SHIRMS 2008 – Y. Potvin, J. Carter, A. Dyskin, R. Jeffrey (eds)

doi:10.36487/ACG_repo/808_137

Analysis of River Bed Cracking Above Longwall Extraction Panels in the Southern Coalfield of New South Wales, Australia

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Abstract

Mining-induced subsidence has adversely impacted the near surface hydrologic cycle and natural surface topography above longwall extraction panels in the Southern Coalfield of New South Wales (NSW), Australia. The distinct element method programme PFC enables simulation of the mechanical behaviour of rock, which is governed by the formation, growth and eventual interaction of microcracks to form explicit fractures. The PFC analysis accurately simulates the monitored surface subsidence, together with the evolution, location and orientation of the explicit fractures that were observed after longwall development. Analysis of the explicit fracturing provides a greater understanding of the altered near-surface hydrologic cycle and enables effective rehabilitation of the damaged river beds.

1 Introduction

There is concern that mining-induced subsidence adversely impacts the integrity of the natural surface topography and the hydrologic cycle above longwall extraction panels in the Southern Coalfield of NSW, Australia. Traditionally, mining-induced subsidence has been analysed via empirical methods and modelling techniques that treat the overburden rock mass as an equivalent continuum material. These methods have been successful in predicting the amount of subsidence expected, but neither method has the ability to investigate the development of the explicit fracture networks that have been observed to develop along escarpments and river valleys above longwall extraction panels. The *Particle Flow Code* (Itasca, 2008), or PFC, has been developed to simulate the mechanical behaviour of rock, which is governed by the formation, growth and eventual coalescence of microcracks to form explicit fractures. The PFC modelling approach is ideally suited to the analysis of overburden fracturing above longwall mining operations. The evolution, location, orientation, persistence and displacement of fractures within the overburden can be investigated for any particular stratigraphy and surface topography.

2 Background

The Southern Coalfield, located approximately 80 km south of Sydney, is one of the five major coalfields within the Sydney-Gunnedah Basin. The Bulli coal seam is immediately overlain by a sequence known as the Narrabeen Group, which is a succession of major sandstone and shale units (Figure 1(a)). The 150 m thick Hawkesbury Sandstone Formation, which overlies the Narrabeen Group, dominates the landforms in the Southern Coalfield. Cross bedding is a distinctive feature of the Hawkesbury Sandstone as described in detail by Pells (2002).

Valley erosion is a conspicuous landform in the Southern Coalfield. The thick layer of Hawkesbury Sandstone is incised by steep valleys and gorges formed by the drainage systems of major rivers. These surface features can be up to 70 m in depth and 60 to 100 m in width. Figure 1(b) illustrates a typical steep sided river valley in the Southern Coalfield. Significant coal reserves within the Southern Coalfield are overlain by river valleys and gorges that form the catchment area for Sydney's fresh water supply.

Holla and Barclay (2000) state that cracking of deeply incised river beds due to mining is not uncommon. Loss of water flow in such cases may be temporary or permanent. Water flow loss may be superficial in that the flow may become sub-surface and therefore is not a loss to the total water flow system, however, there is concern that alteration of the hydrologic cycle has an adverse effect on flora and fauna within the river system.

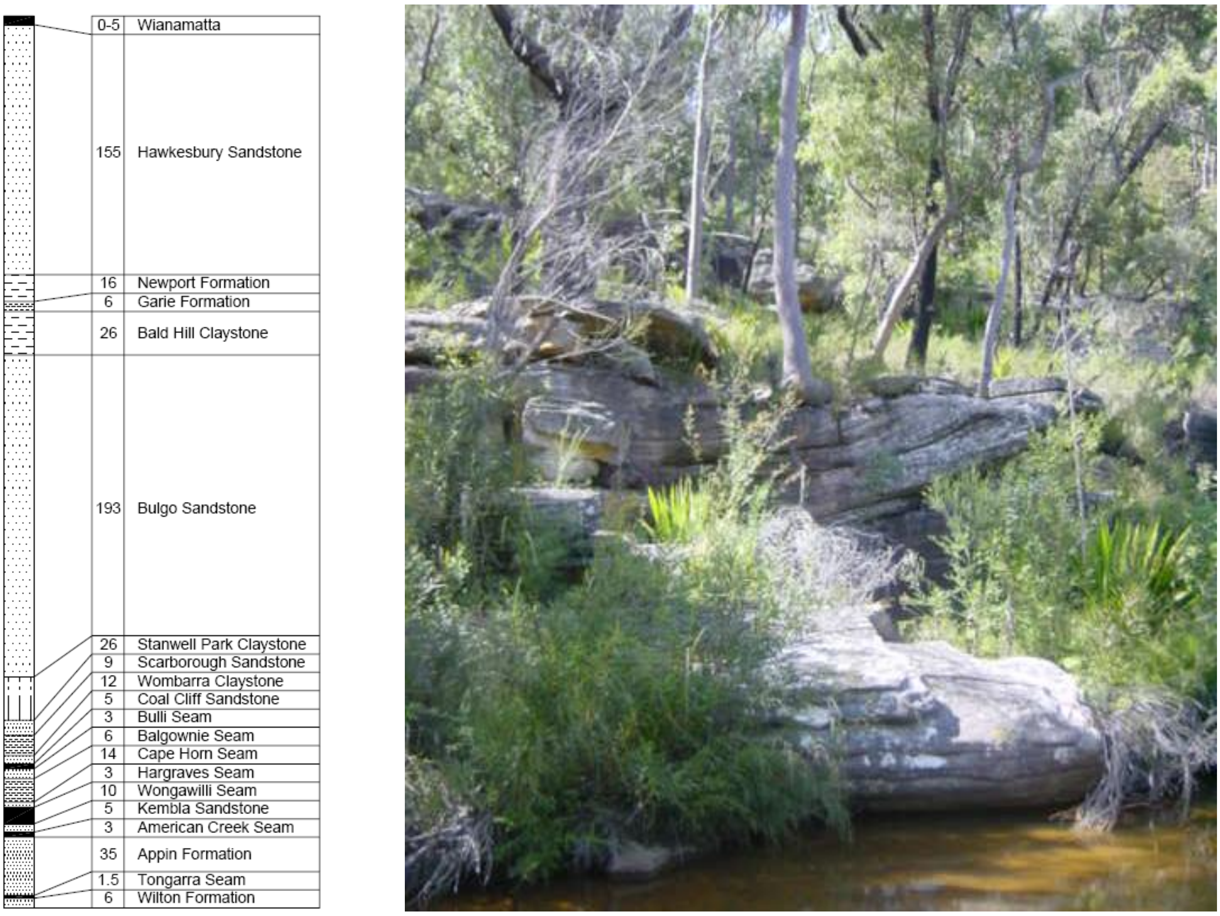

Figure 1 (a) Typical stratigraphic column in the Southern Coalfield (after ACARP, 2001); (b) typical steep sided river valley formed within the Hawkesbury Sandstone

The effect of topographical features on mining-induced subsidence has been widely recognised by many researchers (Holla 1997, Hebblewhite et al., 2000). A number of cases of strain concentrations and humps in subsidence profiles have been reported while mining under gullies, creeks and gorges in the Southern Coalfield. Holla (1997) reasons that mining under a valley induces a concentration of horizontal stress at the base of the valley. The compressed rock mass in the valley floor, being unconfined in the vertical direction, is subject to shear failure (cracking), causing low-angle fractures in the rock mass. High horizontal stresses have been measured throughout the Southern Coalfield, supporting this mechanism. A schematic of the stress-induced mechanism postulated by Holla (1997) is illustrated in Figure 2.

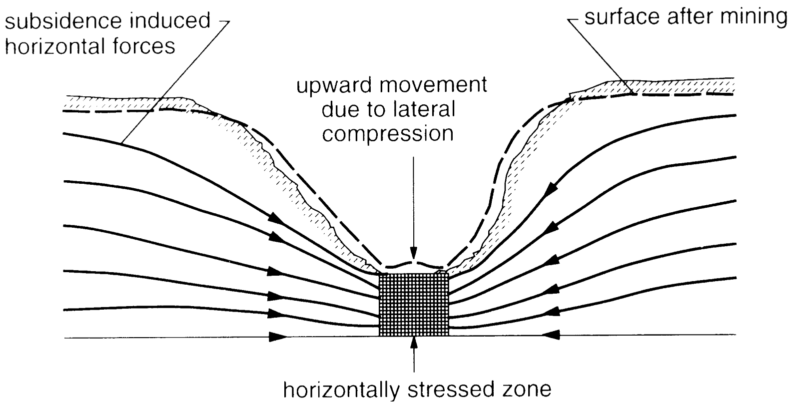

Figure 2 Conceptual model of the upsidence mechanism (after Holla, 1997)

The actual upward movement, also called upsidence, can be attributed to dilation of the rock mass upon shearing. Figure 3 illustrates examples of low-angle shear structures observed in undermined river beds within the Southern Coalfield.

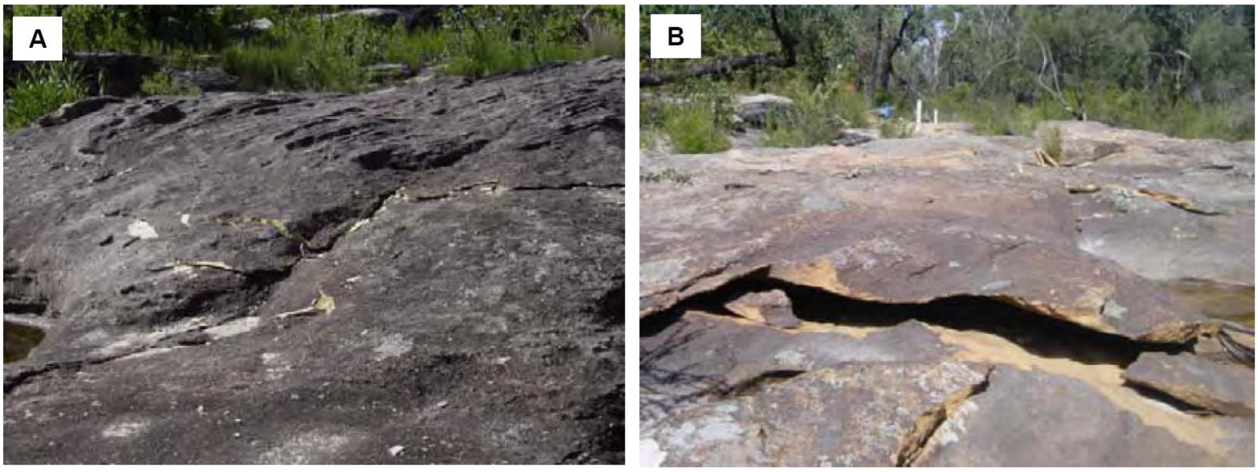

Figure 3 Low-angle shear structures in river beds within the Southern Coalfield

Together with upsidence in the valley floor, tension cracks behind the escarpment face are a common subsidence feature in the Southern Coalfield. This mechanism is likely the result of separation of pre-existing vertical joints within the Hawkesbury Sandstone, as opposed to tensile failure of the intact rock.

Traditionally, mining-induced subsidence has been analysed via empirical methods and modelling techniques that treat the overburden rock mass as an equivalent continuum material. Figure 4 illustrates the results of a two-dimensional analysis with the distinct element code UDEC (Itasca, 2006a) to investigate the effect of mining beneath the Cataract River at the Tower Colliery (ACARP, 2001 and 2002). As observed, only limited shear failure is predicted at the base of the gorge, while yielding near the surface is smeared over a large area. Such analysis methods have been successful in predicting the magnitude of subsidence expected, however, the methods do not have the ability to investigate the development of the explicit fracture networks that have been observed to form on the surface above longwall operations.

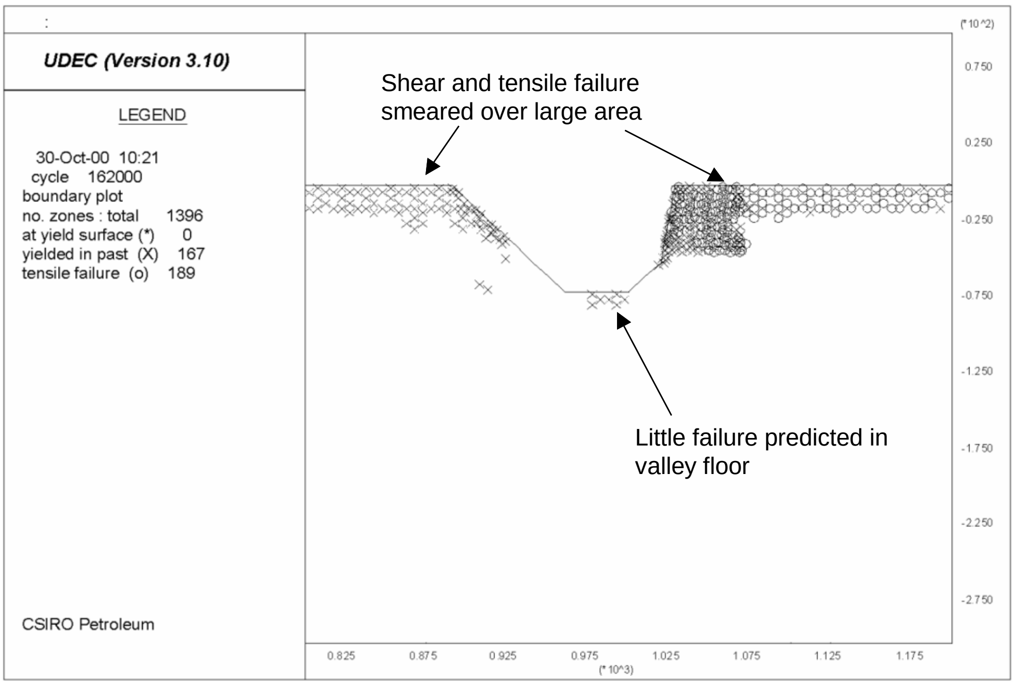

Figure 4 UDEC simulation of longwall mining beneath the Cataract River at Tower Colliery (after ACARP, 2002)

3 The PFC modelling approach

PFC models the movement and interaction of circular (2D) or spherical (3D) particles by the distinct element method (DEM). The original application of this method was as a tool to perform research into the behaviour of granular material, such as the flow of caved rock in underground block cave mines. Particles can be bonded together at their contacts to simulate cement, as illustrated in Figure 5.

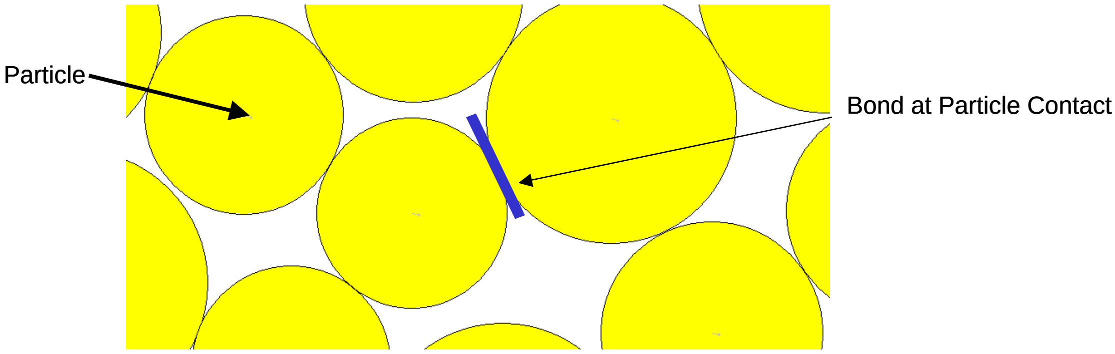

Figure 5 PFC particle and bond geometry

3.1 The PFC bonded model for rock

A thorough description of PFC and its application to modelling rock is found in Potyondy and Cundall (2004). The PFC model for rock mimics the mechanical behaviour of a collection of grains joined by cement. We consider each grain as a PFC particle and each cement entity as a parallel bond. The total force and moment acting at each cemented contact consist of a force arising from particle-particle overlap, and a force and moment carried by the parallel bond. These quantities contribute to the resultant force and moment acting on the two contacting particles. The grain-to-grain and cement behaviours are modelled using two different force-displacement laws. If a parallel bond is not present at a contact, then only the grain-based portion of the force-displacement behaviour occurs. The mechanical behaviour of the PFC model is summarised in Figure 6.

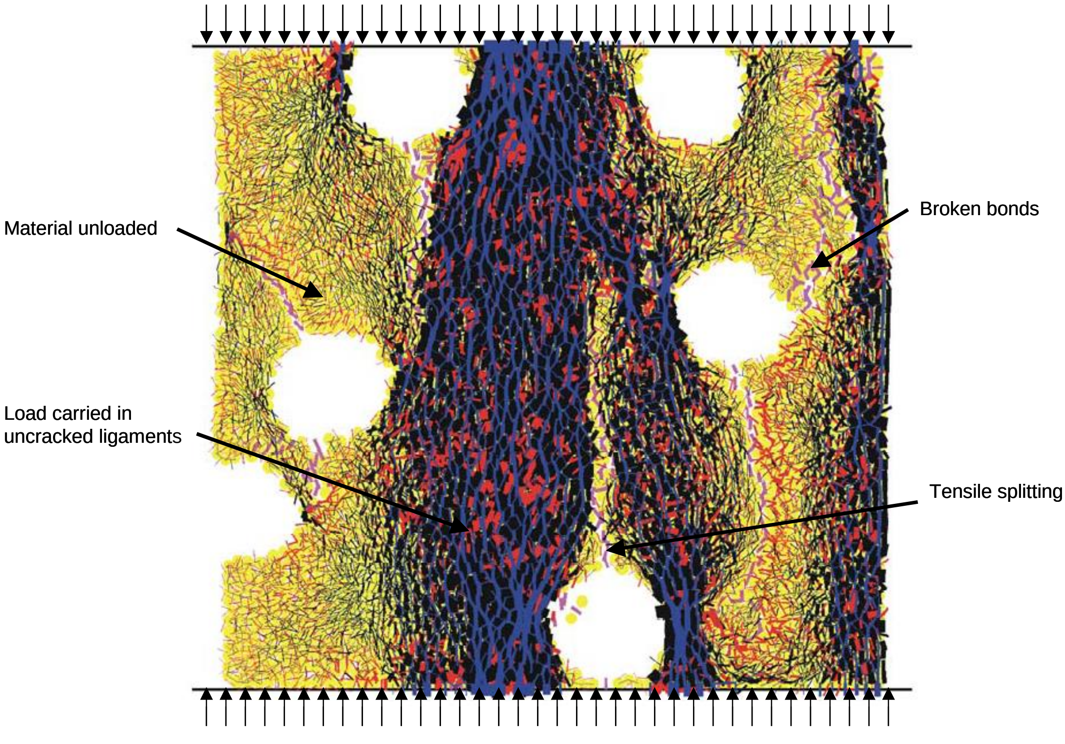

Figure 6 Force distributions and broken bonds in a cemented granular material with six initial holes in the post-peak portion of an unconfined compression test (Potyondy and Cundall, 2004)

4 PFC back-analysis of river bed cracking above panel 8 at the Tower Colliery

The PFC modelling approach is ideally suited to the analysis of overburden fracturing above longwall mining operations. The evolution, location, orientation, persistence and displacement of fractures within the overburden can be investigated for any particular stratigraphy and surface topography.

In order to build confidence in the PFC modelling approach applied to the analysis of river bed cracking in the Southern Coalfield, a back-analysis exercise has been conducted on a case of longwall mining beneath a river valley that has been studied comprehensively at Tower Colliery (Holla and Barclay, 2000; ACARP, 2002). The Cataract River is part of the Hawkesbury-Nepean River System and flows along the base of the Cataract Gorge. The river course has been determined largely by joint and/or fault patterns in the Hawkesbury Sandstone.

5 Observation and monitoring of river bed cracking above panel 8 at the Tower Colliery

Longwall mining at a depth of approximately 500 m beneath the Cataract River commenced in March 1988. During 1993, a comprehensive subsidence monitoring programme was established that consisted of monitoring movements along a plateau and across the gorge floor. Subsidence monitoring above panel 8 indicated 100 mm of upward movement of the floor and 210 mm downward movement of the plateau after mining of panel 8. After mining of panel 10, 150 mm of upward movement of the floor and 180 mm downward movement of the plateau were monitored, as illustrated in Figure 7.

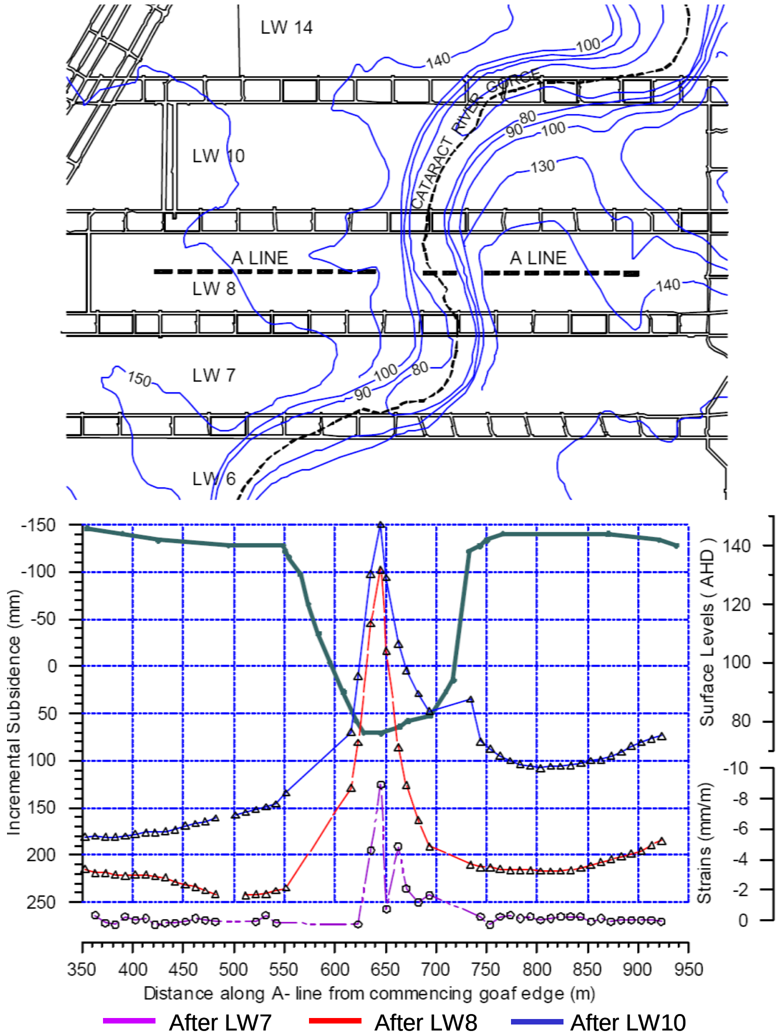

Figure 7 Subsidence monitoring above panel 8 at the Tower Colliery (after ACARP, 2002)

Mapping of the river floor above longwalls 6 to 10 identified numerous low-angle fractures with horizontal displacements in the range of 10–160 mm and vertical displacements of 10–100 mm, as illustrated in Figure 8(a). The direction of movement was toward the centre of the gorge, which implied that the cracking was due to increased horizontal pressure at the base of the gorge (Holla and Barclay, 2000).

Approximately 3.5 km of cliff lines, adjacent to the Cataract River, have been undermined by longwalls 6 to 15 at Tower Colliery. Whilst the level of damage to the cliff lines was not extensive, three localised rock falls were noted over longwalls 10 and 14, following undermining of the cliffs. ACARP (2002) reports that the rockfalls were generally limited to overhangs formed above weaker strata, as illustrated in Figure 8(b). Tension cracks behind the escarpment face were also observed, as illustrated in Figure 8(c).

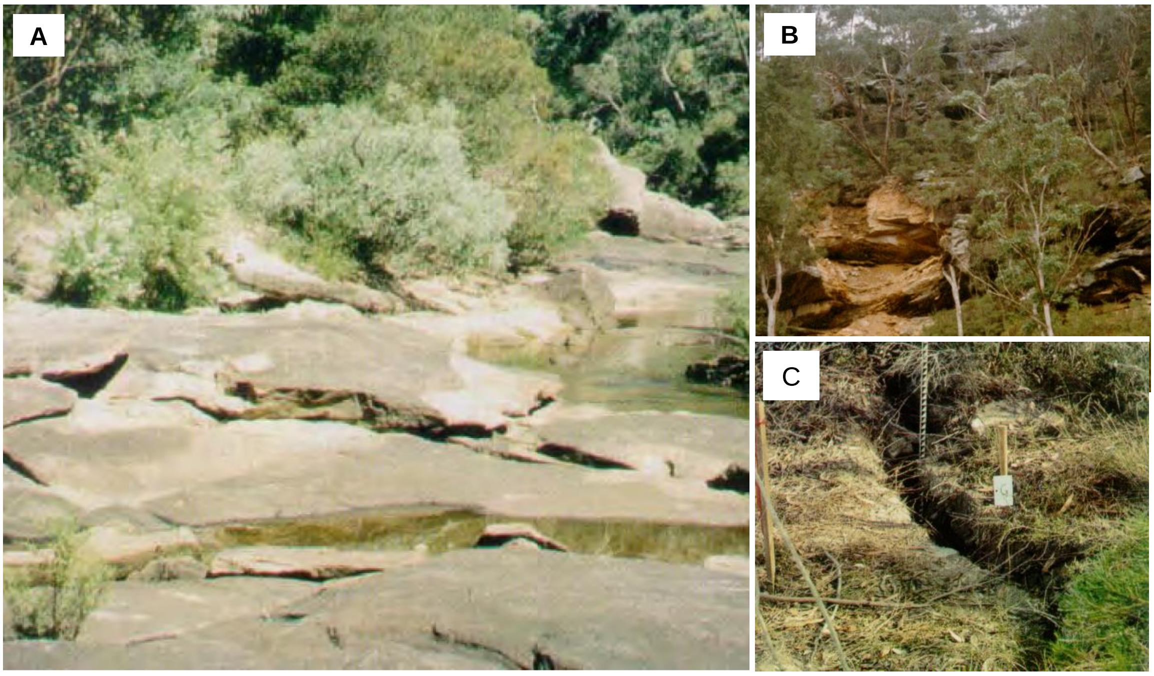

Figure 8 (a) Low-angle fractures observed above panel 8 at the Tower Colliery (after Holla and Barclay, 2000); (b) localised rockfall above Longwall 15 (ACARP, 2002); (c) tension crack behind escarpment (after Holla and Barclay, 2000)

In 1994, it was reported that there was no flow in the river and that most large rock pools had dried out completely. As there was no inflow into the mine workings, it was assessed that surface cracks were not connected to the mine workings. It was estimated that surface cracking might extend approximately 10–20 m below the surface (Everett et al., 1997).

5.1 Determination of PFC material properties (microproperties)

The PFC particle-based microproperties are obtained by testing PFC specimens in a simulated biaxial cell and in a direct-tension device, and comparing the macroscopic response of the simulated tests to the known mechanical behaviour of a rock material. The polyaxial cell loads a parallelepiped specimen between pairs of opposing walls. The walls are made frictionless and assigned a stiffness equal to that of the PFC particles in order to eliminate frictional effects. The top and bottom walls act as loading platens, and the velocities of the lateral walls are controlled to maintain a constant confining stress. Unconfined compression tests are performed by removing the lateral walls. A direct-tension device controls the velocities of a thin layer of boundary particles on the top and bottom specimen faces to apply uniaxial strain.

For the purposes of initial testing and verification of the PFC modelling approach, the Hawkesbury Sandstone overlying the Tower Colliery has been simplified into five main rock classes, based upon diamond drilling and laboratory testing conducted upon Hawkesbury Sandstone at a nearby location within the Southern Coalfield, and previous numerical analysis of mining-induced subsidence at Tower Colliery conducted by ACARP (2001, 2002). Pells (2002) suggests that in practice a field-scale strength of about

20 MPa is adopted for fresh Hawkesbury Sandstone, while a Young's Modulus of between 2.5 to 8 GPa is typically used, indicating a low to average modulus ratio.

A calibration exercise was conducted to determine the appropriate PFC microproperties required to simulate the strength and deformation behaviour of the individual rock classes. Figure 9 illustrates the response of UCS, direct tensile and triaxial compression tests on a PFC material that simulates weak (σ_c = 8.0 MPa) intact Hawkesbury Sandtone material. As observed, the post-peak softening response of the simulated tests compare favourably with the typical stress–strain response of Hawkesbury Sandstone reported by Pells (1977).

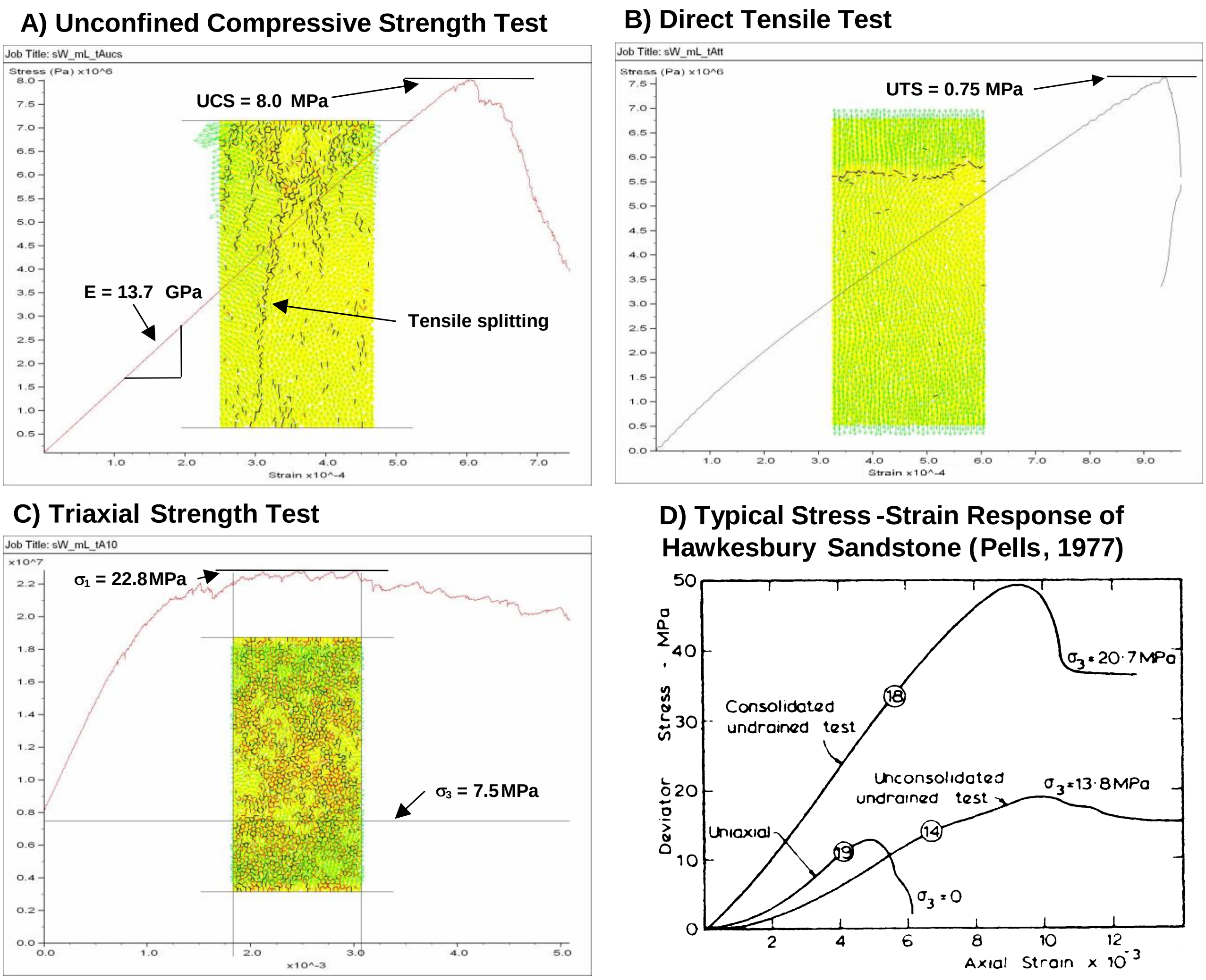

Figure 9 Results of PFC calibration of weak intact Hawkesbury Sandstone

Table 1 presents the particle-based PFC microproperties used to simulate macroscopic mechanical response of the five PFC materials selected to simulate the different layers within the Hawkesbury Sandstone. Table 2 presents the resulting macroscopic response of each calibrated PFC material.

Table 1 PFC microproperties used throughout the modelling exercise

PFC Material	1	2	3	4	5
Min. particle radius (m)	0.013	0.013	0.013	0.013	0.013
Ball/bond modulus (GPa)	7.2	7.2	6.0	7.2	6.3
Ball/bond stiffness ratio	2.5	2.5	2.5	2.5	2.5
Ball friction coefficient	0.5	0.5	0.5	0.5	0.5
Bond normal strength, mean (MPa)	5.2	2.0	0.6	7.8	3.5
Bond shear strength, mean (MPa)	1.3	0.5	0.1	1.9	0.9
Bond normal strength, st. dev. (MPa)	5.2	2.0	0.6	7.8	3.5
Bond shear strength, st. dev. (MPa)	1.3	0.5	0.1	1.9	0.9

Table 2 Macroproperties of simulated PFC materials

PFC Material	1	2	3	4	5
UCS (MPa)	22.9	8.6	2.5	31.2	16.4
E (GPa)	13.7	13.7	11.0	13.8	12.1
c (MPa)	7.0	3.0	0.8	8.3	5.4
ϕ (Deg.)	27	18	23	34	22
σ_t (MPa)	2.3	0.8	0.3	2.9	1.4

5.2 Simulation of discontinuities within PFC

A smooth joint contact model has been implemented within PFC to simulate the slip and separation of explicit discontinuities (Itasca, 2008). The joint geometry of a single smooth-joint contact is defined by a plane that is comprised of two initially coincident planar surfaces. The joint is described as smooth because particles that have been assigned a smooth-joint contact may overlap. This ensures that the particles will slide as expected along the joint, rather than be forced to move around one another. Figure 10 illustrates a direct shear testing environment that has been developed to simulate the laboratory scale behaviour of explicit discontinuities.

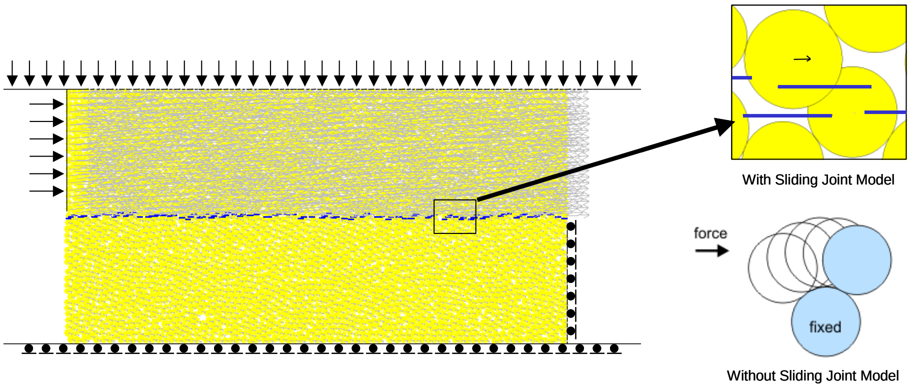

Figure 10 Direct-shear testing environment used to simulate sliding joint macroscopic behaviour

Pells (1977) reports that the cohesion and friction angle of fresh artificially induced fractures in Hawkesbury Sandstone is 0.44 MPa and 40° respectively. A cohesion of 0.1 MPa and friction angle of 30° was used to simulate the macroscopic response of the sliding joints used to represent the bedding planes and vertical joints within the PFC model of Hawkesbury Sandstone, as illustrated in Figure 11.

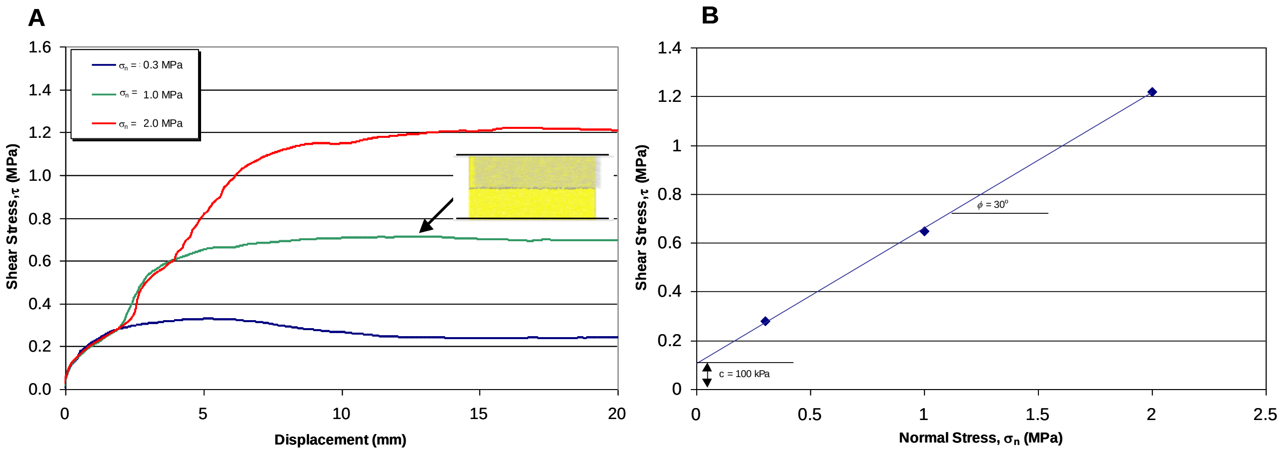

Figure 11 Shear behaviour of sliding joints used to simulate bedding and joint surfaces

5.3 Model geometry and modelling methodology

The geometry of the PFC model used to simulate the near-surface fracturing above longwall 8 at the Tower Colliery in illustrated in Figure 12. The near-surface stratigraphy at the Tower Colliery consists of the Hawkesbury Sandstone rock unit. For the purpose of computational efficiency, the PFC particle size was refined in the area of interest, as illustrated in Figure 12(c).

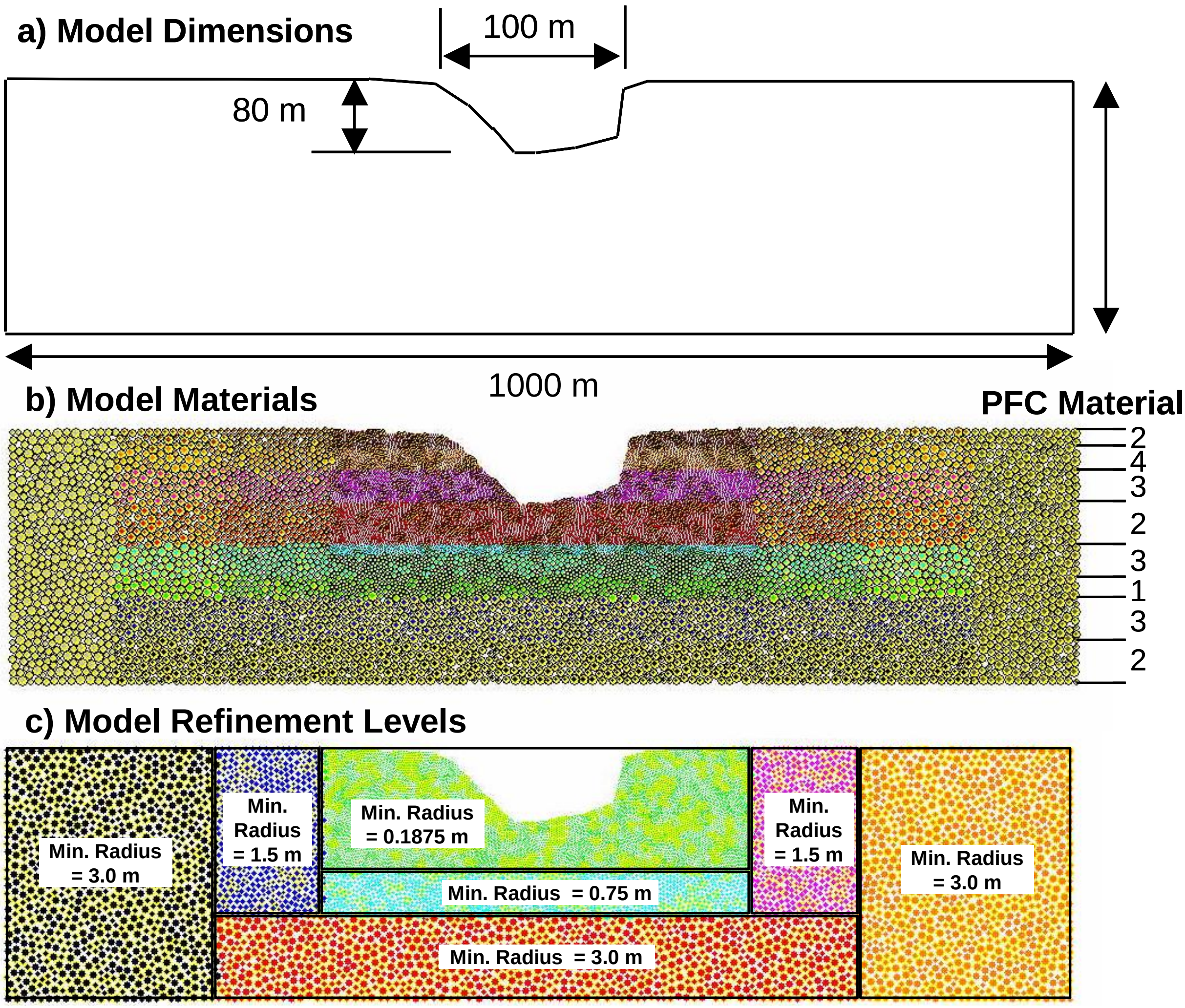

Figure 12 Dimensions, material groups and particle refinement zones of PFC model used to simulate the centreline of panel 8 at the Tower Colliery

ACARP (2002) reports that a very high stress field is present in the overburden sediments at Tower Colliery, exceeding the vertical stress by greater than three times. The orientation of the maximum principal stress lies perpendicular to the general trend of the Cataract Gorge. A stress initialisation routine described in Itasca (2008) was used to install the pre-mining stress regime, which has a ratio of horizontal-to-vertical stress of 3.26.

Based upon a description of the typical spacing and orientation of bedding discontinuities and jointing, provided by Pells (2002), sliding joints have been included within the PFC model to produce a synthetic rock mass (SRM), representative of Hawkesbury Sandstone as illustrated in Figure 13. The SRM modelling approach, pioneered by Pierce et al. (2007) and Mas Ivars et al. (2008), uses a combination of the PFC bonded particle model for the intact rock matrix (Potyondy and Cundall, 2004) and the smooth joint model to explicitly simulate a discrete fracture network. The innovative modelling technique allows for the detailed consideration of the in situ rock fabric which provides the ability to obtain predictions of rock mass scale effects, strength anisotropy and brittleness parameters that cannot be obtained using empirical methods of rock mass mechanical property estimation.

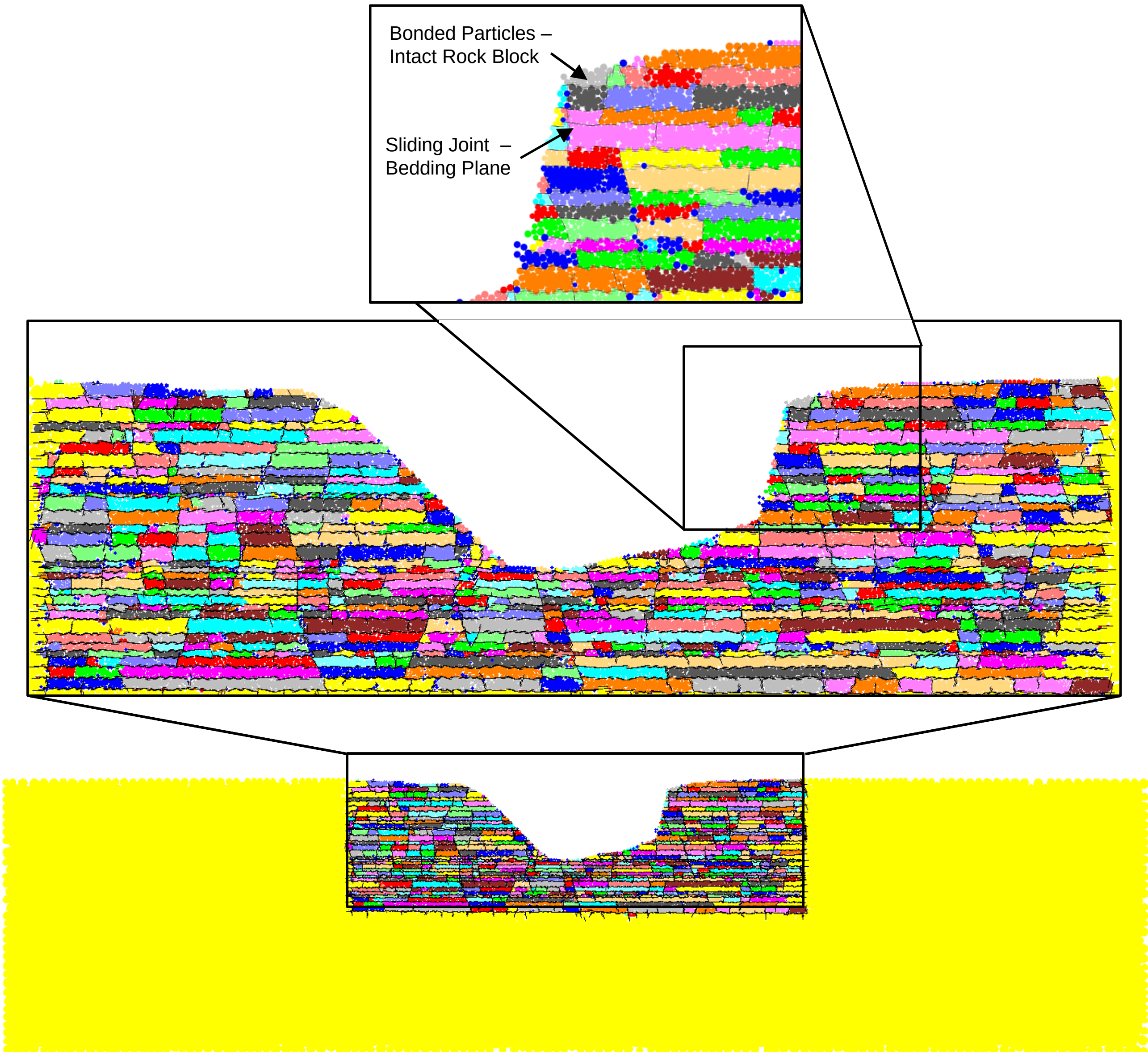

Figure 13 Synthetic rock mass produced to simulate Hawkesbury Sandstone

5.4 Analysis of regional subsidence

Due to the computational intensity of the PFC code, it currently is not feasible to develop a model that includes the entire longwall mining process with sufficient detail to examine the explicit near-surface fracturing that develops as a result of regional subsidence. A simple methodology has been developed to transfer displacements from a large-scale continuum model to the boundaries of the PFC model. The finite-difference code *FLAC* (Itasca, 2006b) was used to develop a large-scale model along the centreline of longwall 8 at the Tower Colliery. The longwall mining process was simulated by incrementally converting a region of material behind the face to an elastic material representative of goaf material. The two-dimensional, plane-strain nature of the *FLAC* model best represents the condition that exists when longwalls 7, 8 and 10 have been extracted.

Table 3 presents the material properties used to simulate the overburden and goaf material within the simplified *FLAC* analysis.

Table 3 Material properties used within simplified *FLAC* model

Material	Young's Mod. (GPa)	Poisson's ratio	Coh. (MPa)	Fric. (deg.)	Tens. (MPa)
Overburden	13	0.30	5.8	44	0.9
Coal	2.5	0.24	1.9	38	0.8
Goaf	0.25	0.4	-	-	-

As illustrated in Figure 14, after extraction of longwall 10, the total vertical subsidence measured outside the gorge is approximately 250 mm. The *FLAC* model was calibrated to match the surface subsidence measured above the panel by altering the height of simulated goaf material. Rather than developing a model to rigorously simulate the longwall caving process, the purpose of the model is to simulate the displacement profile at the location of the PFC model boundary. As illustrated in Figure 14, the x and y-displacements at the location of the PFC boundary were recorded after each mining increment.

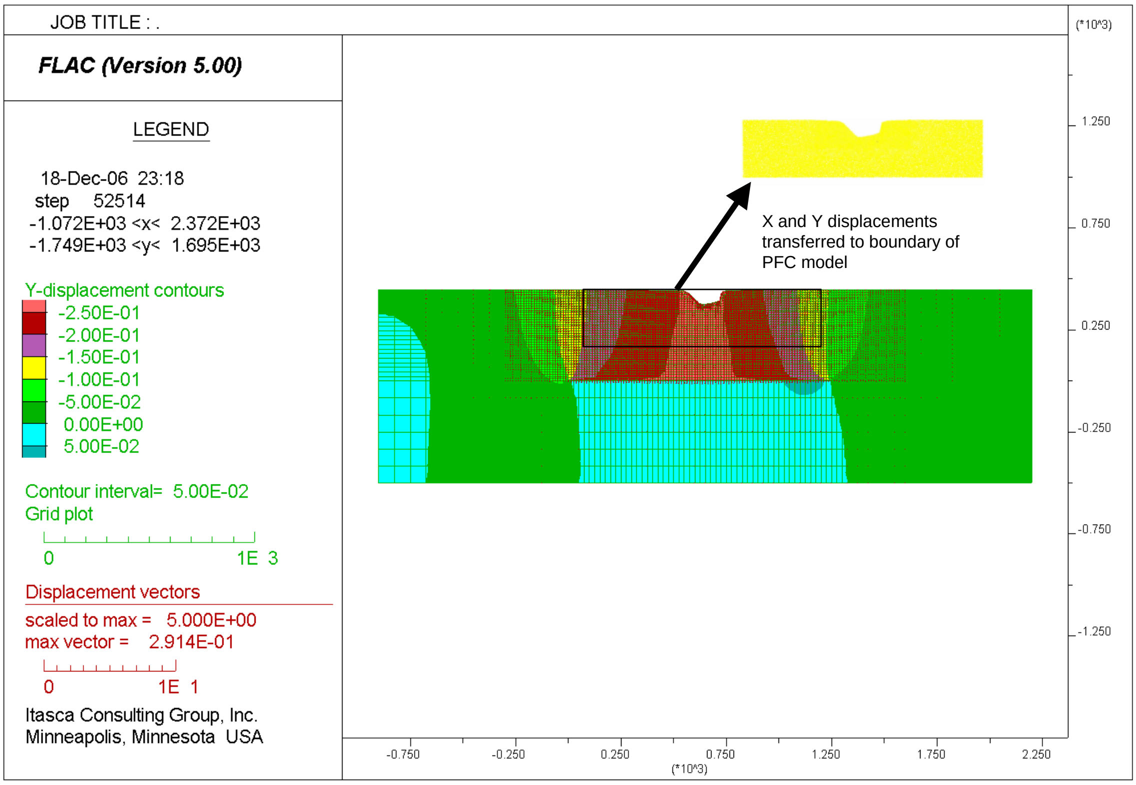

Figure 14 Regional *FLAC* model used to simulate displacement profile at the boundary of the PFC model

5.5 Model results

The evolution of explicit fracturing of the intact rock and joint displacement beneath the gorge is illustrated in Figure 15. Prior to longwall extraction beneath the gorge, only minor bond breakage and joint displacement throughout the overburden is predicted. Once the longwall panel has passed beneath the gorge, a cluster of explicit intact fractures are observed to form at the base of the gorge. At this point, shear and tensile displacement greater than 5 mm is observed on the bedding planes beneath the gorge, while tension cracks are observed to develop behind the escarpment face along the pre-existing vertical joints.

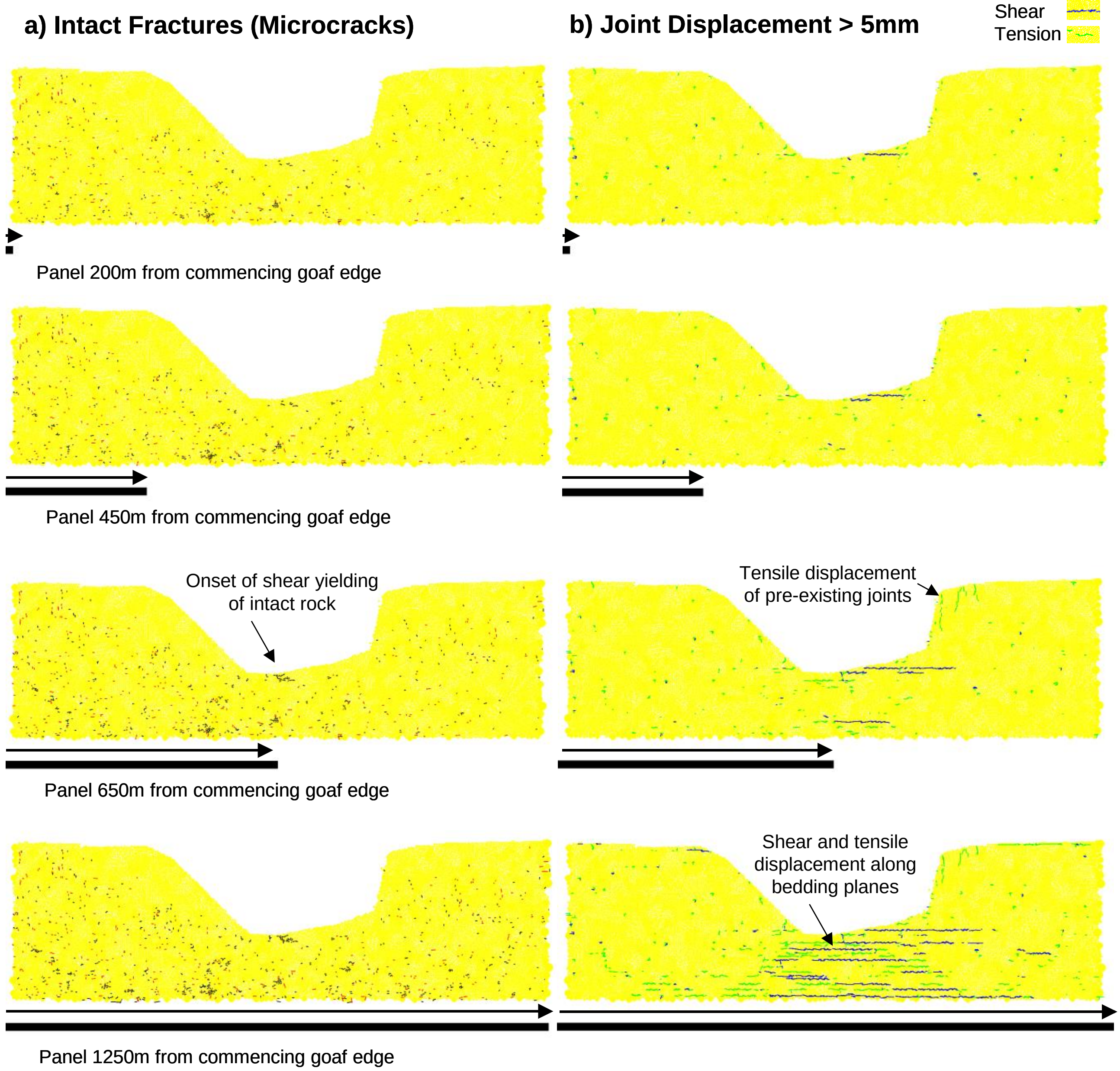

Figure 15 Evolution of fracturing beneath the Cataract Gorge

Figure 16(a) details intact fractures and displacement after extraction of longwall 8. The low-angle, explicit shear fractures that develop in the floor of the gorge, are observed to extend to a depth of approximately 10–20 m. This is consistent with observations made by Everett et al. (1997) after investigation of the water loss in the lower Cataract River. The upsidence phenomenon along the floor of the gorge is displayed in Figure 16(b). This behaviour is caused by dilation upon shear fracturing of the rock mass.

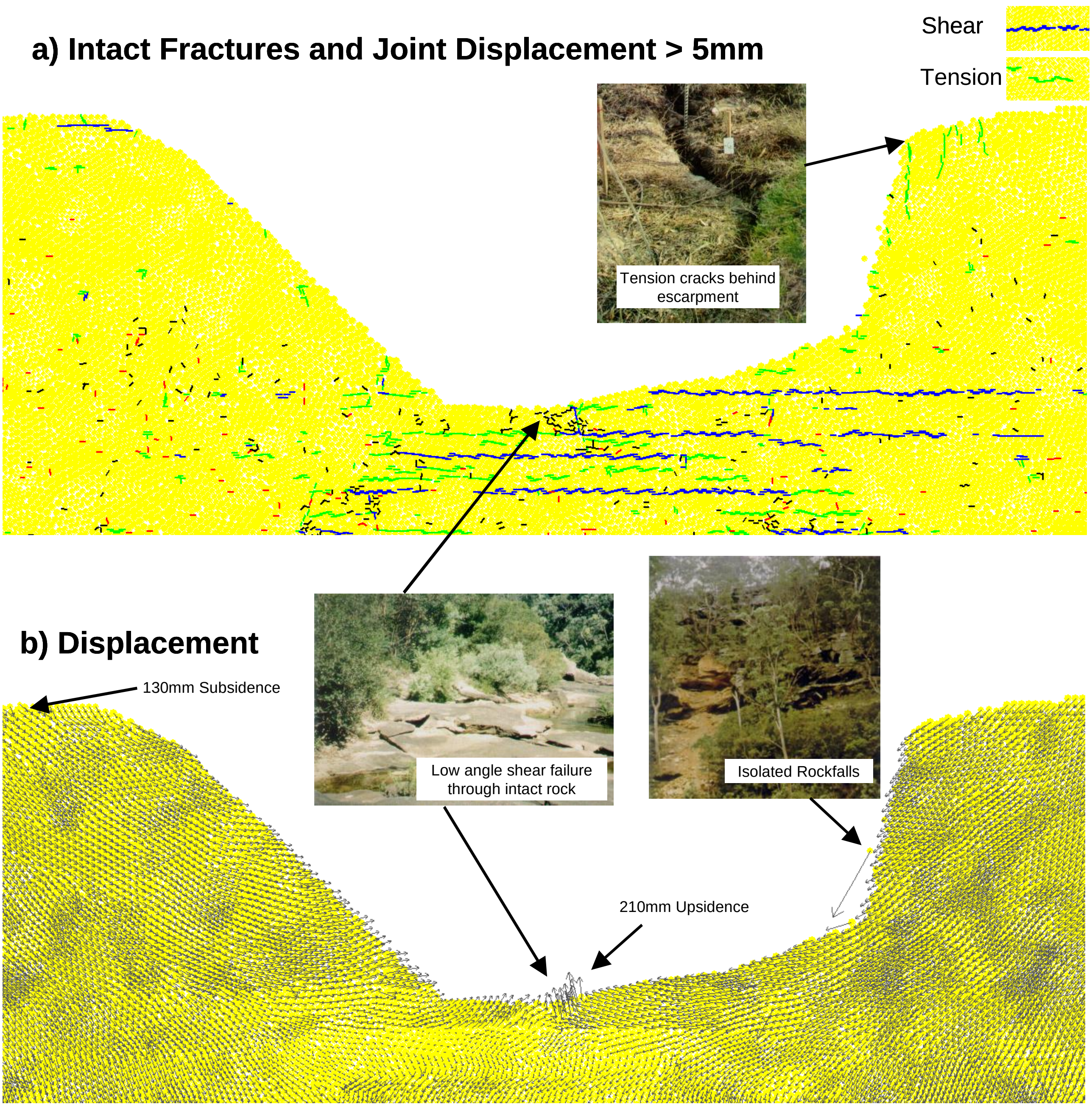

Figure 16 Explicit fracturing and displacement at the base of the Cataract Gorge

6 Conclusions

A back-analysis of observed and monitored river bed cracking above a longwall extraction panel at the Tower Colliery has been conducted. The PFC modelling approach accurately simulates the low-angle, explicit shear fractures that developed in the river bed, extending to a depth of approximately 10–20 m. The upsidence mechanism, caused by dilation of the rock mass upon shear fracturing is also simulated.

Due to the nature of a jointed rock mass, the exact location, orientation and magnitude of the explicit fractures observed in situ is dependent upon the complex structural geology of the near-surface rock units. Without very detailed geological information, this makes if difficult to predict the exact near-surface fracturing at a particular site. The PFC modelling approach provides a useful tool to simulate the effect of different river bed remediation techniques.

Acknowledgements

The assistance of David DeGagne and David Potyondy in preparing specific PFC functions and routines is acknowledged.

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