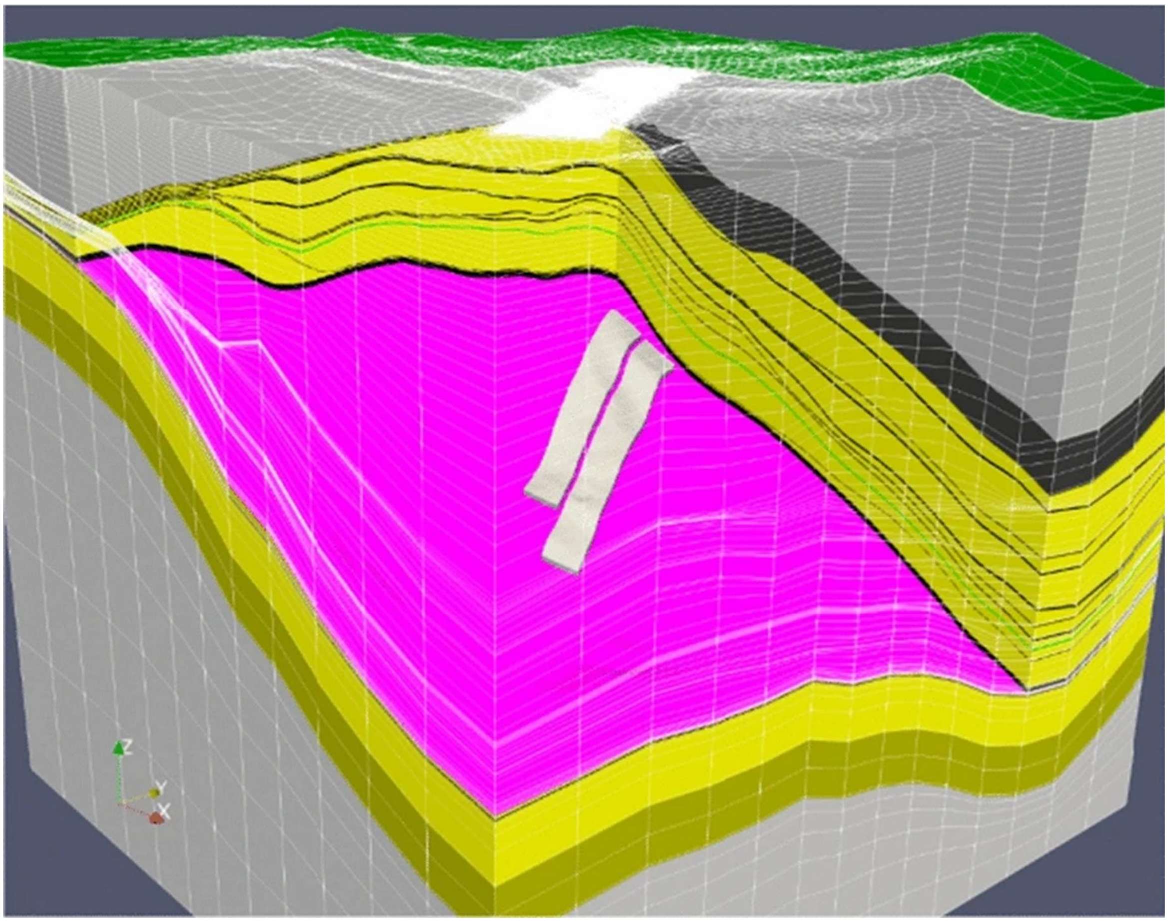
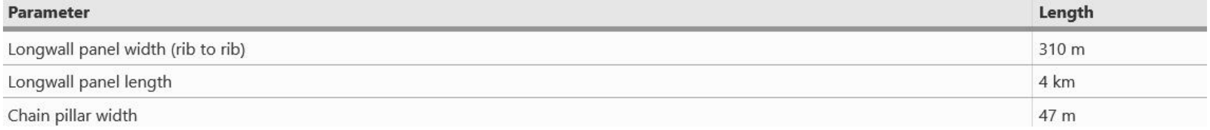


Fig. 2. A view of the 3D COSFLOW model. A part of the model region has been cut out to show two panels. The vertical direction has been exaggerated by a factor of 10. The white lines show the finite-element mesh, which is coarse at the model boundaries and very fine around and above the panels. The model covers approximately 9 km and 6.3 km area with approximately 450 m depth. The panel dimensions are given in Table 1. The mining direction is inwards in the figure

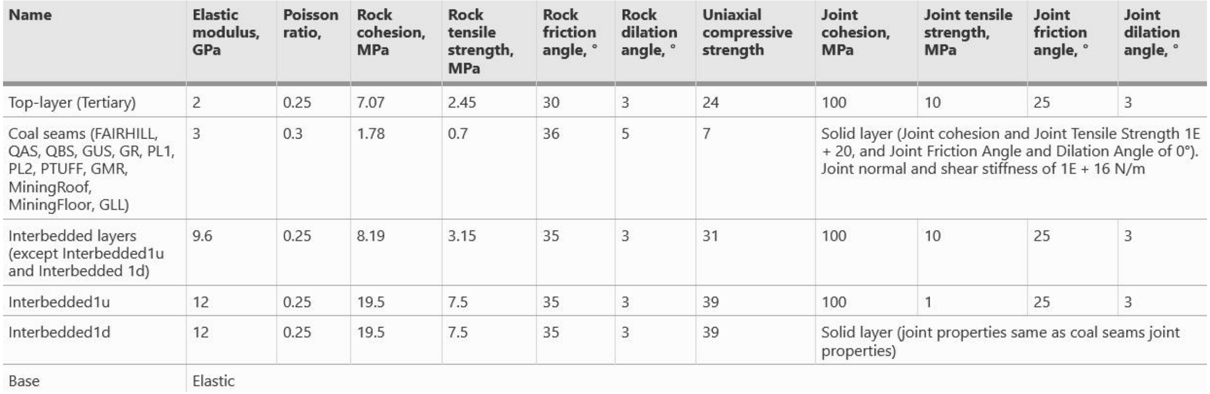
Table 1 shows the longwall parameters used in the model. The first panel is extracted to introduce the pre-mining condition for the panel under investigation. The results discussed in this paper are based on the middle longwall panel. In this location, the *in-situ* horizontal stress direction is 20–25 degree true North with major horizontal stress direction NNE-NE (personal communication). The assigned vertical stress is proportional to the weight of overburden strata by considering the average density of 2500 kg/m^3 and the ratios of major and minor horizontal stress components are respectively assigned as 1.8 and 1 times the vertical stress (SCT 2015). To minimise the boundary effects, excavated panels are placed at minimum of 2 km from model boundaries. The finite-element mesh is built by sweeping a plan mesh vertically. The number of finite elements in the plan mesh for the model is 9108 elements with 97 elements along the vertical direction. Table 2 lists the mechanical properties assigned to each layer in the numerical model. These properties are collated and derived from available reports (for example, (SCT 2016)) and experience gathered from similar studies. The properties are refined until the measured parameter, in this case subsidence, has been matched with the model predicted value. Elastic perfectly plastic Mohr–Coulomb constitutive model has been used for the rock strata and Mohr–Coulomb slip model for the Cosserat joints. Each excavation step is defined by removing 20 m and 10 m along the panel of coal material from the working seam. Explicit faults and joints, apart from the bedding-plane weaknesses described by the Mohr–Coulomb slip model are not considered in the numerical model.

Table 1 Longwall parameter



Parameter	Length
Longwall panel width (rib to rib)	310 m
Longwall panel length	4 km
Chain pillar width	47 m

Table 2 Mechanical properties assigned to the COSFLOW model



Name	Elastic modulus, GPa	Poisson ratio,	Rock cohesion, MPa	Rock tensile strength, MPa	Rock friction angle, °	Rock dilation angle, °	Uniaxial compressive strength	Joint cohesion, MPa	Joint tensile strength, MPa	Joint friction angle, °	Joint dilation angle, °
Top-layer (Tertiary)	2	0.25	7.07	2.45	30	3	24	100	10	25	3
Coal seams (FAIRHILL, QAS, QBS, GUS, GR, PL1, PL2, PTUFF, GMR, MiningRoof, MiningFloor, GLL)	3	0.3	1.78	0.7	36	5	7	Solid layer (Joint cohesion and Joint Tensile Strength 1E + 20, and Joint Friction Angle and Dilation Angle of 0°). Joint normal and shear stiffness of 1E + 16 N/m			
Interbedded layers (except Interbedded1u and Interbedded 1d)	9.6	0.25	8.19	3.15	35	3	31	100	10	25	3
Interbedded1u	12	0.25	19.5	7.5	35	3	39	100	1	25	3
Interbedded1d	12	0.25	19.5	7.5	35	3	39	Solid layer (joint properties same as coal seams joint properties)			
Base	Elastic										

To demonstrate that the material properties and stratigraphy has been chosen appropriately, the results from the numerical model are compared with the measured surface subsidence, which is the only available parameter. Figure 3 shows the mine measured data and model predicted subsidence data. The good agreement confirms that the COSFLOW model is suitably calibrated. As can be seen in the figure, the subsidence measured at about 500 m and 1500 m chainages differs significantly from the numerical models; local variations on geology/geomechanical properties or presence of natural feature (e.g., Isaac river) which is not captured by the model might have caused this mismatch in the values.

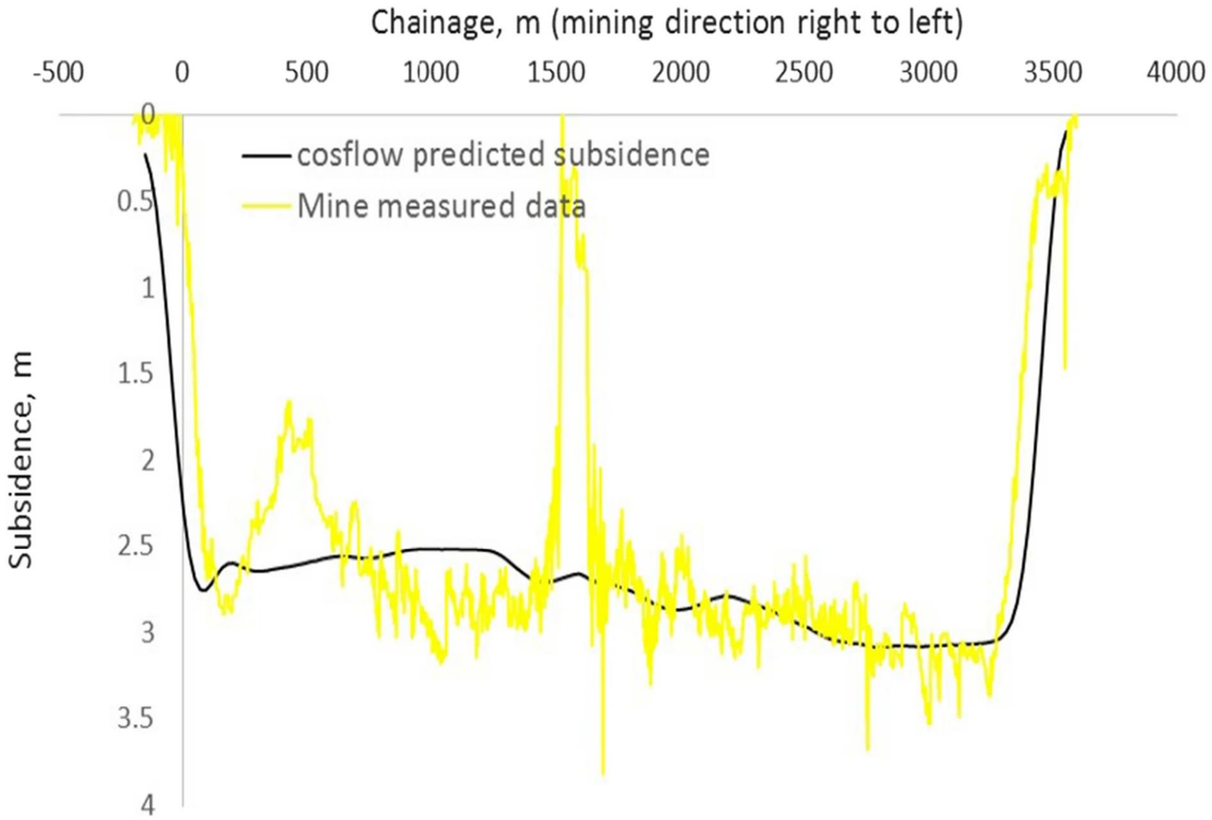


Fig. 3. Mine measured data and COSFLOW predicted subsidence for the first longwall (Adhikary et al. 2019)

Results and Discussion

Absolute Horizontal Displacement

The approximate location of failed vertical goaf gas drainage holes is provided by the mine (personal communication). The resultant horizontal displacement along the vertical goaf gas drainage holes are plotted on these locations from the calibrated COSFLOW model and shown in Fig. 4. The figure shows that maximum horizontal displacements are in excess of 400 mm indicating a possibility of significant vertical hole displacement in this region. However, this measurement of absolute displacement alone could be deceptive as discussed in (Adhikary et al. 2019).

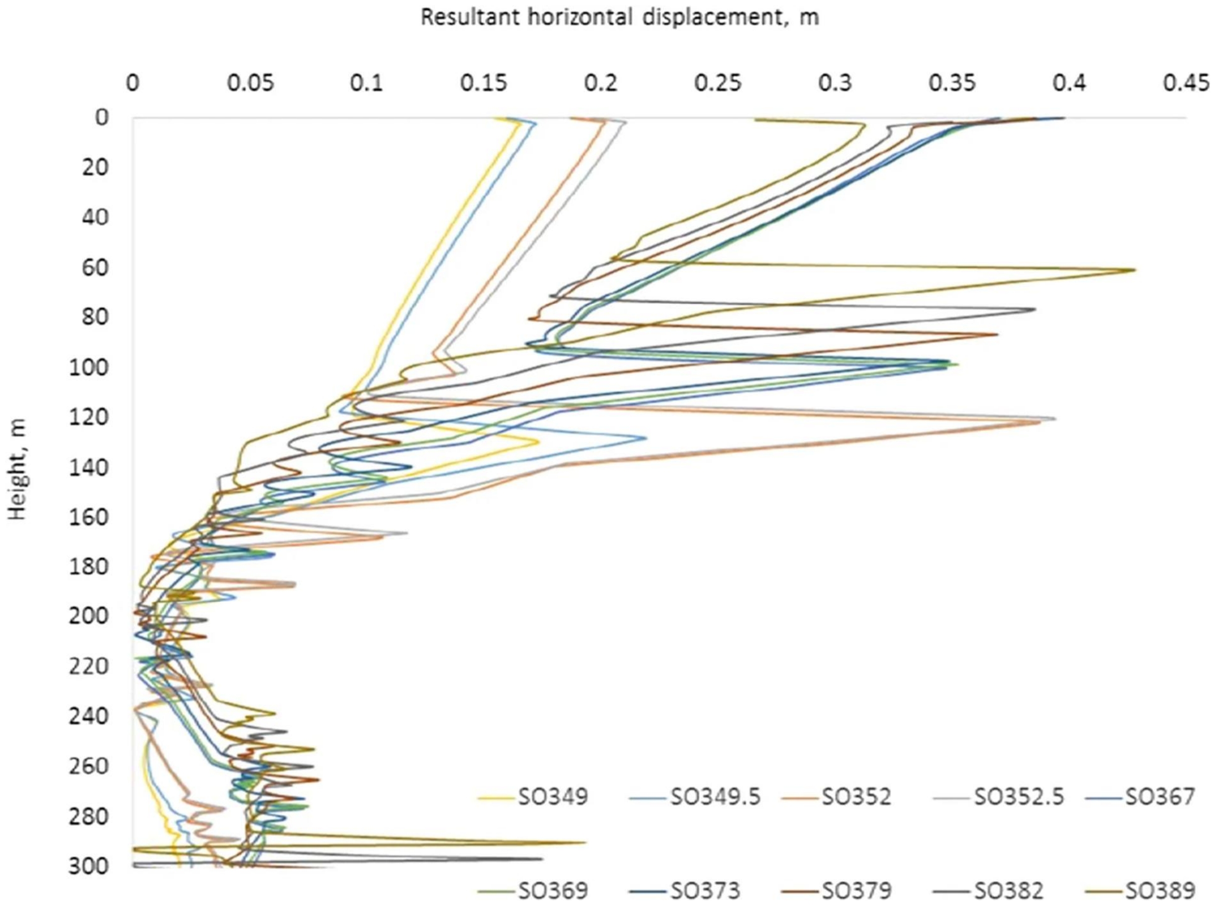


Fig. 4. Resultant horizontal displacements along the failed hole locations

Relative Development (shear)

Figure 5 shows the transverse and longitudinal shear components measured at the middle section of the panel. The figure shows the relatively small shear in the vertical holes at the panel-void edge. This almost no shears at the edge of the panel suggest that there is also no impact on the shear displacements due to the mining of previous panel (pre-mining condition). As the distance from the panel void edge increases, the longitudinal shear started to increase and reaches in excess of 300 mm at the centre of the panel. This value of maximum shear may be different at different locations, as noted in Fig. 4. Similarly, as the distance from the panel void edge increases, the transverse shear increases up to a certain distance then started to decrease towards the centre of the panel. The shear is severe at the multiple positions as seen in the figure. The comparative analysis of the shears at both sides (tailgate and maingate) of the panel edge shows almost similar shear trend and magnitudes. This observation suggests that the vertical hole may undergo possibly near equal shearing if the vertical gas drainage holes are placed at an equal distance from the panel edge on either side.

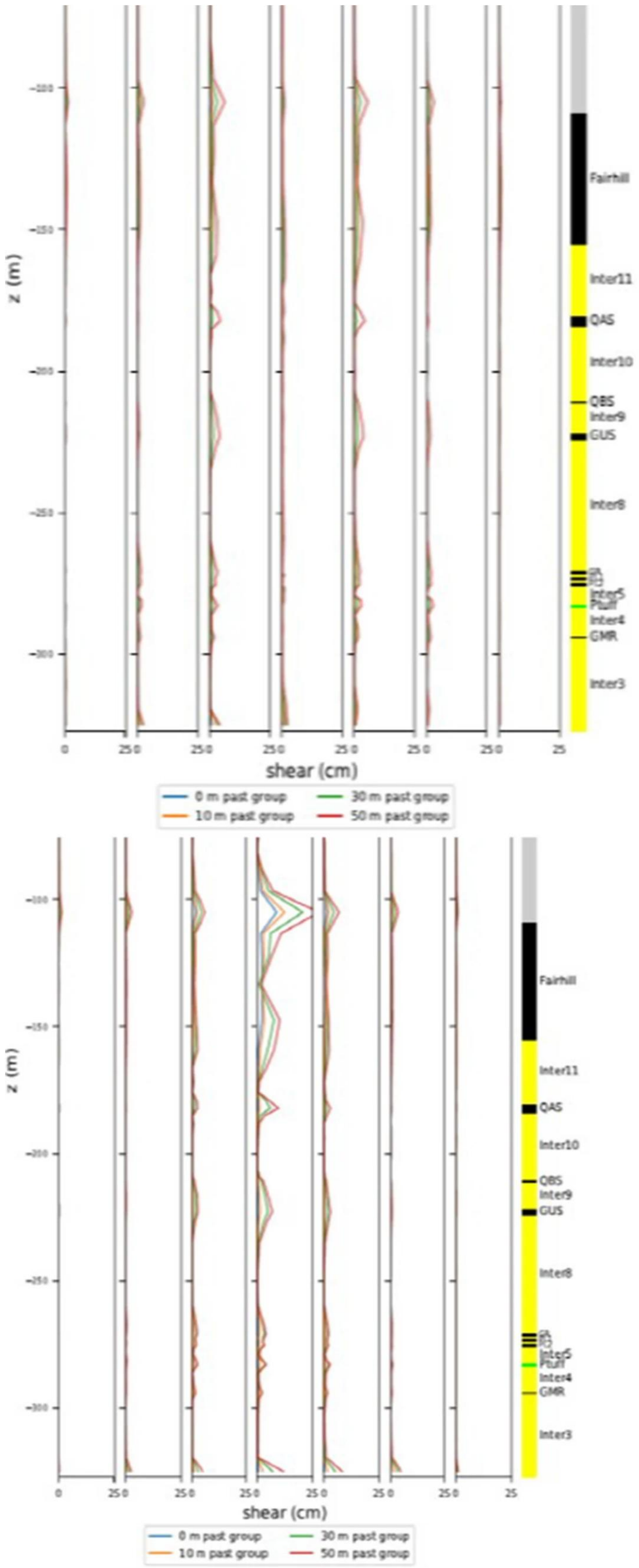


Fig. 5. Transverse (left) and longitudinal (right) shear along the vertical goaf gas drainage holes at the centre length of the panel (left to right shows the shear from tailgate edge, 20 m, 40 m, 155 m, 270 m, 290 m, 310 m from the tail gate edge respectively)

Bonded Particle Model (BPM)

Figure 5 shows the vertical goaf gas drainage hole shearing mechanism from the surface up to the excavation seam. This figure does not consider the connectivity from goaf region to the vertical goaf gas drainage hole. The connectivity of the goaf region to the hole is discussed below with the bonded particle model approach.

It is well known that the geotechnical condition of the immediate roof broadly dictates the mining induced fracturing characteristics of the immediate roof. The fracturing characteristics of the strata between the mining seam and 40 m into the roof strata is investigated using a Bonded Particle Model (BPM) approach with PFC (Itasca 2017). The P-tuff unit, also called as marker unit, is located 40 m above the mining seam in the roof. The half symmetry model has been developed for this fracturing study. To isolate roof competency from lithological impacts of strata sequence and strength, a simplified model consisting of five units with the thickness and strength attributes shown in Table 3 is created. In the simulations only the strata conditions in the 40 m, between the GM seam and P tuff, are varied. Above the P tuff, a uniform distribution of fractures in a non-continuous ‘brick’ pattern is prescribed with 5 m spacing of sub-horizontal bedding and 20 m spacing of non-transecting sub-vertical joints. The BPM representing the mining seam, base and overburden is developed as shown in Fig. 6. The normal and shear stiffness of 10 and 20 GPa, respectively, cohesion 0.5 MPa and tensile strength 0.2 MPa with friction angle of 30° are assigned to the discrete fracture network (DFN). The DFN are assigned to the layers except Base and P tuff. This DFN and its associated properties is independent of the lithology and UCS values tabulated in Table 3. This DFN represents fractures and other discontinuities present in the rock mass. The overprinting of the DFN may reduce the modelled strength in addition to the scale factor of 0.58 already specified.

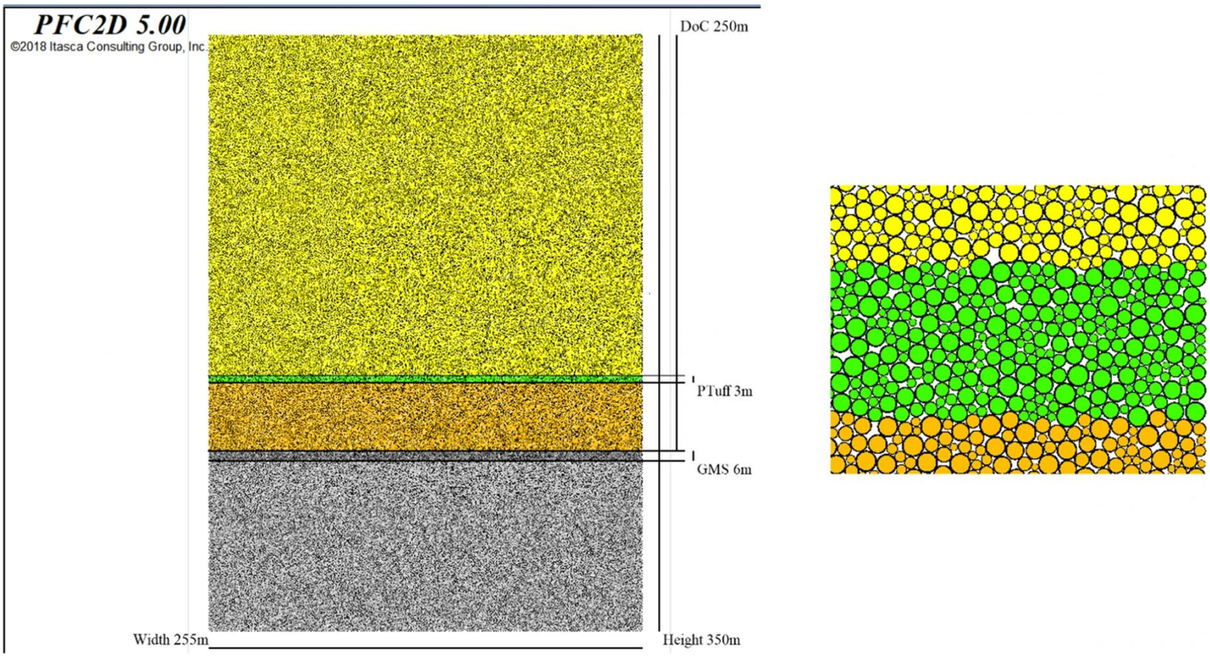
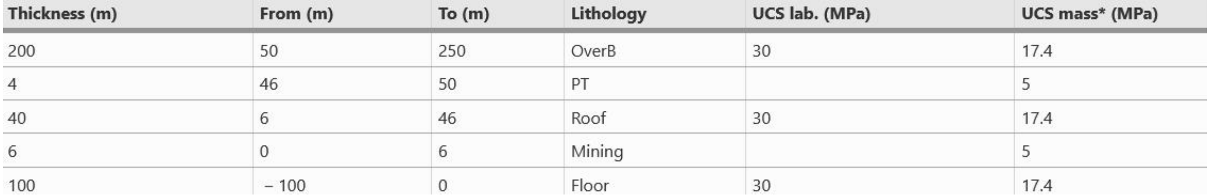


Fig. 6. BPM of idealised second longwall in cross-section, full model (left) and detail (right). Mining seam is GMS and seam cover depth 250 m, total numerical model height 350 m

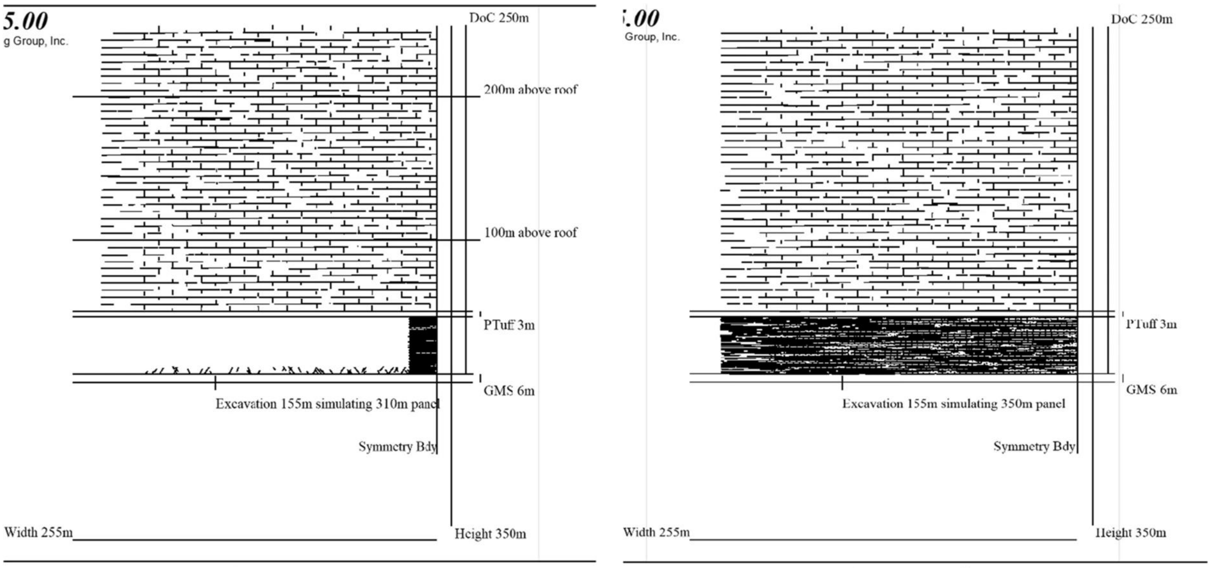
Table 3 Roof strata strength attributes



Thickness (m)	From (m)	To (m)	Lithology	UCS lab. (MPa)	UCS mass* (MPa)
200	50	250	OverB	30	17.4
4	46	50	PT		5
40	6	46	Roof	30	17.4
6	0	6	Mining		5
100	− 100	0	Floor	30	17.4

*a scale factor of 0.58 is applied to the rock

Model variations are undertaken by modifying the density of DFN in the region between GM and P tuff units (a 40 m thick section). The lowest and highest number of DFNs are represented in Fig. 7. Other variations (weak, moderate and strong) are in between these limits. For the very weak variation, the bedding spacing is 1 m and vertical joint spacing is 4 m. The very strong variation has no bedding and vertical joint spacings.



Very strong

Very weak

Fig. 7. Example of Strongest (left) and weakest (right) DFN

Results and Discussion

Figure 8 shows the predicted caving patterns connecting goaf gas region with the fractures developed in the strata. From the figures, two types of fractures can be noted. The first type of fractures is associated with the greater shear and normal displacements and hence, have greater fracture apertures and allow unhindered gas flow. The second type of fractures is associated with the non-continuous fractures, hence have hindered gas flow compared to the first type of fractures. In these figures, it can be noted that the fractures extend upwards with the angle of break.

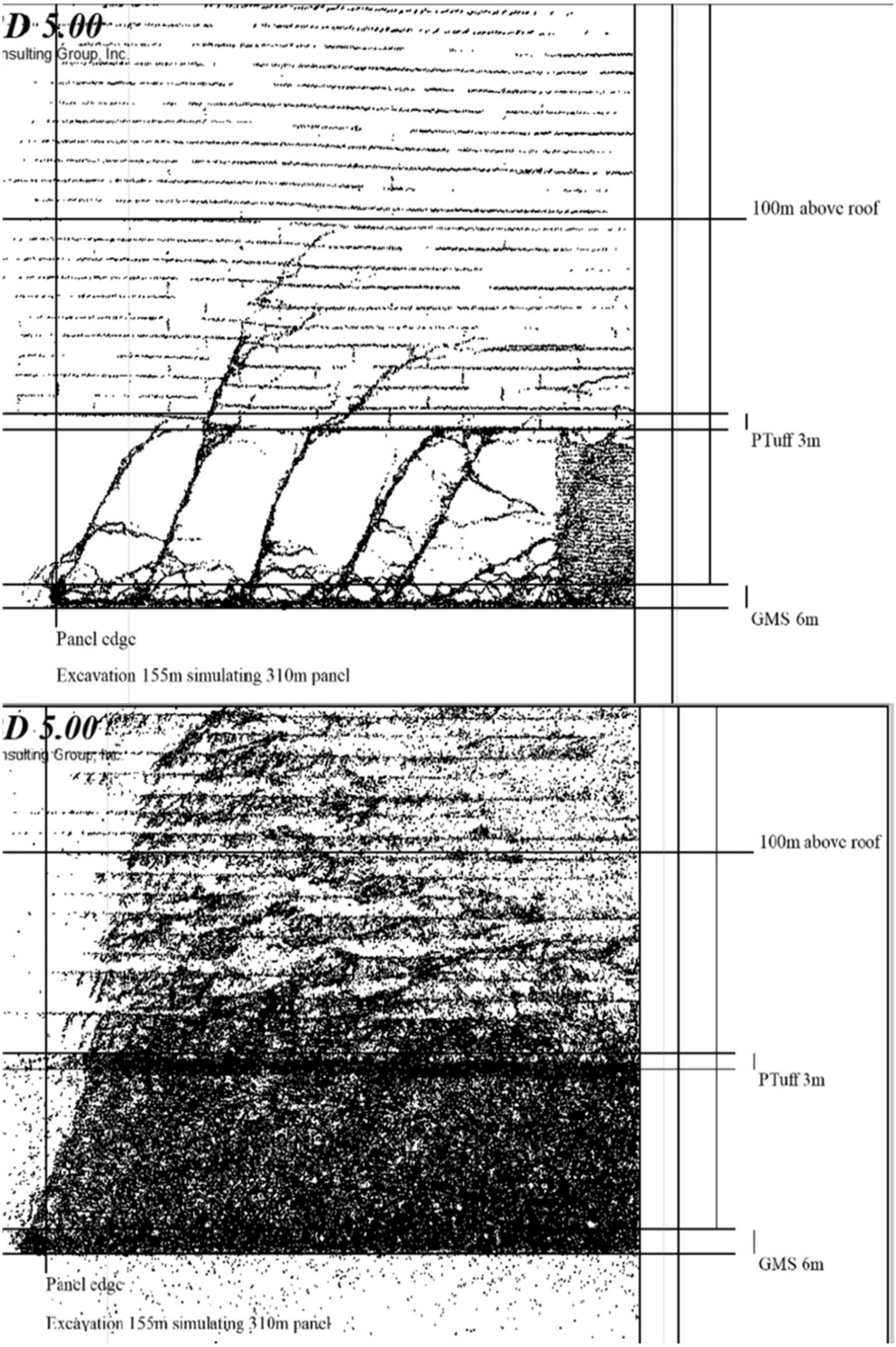
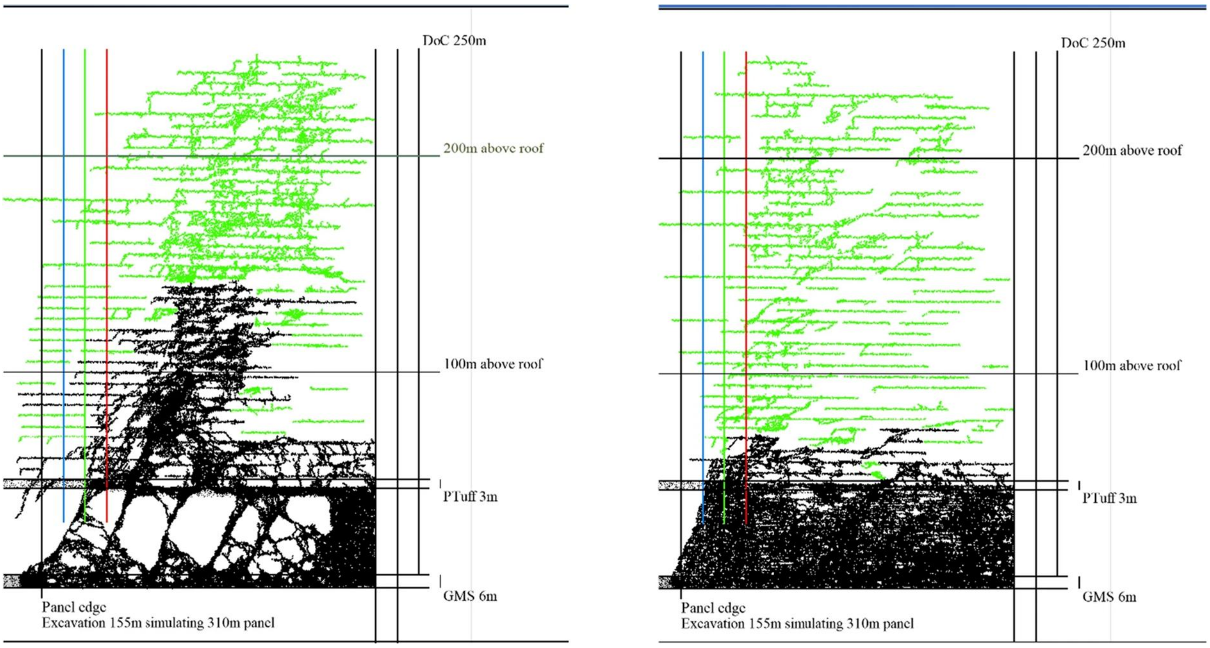


Fig. 8. Fracture patterns associated with very strong (left) and very weak (right) cases

The weak and very weak variations cave in a uniform, consistent manner and bulk to support the overburden. For the weaker variations, bridging within the overburden occurs about 10 m above the P tuff and this height approximately defines the height of the fracture zone. In contrast, the strong and very strong variations do not bulk to the same extent, with large blocks of rock falling into the goaf. For the stronger variations, bridging within the overburden occurs approximately 20—60 m above the P tuff. Bulking of the rockmass is directly related to surface subsidence in these simulations; when bulking is reduced due to the stronger rock, the overburden has greater opportunity to sag, resulting in increased subsidence. A connective fracture analysis of the strength variations is visualised in Fig. 9. In these figures, fractures connected to workings are visualised in black and those not connected to the workings are coloured green. It is evident that caving of the very strong variation is cyclic resulting in large, relatively intact, blocks in the goaf and a fracture zone of high permeability connected fractures to approximately 140 m above the roof. By comparison caving in the very weak variation is uniform and regular with a well-connected, high permeability fracture zone extending to approximately 70 m above the seam roof.



Very strong

Very weak

Fig. 9. Connective fractures (black) and fractures not connected with the goaf (green). Blue, green and red lines represent vertical goaf gas drainage holes 10, 20 and m, respectively, from the panel-void edge

Figure 10 presents a sketch of possible fractures on plan view in the strata between the GM Seam and P tuff. The density of mining induced fractures will be high close to the GM Seam and gradually decrease with the distance above the mining seam. In Fig. 10 a number of vertical goaf gas drainage holes are drilled at different distances from the tailgate; vertical goaf gas drainage holes that seem to intersect the fractures are coloured red and those not intersecting the fractures are marked blue. The chances of intersecting or not-intersecting the fractures seem to be random (which reflects the randomness observed at the mine site); however, the chances of intersecting the fractures would be higher for the holes ending deeper. For the case of very strong roof, it can be seen from the geomechanics point of view that the holes ending deeper (less than 6 m above the mining height) are most likely to intersect the fractures connected to the goaf as this strata zone would be heavily fractured.

Thus, we recommend that proper mine site caving characteristics needs to be fully understood and considered when deciding on goaf-hole-depth (i.e. the distance between the goaf hole end point and the mining roof) to be able to efficiently drain and effectively manage the goaf gas.

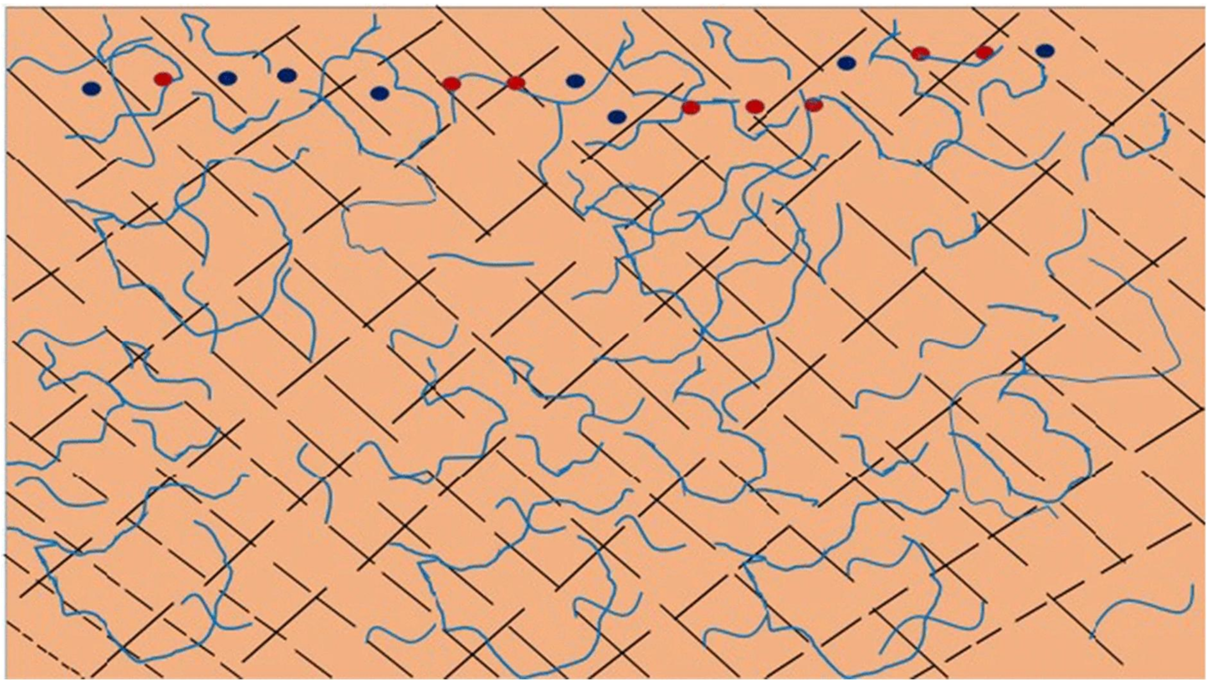


Fig. 10. A plan view-sketch of possible fractures in the strata between GM Seam and P tuff; black lines denote pre-existing discrete fracture network and blue lines denote mining induced fractures. Dots indicate vertical goaf gas drainage hole positions

Conclusions

The paper presented a case study of goaf hole failure at a longwall coal mine in Australia. The paper demonstrated the use of advanced numerical methods to understand the goaf hole shearing mechanism at various strata above the mining seam and fracturing profile at the immediate roof strata. Various possible strata strength combinations were investigated to understand the impact of the goaf fracture network development on goaf hole stability.

For the considered case, there is almost a negligible effect of mining of previous panel on future longwall panel. The shear displacements close to the panel-void edges are relatively small compared to the displacements at some distance away from the panel-void edge. The difference in shear displacements between the tailgate side and the maingate side is small. Based on the bonded particle method using DFN, the fracturing of the strata varies significantly between the models for various strength of the strata. For the stronger variations, the fracture forms long, discrete, discontinuities extending, typically, at the angle of break. The chances of intersecting or not-intersecting the fractures seem to be random; however, the chances of intersecting the fractures would be higher for vertical goaf gas drainage holes ending closer to the mining seam.

Based on the current modelling work, it may be suggested that, by considering intersecting fractures (above the goaf) and minimising mining induced shearing goaf holes located as close to the panel void edge as possible could provide relatively better stability of the goaf holes.

The next step of the research is to investigate the design of goaf holes including the liner materials used in the holes. Also, a detailed localized model could provide a further insight of localized behaviour of the goaf holes during longwall advancement.

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