Numerical Analysis of the Melbourne Metro State Library Station Cavern

D. Sainsbury
Geotechnica Pty Ltd, Melbourne, Australia

B. Coombes
Noma Consulting Pty Ltd, Melbourne, Australia

R. Storry
Bouygues Construction Australia, Melbourne, Australia

A. Amon
Noma Consulting Pty Ltd, Melbourne, Australia

ABSTRACT: The Melbourne Metro Tunnel Project is delivering twin nine-kilometre rail tunnels in Melbourne, Australia. In addition to the tunnels, five new underground stations are being constructed. Two of the new stations – State Library and Town Hall – are complex cavern and adit excavations located in Melbourne's City Centre. The State Library Station, located predominantly underneath Swanston Street and a busy tram route, is surrounded by a mixture of modern, educational and heritage developments requiring the excavation sequence and primary support to be designed to ensure minimal surface impacts. To simulate the anisotropic rock mass response to the excavation of the State Library Station, FLAC3D numerical analysis was undertaken. The analysis adopted the ubiquitous joint constitutive model approach and was used to assess the performance of the primary lining design and to determine the impacts the predicted ground displacements may have on the surrounding structures. Calibration and validation of the ubiquitous joint modelling parameters for the Melbourne Formation has been completed against the measured and observed responses throughout excavation.

1 INTRODUCTION

The Melbourne Metro Tunnel Project is a metropolitan rail infrastructure project located in Melbourne, Australia. The project comprises the construction of twin nine-kilometre tunnels with five underground stations. The two stations under Swanston Street, State Library and Town Hall, were constructed as a mined trinocular form caverns with the central 'station' tunnel excavated prior to the outer 'platform' tunnels using sequential excavation methods (Figure 1a). Storry et al (2023), within these proceedings, provides a broad description of the project and construction techniques used.

To simulate the anisotropic rock mass response to the excavation of the State Library Station, a three-dimensional numerical analysis was undertaken with FLAC3D. The analysis adopted the ubiquitous joint constitutive model approach and was used to assess the performance of the primary lining design and to determine the impacts the predicted ground displacements may have on the surrounding infrastructure.

2 GEOLOGY AND GEOTECHNICAL CONDITIONS

The Melbourne Formation (also known as the Melbourne Mudstone) is an anisotropic rock mass, both in terms of its intact properties and in terms of its structural geological features.

The predominant rock type in the Melbourne Formation is siltstone, which typically comprises 70% to 80% of the formation. Bedding in the siltstone is typically well-developed and varying in the range 10 mm to 300 mm thick, but more typically in the range 30 mm to 60 mm thick. The remainder of the formation comprises sandstone and rare (<2%) beds of conglomerate and claystone. The bedding defects are highly persistent, limited only by fold hinge axes, major fault structures and igneous dykes (Figure 1b), which resulted in anisotropic strength and deformation behaviour.

When un-weathered, the siltstone rock is a moderately strong rock with uniaxial compressive strengths in the order of 20 to 50 MPa. The weathering of the Melbourne Formation ranges from extremely weathered to fresh and is represented in the oxidized environment by a colour change from light yellow and grey through yellow browns to dark grey (Paul et al, 2017). At the State Library Station, the weathering profile of the encountered Melbourne Formation was complex because of the geological structure (intrusive igneous dykes and folds) and varied significantly over short distances.

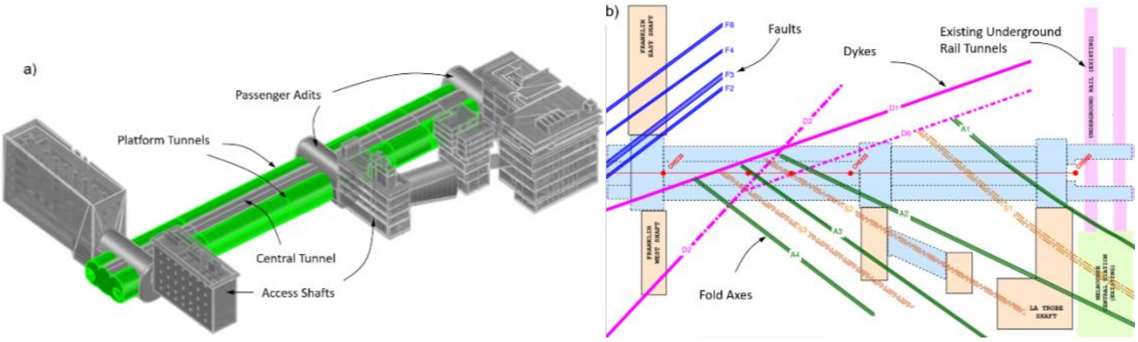

Figure 1. a) State Library Station configuration; b) Geological plan view showing major structures

3 NUMERICAL ANALYSIS OF THE STATE LIBRARY STATION

3.1 *Background*

Geotechnical numerical modelling techniques can be broadly grouped into continuum, discontinuum and equivalent continuum methods. The most common equivalent continuum method is the ubiquitous (or subiquitous) joint constitutive model which has been implemented within the finite difference codes FLAC, FLAC3D, UDEC and 3DEC (Itasca, 2018). Due to the inherent nature of the ubiquitous joint formulation, it has been found that direct use of discontinuum properties in a ubiquitous joint model without careful calibration of the material response can provide misleading model results by not capturing the rock mass response accurately (Sainsbury et. al 2017; Perras and Diederichs, 2009).

Various discontinuum modelling techniques are available that explicitly simulate joints and discontinuities within an anisotropic rock mass. Due to the computational intensity of these numerical techniques, it is not practical to explicitly simulate the joint fabric of an entire rock mass for routine analyses of large-scale excavations. To overcome this, the continuum based ubiquitous joint constitutive model is commonly used to represent the strength and deformation behaviour of anisotropic rock masses (Clark, 2006, Leitner et al, 2006).

This approach to numerical analysis was completed for all adits and cavern primary ground support design packages prior to construction. The advantage of using this technique was the improved understanding of the rock mass response with the inclusion of structural elements, allowing for improved accuracy with respect to predicted structural element forces allowing greater efficiency with the design of these elements. This numerical analysis approach also had the benefit of a more realistic rock mass response for inclusion in the ground movement and building impact assessments given the dense, urbanised environment that the State Library Station was constructed.

3.2 *Constitutive Model*

The Ubiquitous Joint model corresponds to a Mohr-Coulomb material that exhibits a well-defined strength anisotropy due to embedded planes of weakness. As shown in Figure 2a, the planes of weakness can be assigned different orientations for each zone in the model. The criterion for failure on the plane of weakness consists of a composite Mohr-Coulomb envelope with a tension cut-off. The propagation of damage within a Ubiquitous-Joint model can be observed through the progressive degradation of matrix cohesion and ubiquitous joint-failure plots at various stages of loading in a simulated unconfined compressive strength test, illustrated in Figure 2b.

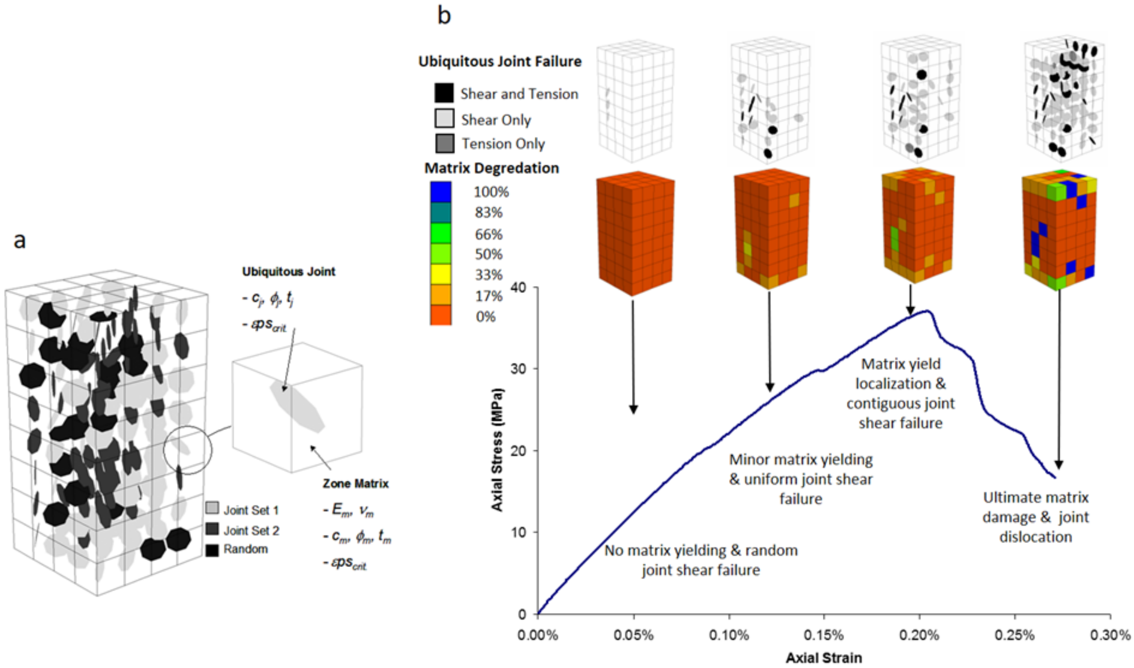

Figure 2. (a) Ubiquitous joint model: matrix and joint properties, (b) stress-strain response of simulated ubiquitous joint rock mass (Sainsbury et al, 2008)

The Ubiquitous-Joint model formulation assumes infinitesimal spacing and no length scale to their implementation. As such, a ubiquitous-joint material cannot account for the bending stiffness of the individual layers of rock. As demonstrated by (Leitner et al, 2006, Sainsbury and Sainsbury, 2017), the selection of matrix and joint properties based on direct input of the measured block and joint strength will result in a simulated material response that does not represent the true rock mass strength or deformational profile and provide misleading model results.

To provide meaningful modelling results, careful calibration of the matrix and ubiquitous joint parameters to the emergent behaviour from discontinuum modelling techniques and in situ monitoring and observation is required. A detailed Ubiquitous Joint Rock Mass (UJRM) calibration procedure to account for rock mass anisotropy in open pit rock slopes, block cave mines, deep mine access development and civil tunnelling has been developed continuously since 2006 (Clark, 2006, Sainsbury and Sainsbury, 2017, Sainsbury et al, 2016 and Johnson et al, 2016). This included back-analysis of historical underground excavations in the Melbourne Formation, notably the Melbourne Underground Rail Loop and City Link Domain Tunnel were conducted and reported by Sainsbury and Amon (2017).

During the tender and detailed design phases of the Metro Tunnel project, detailed UJRM parameter calibration was conducted based upon laboratory testing and field measurement data (including bedding spacing and persistence measurements at notable exposures of Melbourne Formation).

Figure 3 illustrates the discrete fracture network (DFN) used to represent the Melbourne Formation, while Figure 4 illustrates the response of a large-scale, discontinuum (3DEC), synthetic rock mass specimen on Melbourne Formation with horizontal bedding (β=0). Figure 5 presents the calibrated continuum (FLAC3D) strength response to the discontinuum (3DEC) model response at bedding orientations from horizontal to vertical. The emergent strength anisotropy in both discontinuum and continuum modelling approaches can be observed.

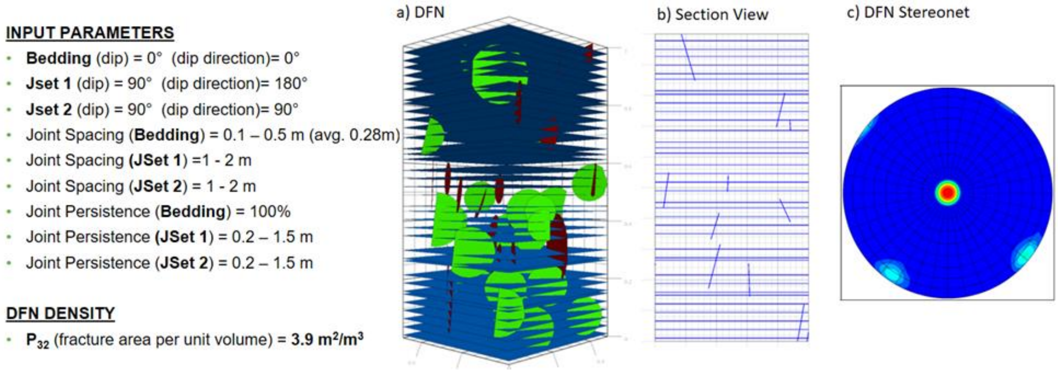

Figure 3. Discrete fracture network (DFN) to represent the Melbourne Formation siltstone

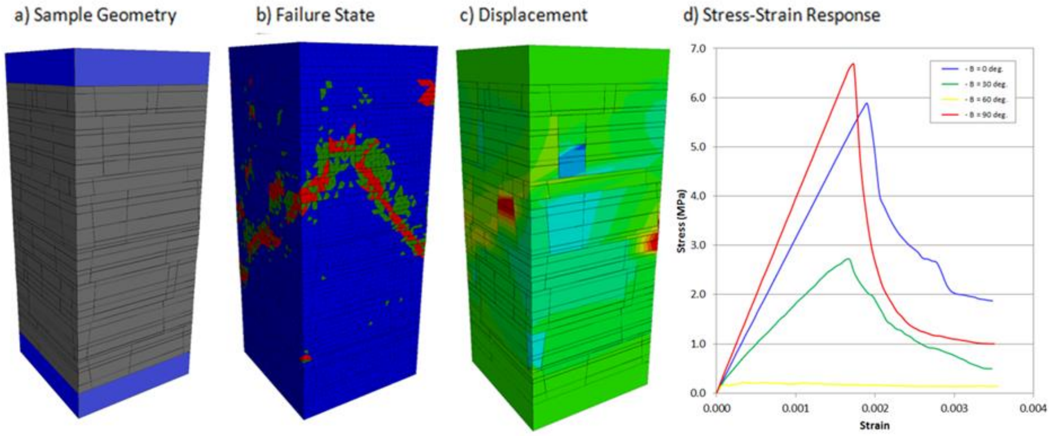

Figure 4. 3DEC model of simulated Melbourne Formation, $\beta = 0$, $\sigma_3 = 0$ MPa

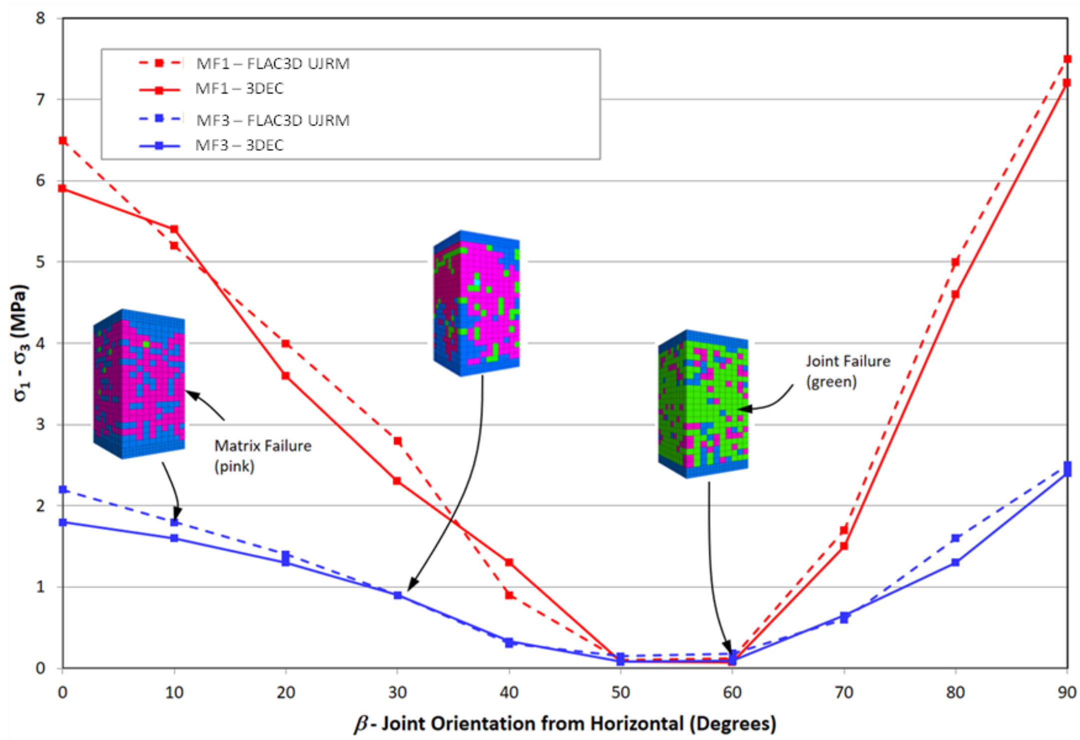

Figure 5. Calibrated UJRM anisotropic strength response compared to the discontinuum anisotropic response for Melbourne Formation

4 MODEL GEOMETRY

Multiple three-dimensional FLAC3D models were constructed to cover the entire State Library Station Cavern and associated access shaft infrastructure. Figure 6a shows the model geometry constructed to simulate the northern end of the station. The primary support simulated, which consists of fibre reinforced shotcrete with local reinforcement, canopy tubes, spiles, rock bolts and steel columns, is presented in Figure 6b.

Within the global models, the fibre reinforced shotcrete is simulated with two-dimensional, linear elastic shell elements installed in-cycle after each 1.5m excavation advance, while the rock bolts have been modelled with one-dimensional cable elements, that simulate the axial behaviour of the rock bolt itself and the shearing resistance along grout / rock interface. The primary steel columns within the central tunnel were simulated as a single beam element connected to the shotcrete liner and permanent base slab.

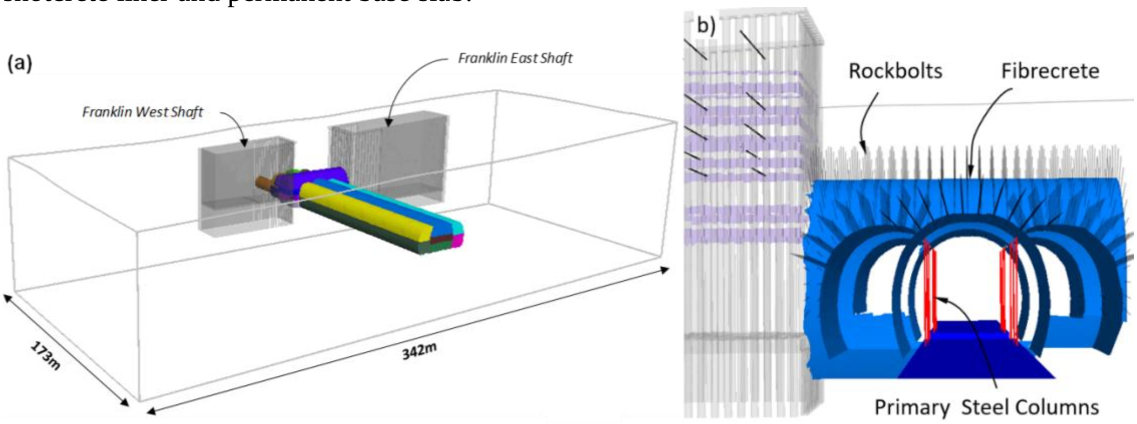

Figure 6. a) FLAC3D model geometry of the northern end of the State Library Station

5 GEOTECHNICAL PARAMETERS

The State Library Station Geotechnical Interpretive Report (GIR) was the basis for the fundamental geotechnical material properties (Wilson, 2018). Sainsbury and Amon (2017) previously reported the calibrated UJRM input properties that were used in the design development, while further refinement of the UJRM properties have been reported by Coombes et al (2023). The calibrated UJRM input parameters used throughout these analyses are shown in Table 1.

Table 1. Melbourne Formation modelling parameters (calibrated UJRM input properties)

Domain	Unit Weight [kN/m3]	Modulus [GPa]	Poisson's Ratio	Matrix Properties			Joint Properties	
				c [kPa]	ϕ [deg]	σ_t [kPa]	c [kPa]	ϕ [deg]
MF3	23.5	1.6	0.26	126	42.0	5	0	20
MF2	24.5	4.2	0.25	336	44.8	30	0	32
MF1	26.0	9.2	0.24	964	47.7	150	0	32

The geotechnical domains, major structures and bedding fabric simulated throughout the FLAC3D model of the State Library Station is presented in Figure 7. An example of the disturbed nature of the rock mass is evident in Figure 8, where Figure 8a is a face photograph taken during geological mapping and Figure 8b is the numerical analysis representation of the same location.

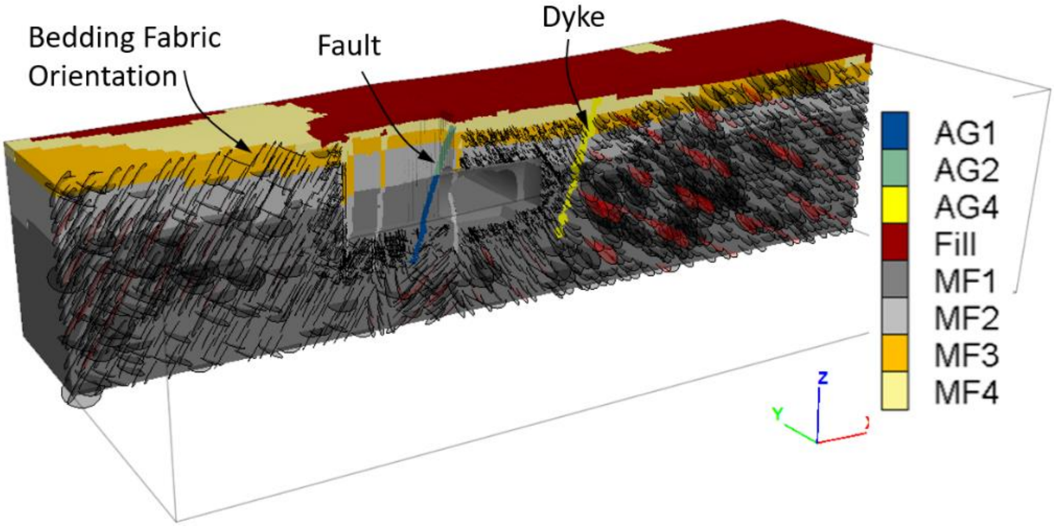

Figure 7. Geotechnical domains, major structures and bedding fabric simulated with the FLAC3D model.

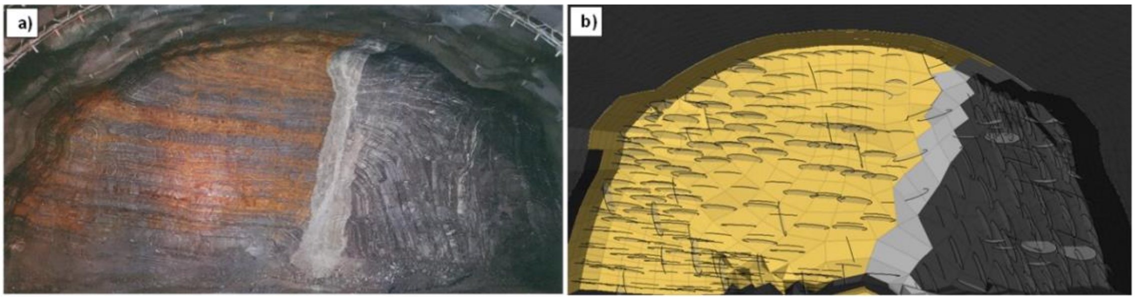

Figure 8. (a) Photograph of excavated face, (b) FLAC3D central tunnel (top heading) model geometry (disks showing ubiquitous joint orientation).

6 CALIBRATION ASSESSMENT

Ground displacement calibration in the form of vertical settlement at the ground surface along the centreline was completed for the central tunnel and the cavern excavation stages. Additional, calibration based on displacement of the primary steel columns within the central tunnel cavern is discussed by Coombes et al. (2023).

6.1 *Instrumentation and Monitoring*

Instrumentation and monitoring of the excavation and primary support elements was monitored with an extensive array of in-tunnel convergence prisms, and surface monitoring points (SMP's) which were surveyed via manual survey techniques and ATS.

The State Library Station surface was monitored with nearly 300 SMP's plus a suite of utility monitoring points and building monitoring points.

6.2 *Surface Settlement*

The predicted surface settlements after the excavation of the central tunnel and the eastbound and westbound platform tunnels, to form the trinocular cavern are shown in Figure 9.

Predicted settlement from the central tunnel (Figure 9a) above Franklin Adit was predicted to be 15 mm with a maximum predicted settlement at CH9295 of 20 mm. With continued excavation of the platform tunnels, the predicted settlement from the excavation (Figure 9b) above Franklin Adit was predicted to be 22 mm. At this excavation stage, it also becomes apparent the impact dyke orientation has with a skew in the predicted settlement orientation matching the dyke orientation. The maximum predicted settlement from the excavation increased from 20 mm to 34 mm. The overall settlement profile with increasing chainage demonstrated a settlement trough associated with Franklin Adit before settlement decreased. With the first intersection of the dykes, the settlement progressively increased with settlement greatest between CH9280 and CH9305.

Figure 10 shows the measured settlement along the centreline of the central tunnel alignment compared to the settlement predictions with both the best-estimate and lower-bound K_0 simulations.

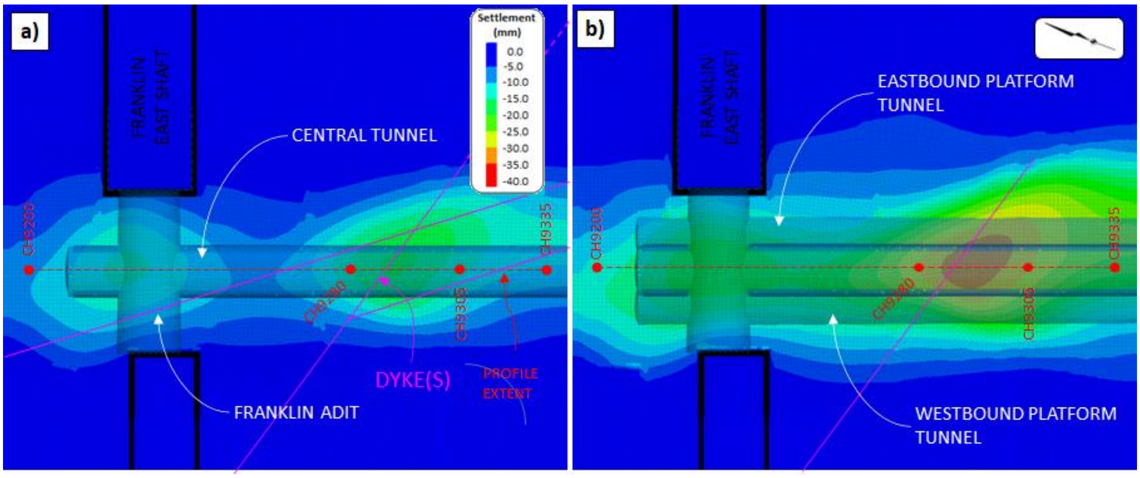

Figure 9. Estimated settlement (a) central tunnel and (b) trinocular cavern

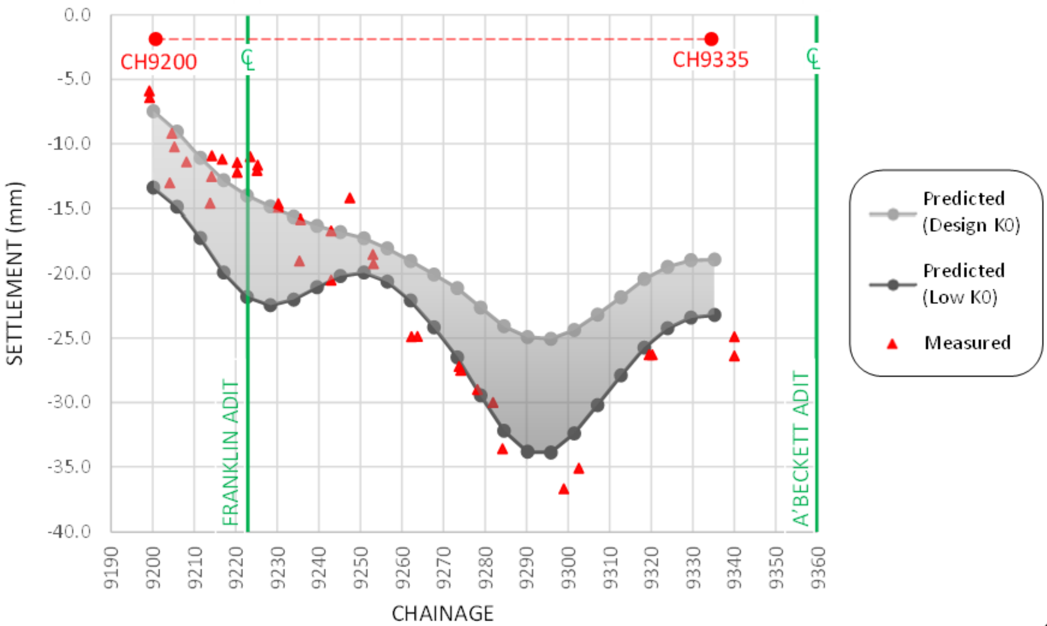

Figure 10. Calibration of predicted versus measured settlement for trinocular cavern

7 CONCLUSIONS

Discontinuum analyses will always provide the most rigorous assessment of anisotropic rock mass strength and deformation behaviour. However, when large-scale analysis of anisotropic rock masses dictates the need for a continuum-based model, careful calibration of the material response to a series of discontinuum numerical experiments provides significant insight, understanding and robust modelling results. The critical step, where possible, is careful calibration of the geotechnical parameters against a measured response. The calibration process of the numerical analysis of State Library Station was considered successful when compared against both rock mass response and structural element response.

The complex geological conditions encountered at State Library Station between Franklin and A'Beckett Adits highlights the need for good geotechnical understanding within the numerical analyses. Achieving a calibration would be almost impossible without this understanding. All data can be useful, even passing conversations with superintendents can reveal good geotechnical knowledge to improve the geotechnical understanding.

The UJRM numerical analysis approach adopted provided the project with a robust design that gave all stakeholders confidence in the station cavern design. As anisotropic rock masses represent a significant proportion of the worlds near surface rock masses, this is an advance in the design of large scale, complex underground excavations. While this project was focussed on the Melbourne Formation, the UJRM approach can be adopted for any anisotropic rock mass.

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