Advanced Analysis of Tunnel Excavation within the Anisotropic Melbourne Formation

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Abstract: *The Melbourne Formation is a highly variable, inter-bedded siltstone / sandstone rock mass that forms the bedrock of large areas of the Melbourne CBD and surrounding suburbs. The bedding defects have been widely described as highly persistent, limited only by fold hinge axes and major fault structures, which result in anisotropic strength and deformation behaviour.*
Although many attempts have been made to describe the strength of rock masses that exhibit a preferred orientation of weakness, no general methodology has emerged throughout the literature to simulate anisotropic behaviour in a three-dimensional numerical model of tunnel excavation and support.
To simulate the anisotropic response of the Melbourne Formation, a hybrid discontinuum – ubiquitous joint modelling methodology has been developed. The modelling methodology has been validated via back-analysis of the deformation response monitored during construction of the Melbourne Underground Rail Loop (MURL), Lonsdale Street Cable Tunnel and CityLink Domain Tunnel.

Keywords: *anisotropic rock strength, Melbourne Formation, numerical simulation, tunnelling*

1. INTRODUCTION

The strength and deformation behavior of a rock mass is governed strongly by (a) the 'intact' strength of the rock blocks and (b) the presence of planes of weakness such as joints, bedding, foliation and other discontinuities. Anisotropic rock mass strength and deformation behavior is usually observed when a significant portion of the discontinuities are aligned in a preferred direction, such as the Silurian aged, Melbourne Formation which is an inter-bedded siltstone / sandstone rock mass that forms the bedrock of large areas of the Melbourne CBD. Figure 1 illustrates the typical bedding fabric that controls the anisotropic strength and deformation behavior of the Melbourne Formation (formerly Dargile Formation).

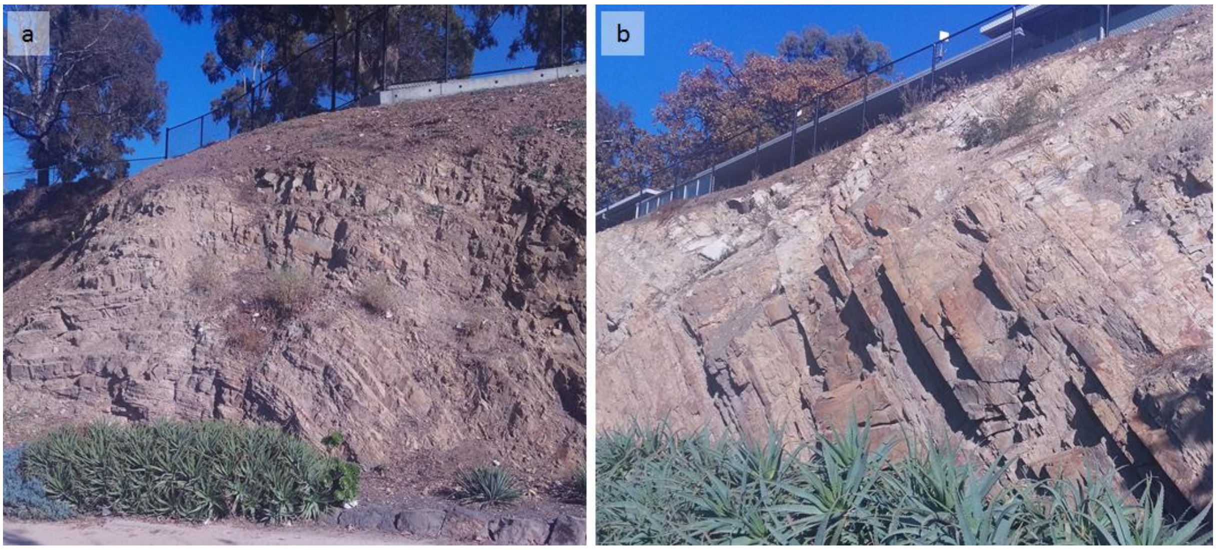

Figure 1 – Exposure of Melbourne Formation along Alexandra Avenue beneath the Kings Domain

Various discontinuum modeling techniques are available that explicitly simulate joints and discontinuities within an anisotropic rock mass. However, 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 [1] [2]. To overcome these computational limitations, the commercially available, continuum based Ubiquitous-Joint constitutive model is commonly used to represent anisotropic and foliated rock masses ([3], [4], [5]).

2. BACKGROUND

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 cutoff. 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.

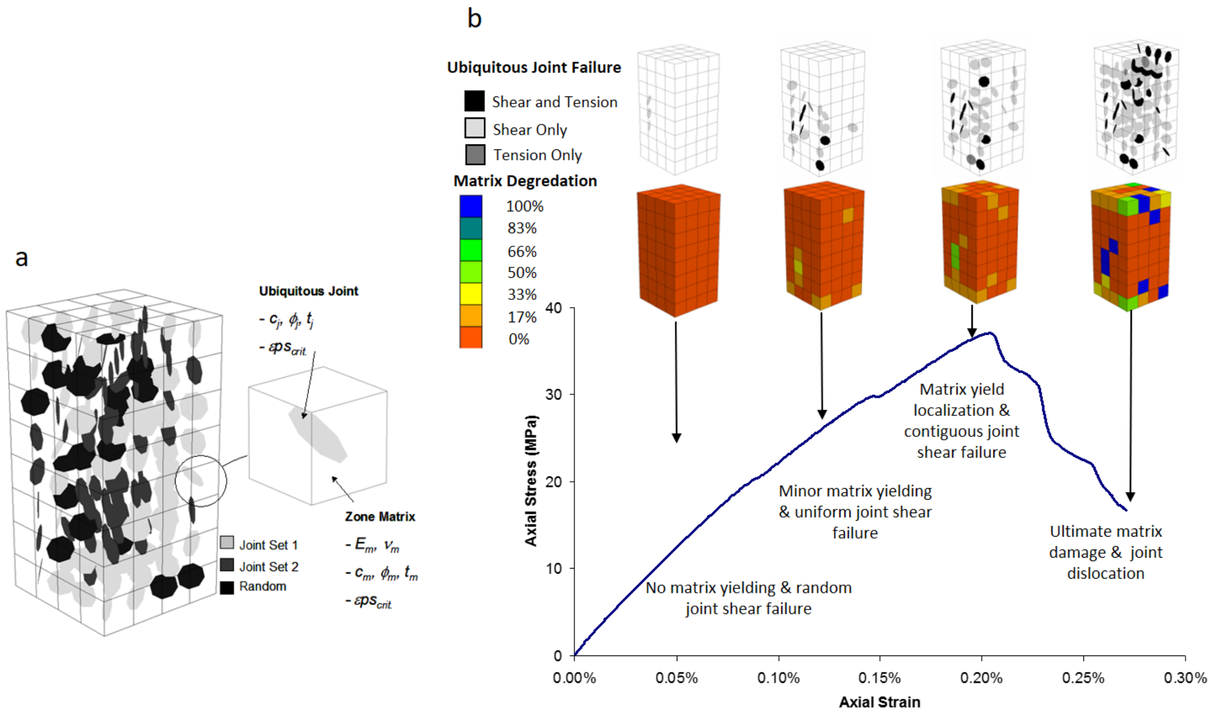

Figure 2 – a) Ubiquitous joint model: matrix and joint properties, b) Stress-strain response of simulated ubiquitous joint rock mass

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 [5] and [6], 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.

In order 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 and deep mine access development has been developed continuously since 2008 [7]; [8], [6].

As described in [6], the analysis of anisotropic tunnel deformation within an inter-bedded sandstone, siltstone and shale rock mass, similar to fresh Melbourne Formation, has been conducted at the Ballarat Gold Project in central Victoria. The UJRM modelling methodology was applied to the anisotropic rock mass and the deformation results compared to in situ monitoring and discontinuum modelling results of the same tunnel section. Figure 3 illustrates the close match achieved between the UJRM model and convergence monitoring conducted during tunnel excavation.

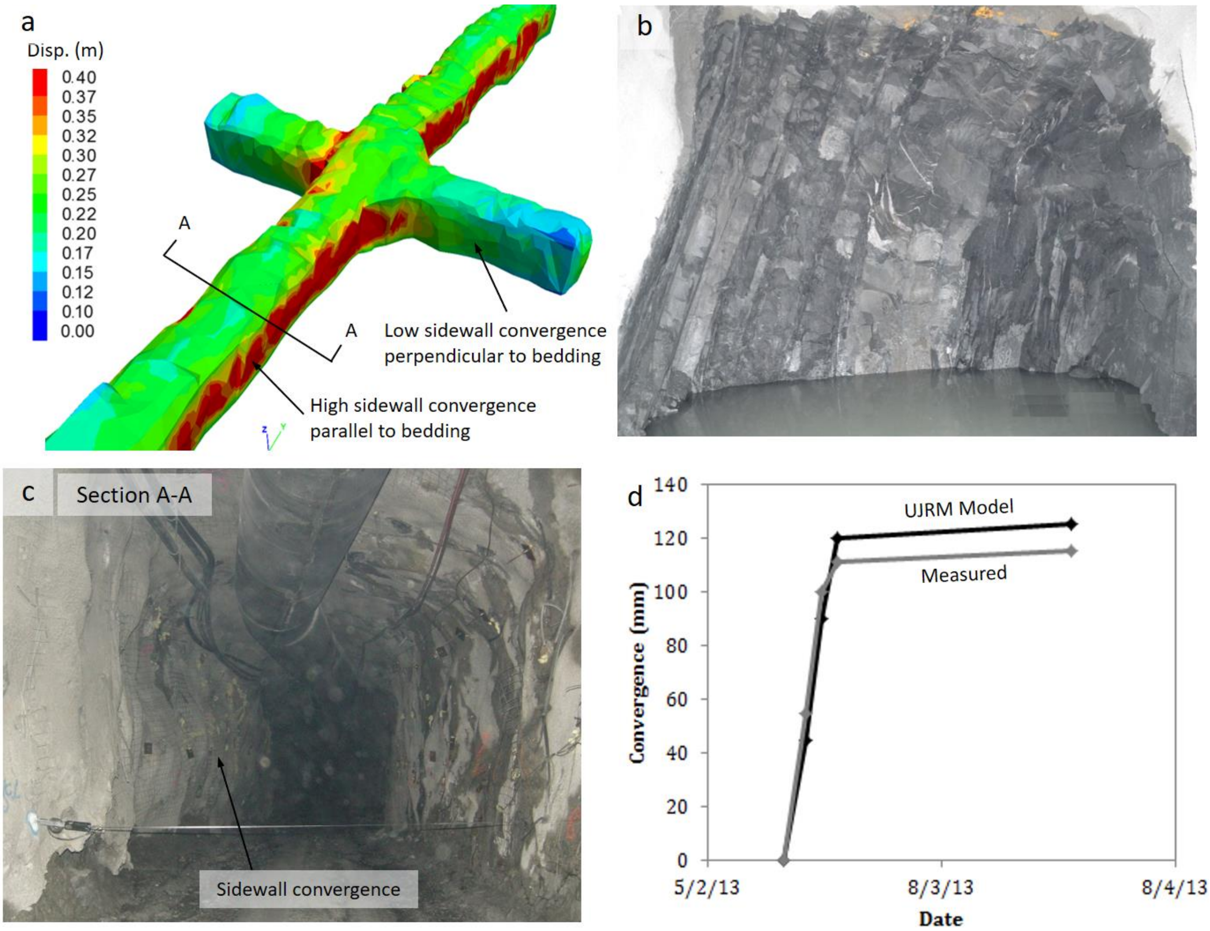

Figure 3 – UJRM model of anisotropic tunnel deformation at the Ballarat Gold Project

For the Ballarat Gold Project, discontinuum modelling was also conducted with the three-dimensional distinct element program 3DEC to compare the anisotropic deformation and yielding response observed in the UJRM (continuum FLACD) model. A comparison of the simulated excavation responses using each of the techniques are provided in Figure 4. The discontinuum model is considered to be the most rigorous representation of the anisotropic jointed rock mass behaviour. However, the calibrated UJRM model provides a close match to the anisotropic deformation and yielding response simulated in the discontinuum model and the measured in situ response of the rock mass to excavation. This provides confidence in the application of the more efficient UJRM modelling methodology to the three-dimensional analysis of larger excavations in anisotropic rock masses.

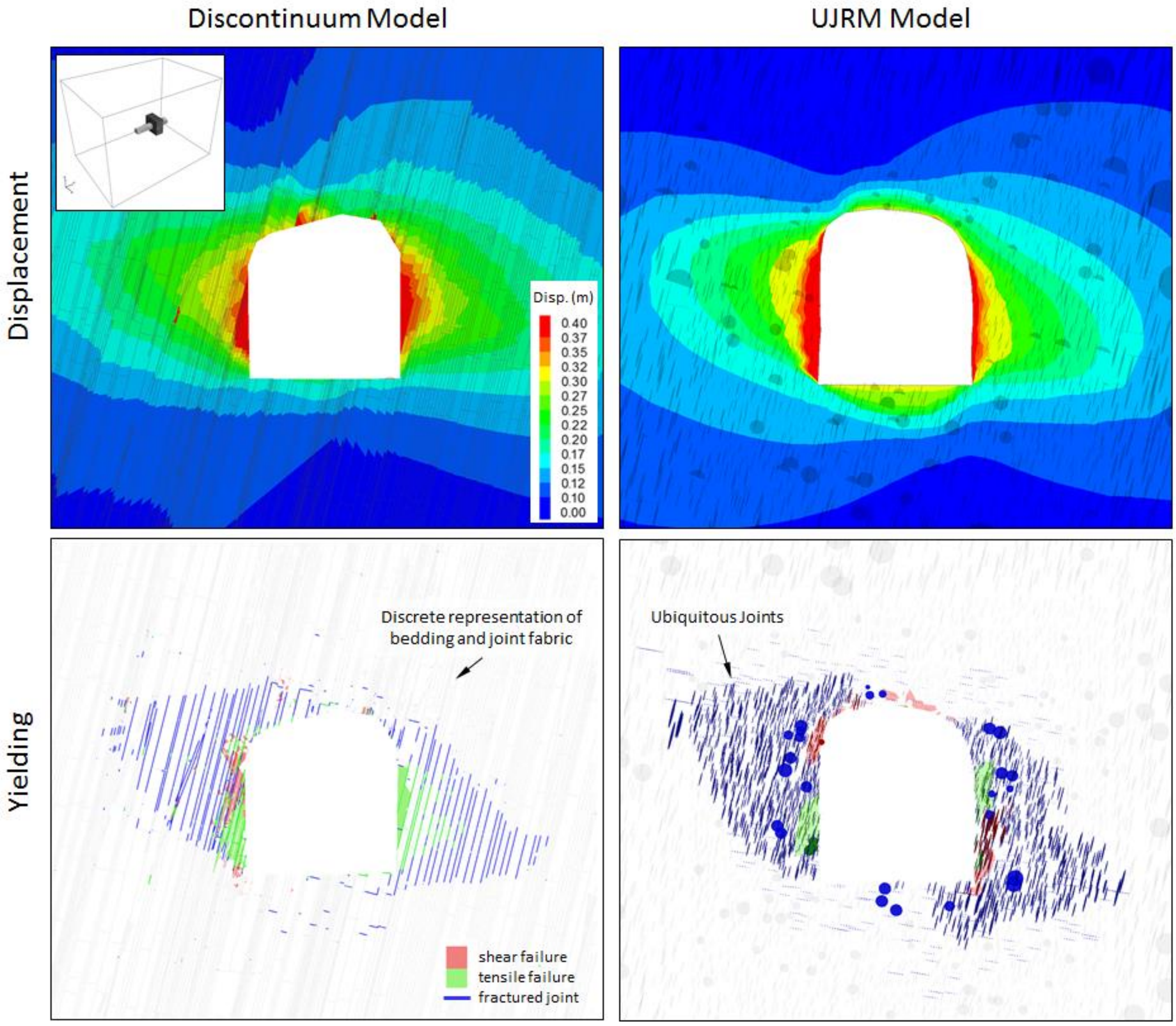

Figure 4 – Comparison of discontinuum and UJRM model response

3. DEVELOPMENT OF UJRM MATERIAL PROPERTIES FOR THE MELBOURNE FORMATION

The Melbourne Formation is a highly variable inter-bedded siltstone, sandstone rock mass, typically with defect spacing of 100 mm to 300 mm but with localised highly fractured zones. This is consistent with the description from the 1966 MURL investigations of an average joint spacing of 150 mm. The bedding defects are described as highly persistent and limited only by folding hinge axes and major fault structures. Faults, which typically present as sheared zones, crushed seams or highly fractured zones are encountered where movement along a discontinuity has occurred.

Typical Hoek-Brown parameters for the Melbourne Formation are presented in Table 1.

Table 1 Typical Hoek-Brown Parameters

Domain	GSI	σ_{ci} (MPa)	m_i
Highly Weathered	30	4	13
Moderately Weathered	40	8	13
Fresh	50	25	13

Numerical experiments with discontinuum modelling techniques provide significant insight and understanding of rock mechanics processes that are not possible to test in the laboratory due to specimen scale. The following sections describe the use of simulated large-scale laboratory experiments with discontinuum models under various stress paths to provide an understanding of the anisotropic strength and deformation behaviour of the Melbourne Formation. The emergent behaviour from the discontinuum models can be calibrated within the Ubiquitous (or Subiquitous) Joint constitutive model for use in large-scale excavation analyses.

3.1. Analysis of Bedding and Joint Fabric

In order to simplify the discontinuum modelling process, a single discontinuity realisation was developed to simulate all Melbourne Formation weathering grades. The basic bedding and joint fabric information used to develop a Discrete Fracture Network (DFN) for use in the discontinuum models is illustrated in Figure 5. The resulting P_{32} (area of joints to volume of rock) of 3.9 m^2/m^3 for the simulated Melbourne Formation DFN indicates a blocky rock mass that is dominated by the bedding and joint fabric with little rock bridge interaction. The average rock block volume (V_b) is 0.62 m^3.

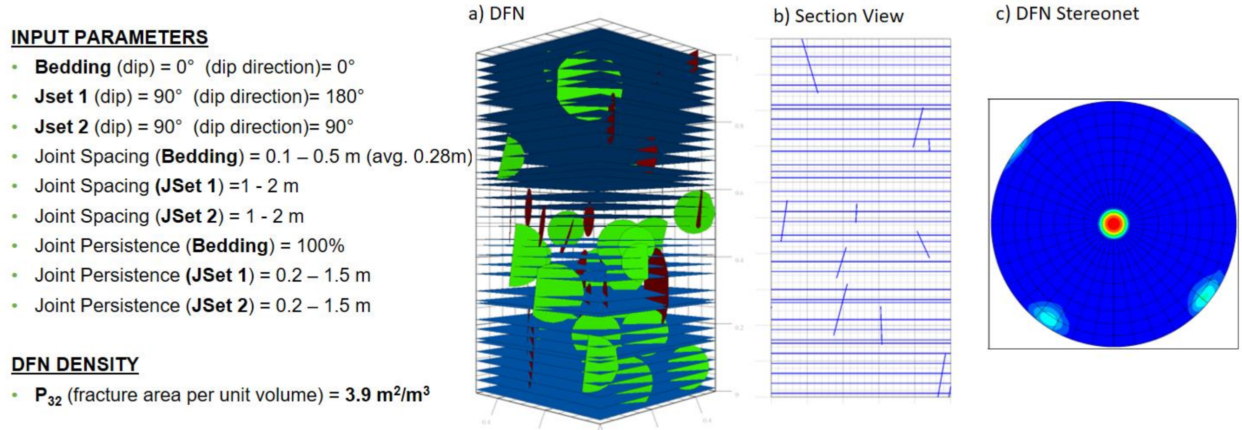

Figure 5 – Discrete Fracture Network (DFN) used to the Melbourne Formation

3.2. Discontinuum Analysis of Anisotropic Strength and Deformation Response

The DFN was imported into a simulated numerical compression testing environment in 3DEC, as illustrated in Figure 6b.

To account for the significant impact that micro-flaws (pores, open cracks, veins) and weathering/alteration can have on the strength scale effect, the rock block strength was assigned to be 30% of the σ_{ci} presented in Table 1. This value is based on an empirical scale effect relation for intact rock developed by [9] and extended by [10]. [11] report on a large-scale (450 mm diameter) UCS test on siltstone that was used for estimation of rock block strength for the Brisbane Airport Link Project (APL). The strength ratio obtained based on the average UCS values of the small-scale test results (60 mm) was also 30%.

Figure 6a, b and c illustrates the UCS response of fresh Melbourne Formation material with a β angle of 0^o, which results in a UCS of 6.0 MPa. Figure 6d presents the uniaxial stress – strain response of the simulated test results at β angles of 0, 30, 60 and 90 degrees. As illustrated, the anisotropic deformation modulus and post-peak response is also emergent from the discontinuum models.

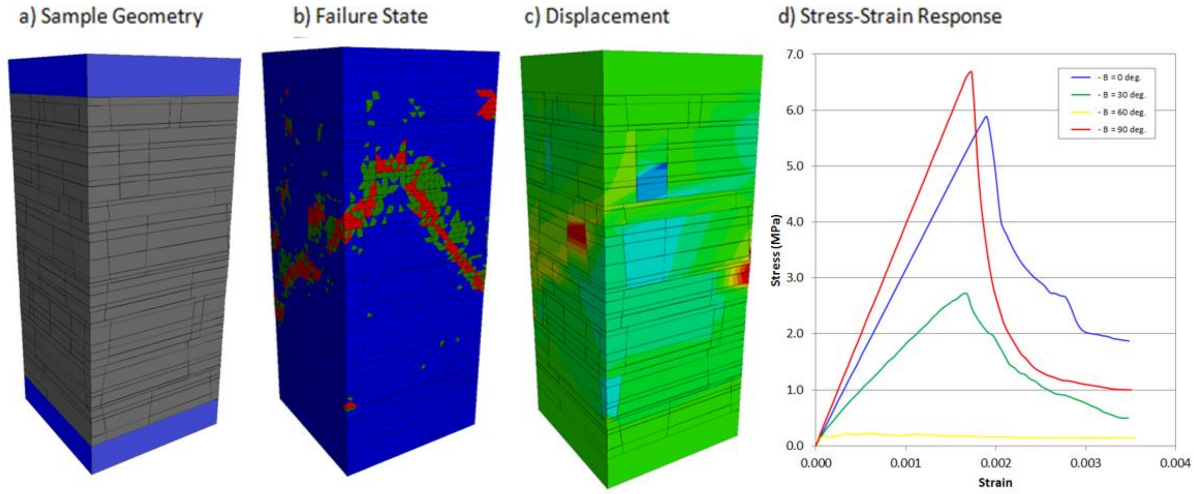

Figure 6 – 3DEC model of simulated fresh material, β = 0, σ3 = 0 MPa

A series of UCS tests were simulated with β angles from 0º to 90º. Figure 7 illustrates the resulting U-shaped strength curve for the simulated fresh and moderately weathered Melbourne Formation domains. As illustrated, when β = 90º a tensile splitting mechanism along the bedding develops, while a sliding mechanism along the bedding develops when β = 60º.

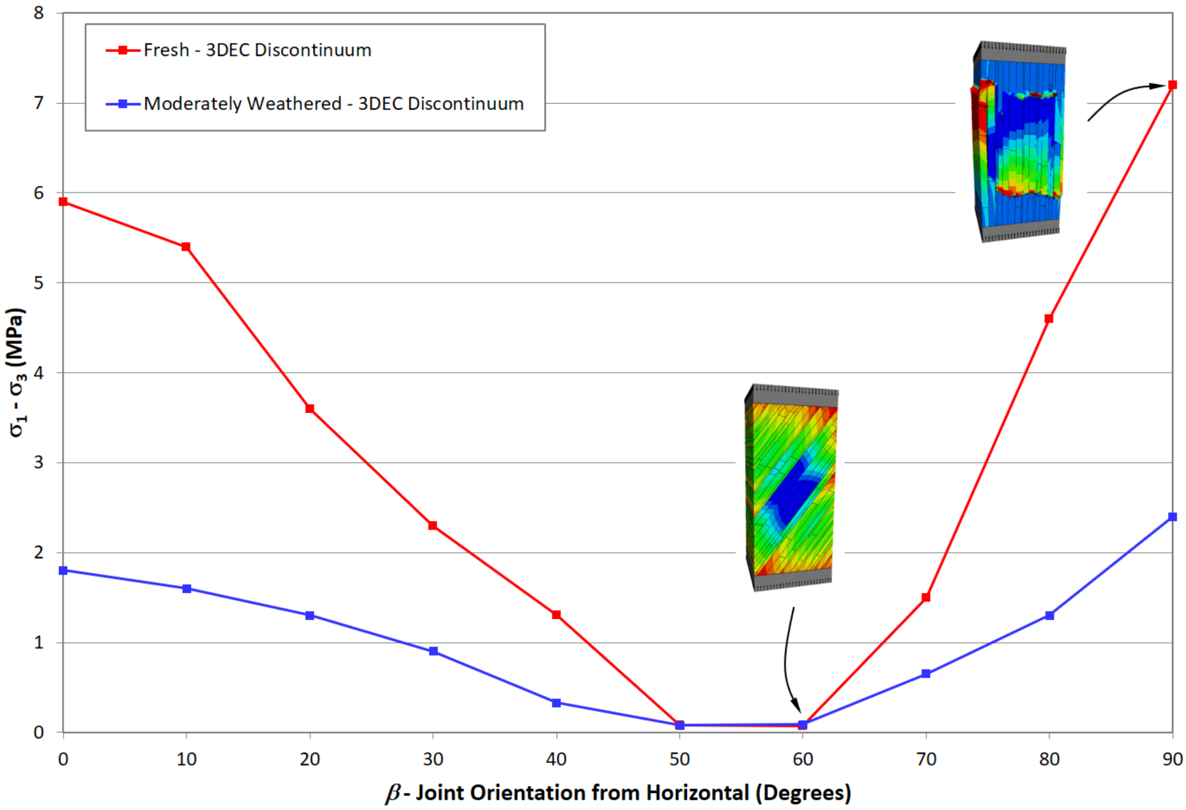

Figure 7 –Anisotropic response for the fresh and moderately weathered Melbourne Formation

3.3. Calibration of Anisotropic Strength with a UJRM Continuum Model

In order to derive the zone based UJRM properties for the fresh and moderately weathered Melbourne Formation material, the same testing procedure described in Section 3.2 was conducted in FLAC3D.

Assumptions used in the calibration procedure include:

(i) The results of the discontinuum analyses accurately quantify the rock mass anisotropic behavior.
(ii) The actual bedding plane cohesion and friction angle must be used to describe the peak ubiquitous-joint strength to provide a close match to the shear strength of the rock mass under planar sliding conditions.
(iii) The matrix strength and deformation response must be calibrated to help compensate for the lack of length scale and stiffness parameters in the ubiquitous-joint formulation.

Within the UJRM samples 5% of the ubiquitous joints were rotated to be orthogonal to the bedding fabric. The inclusion of orthogonal ubiquitous joints was found by [6] to promote continuously variable strength with increasing β angles and also introduces some bending resistance within the ubiquitous joint system. Figure 8 illustrates the resulting U-shaped strength curve for the UJRM material, together with the results from the discontinuum simulations.

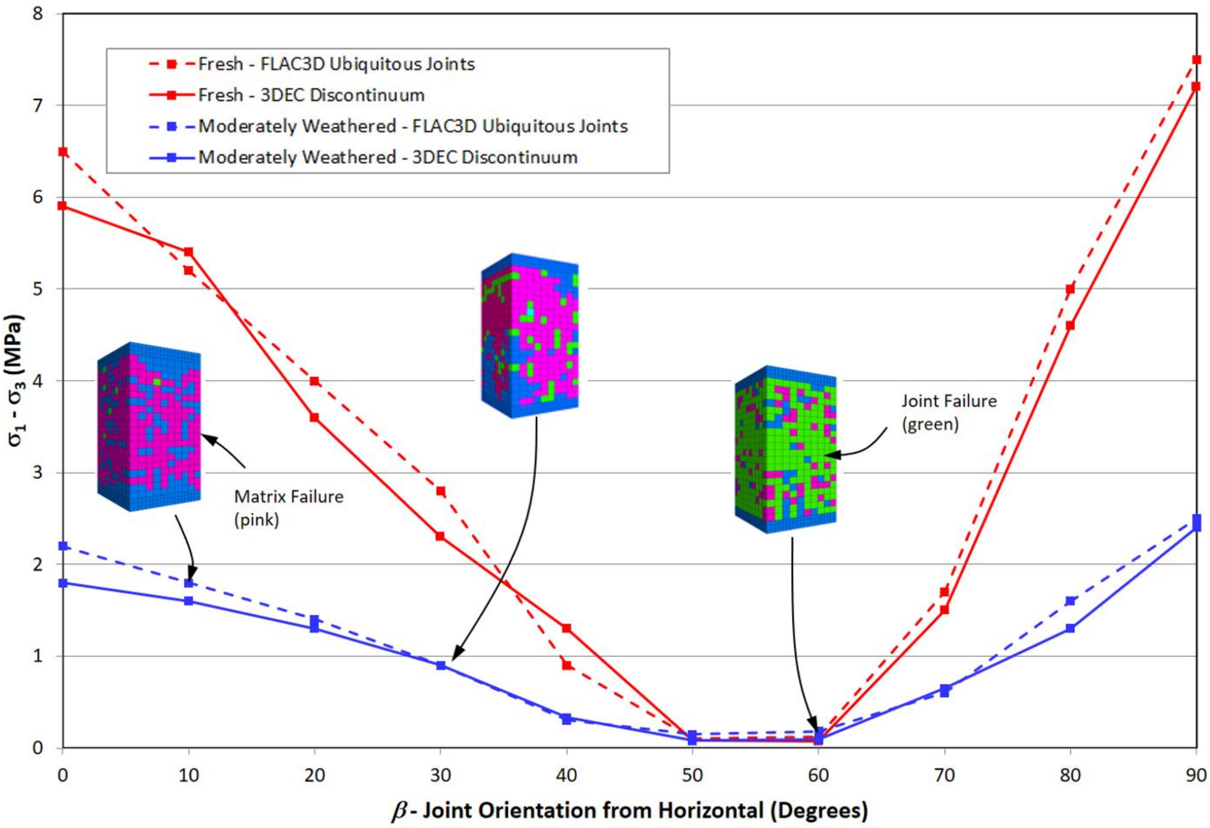

Figure 8 – Calibrated UJRM anisotropic strength response compared to the discontinuum anisotropic response for the fresh and moderately weathered Melbourne Formation

The calibrated UJRM input properties for the fresh and moderately weathered Melbourne Formation domains are presented in Table 2. A detailed discussion on the ubiquitous joint calibration procedure, matrix and joint softening is provided in [6].

Table 2 Calibrated UJRM input properties

Domain	***E [GPa]***	ν	**Matrix Properties**			**Joint Properties**	
			c_p **[kPa]**	ϕ_p **[deg]**	σ_t **[kPa]**	c_p **[kPa]**	ϕ_p **[deg]**
Moderately Weathered	3.8	0.26	283	48	28	10	25
Fresh	9.3	0.25	1295	55	129	50	30

4. LONSDALE STREET CABLE TUNNEL

The design and construction of a series of shallow cable tunnels and connection chambers in the Melbourne CBD was completed from 1978 to 1981. The 3.3 m diameter Lonsdale Street tunnel was excavated within moderately weathered Melbourne Formation with a roadheader at a depth of 5 to 8 m. Figure 9 illustrates a plan view of the tunnel layout and geological interpretation.

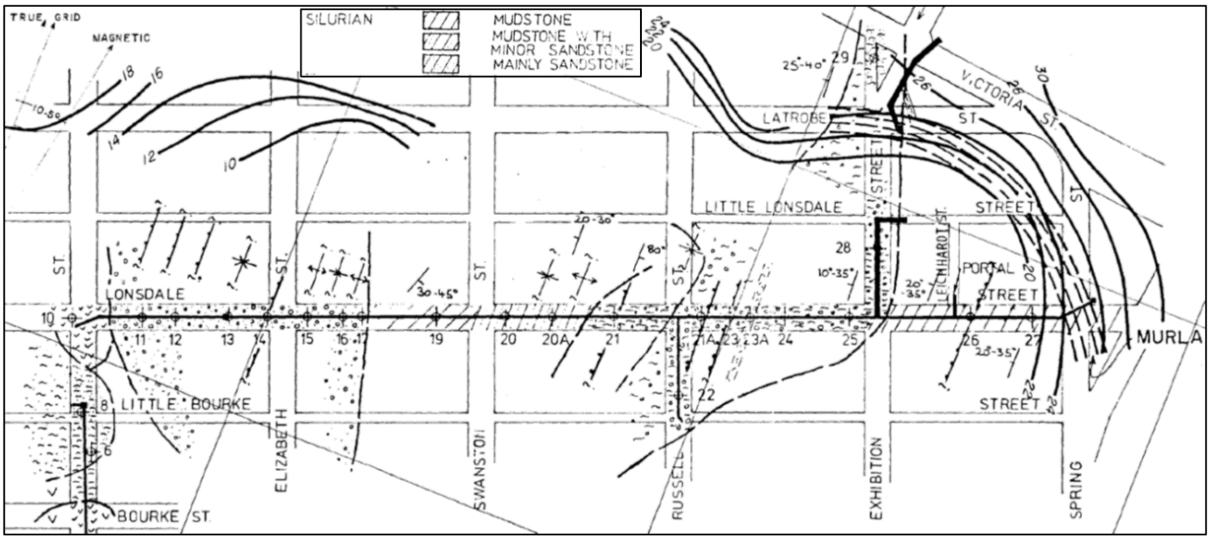

Figure 9 – Lonsdale Street tunnel layout and geological interpretation (after, [12])

The pale brown-grey mudstone is described by [12] as moderate strength (UCS = 4-10 MPa) with clay coated joint surfaces and clearly defined bedding. Figure 10 presents the core photo from Borehole 20 which was located near the corner of Lonsdale and Swanston Streets which, displays a competent rock mass. The rockmass encountered throughout the tunnel was above the watertable and was dry.

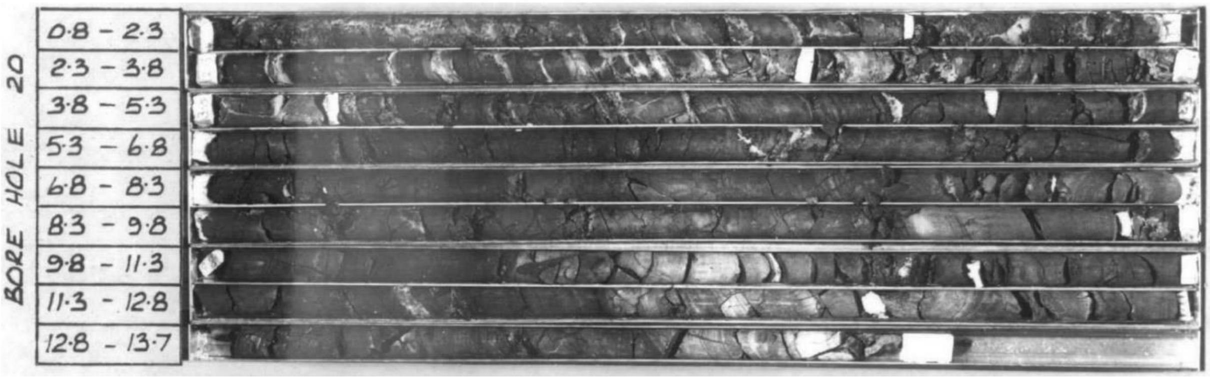

Figure 10 – Core photo from Borehole 20 (after, [12])

The face advance was limited to 1.5 m, with expedient installation of 1.0 m spaced steel sets and timber lagging. This excavation and support method resulted in minimal overbreak attributable to falling blocks from the crown or slumping along the walls. Subsidence of up to 2 mm is reported by [14] to be attributed to excavation of the tunnel.

In order to validate the UJRM properties for moderately weathered Melbourne Formation, a section of the Lonsdale Street tunnel in the vicinity of the Swanston Street intersection has been analysed. Figure 11 illustrates the typical tunnel cross-section together with the model geometry constructed based upon geological logging of Borehole 20. The moderately weathered Melbourne Formation was simulated with the UJRM model while the highly and extremely weathered material was simulated with an isotropic Mohr-Coulomb model.

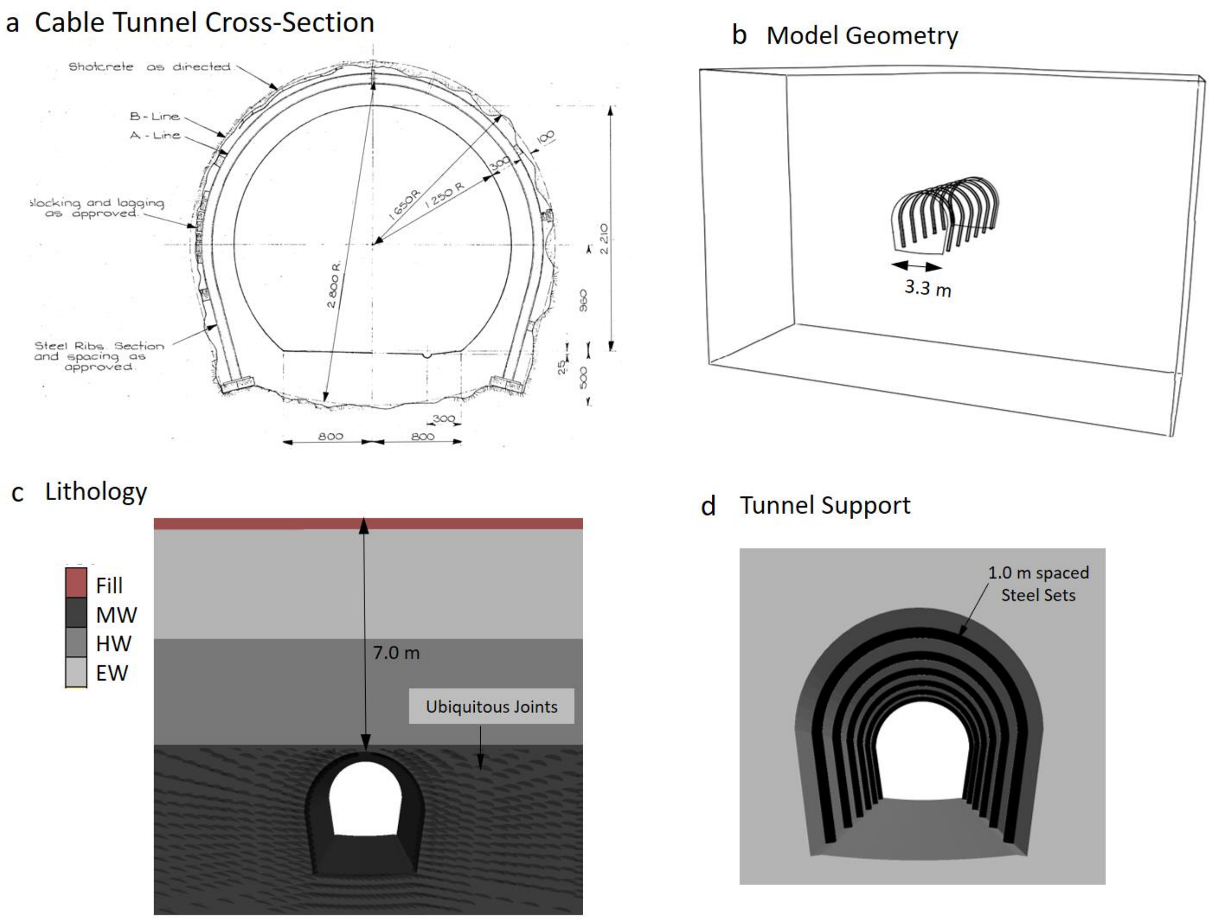

Figure 11 – Tunnel and model geometry

Figure 12 presents the displacement and yielding response of the model after excavation of the tunnel. The results provide a close match to the monitored surface subsidence, while minor tensile separation of the ubiquitous joints within the crown and floor of the tunnel is consistent with the very minor damage observed during construction.

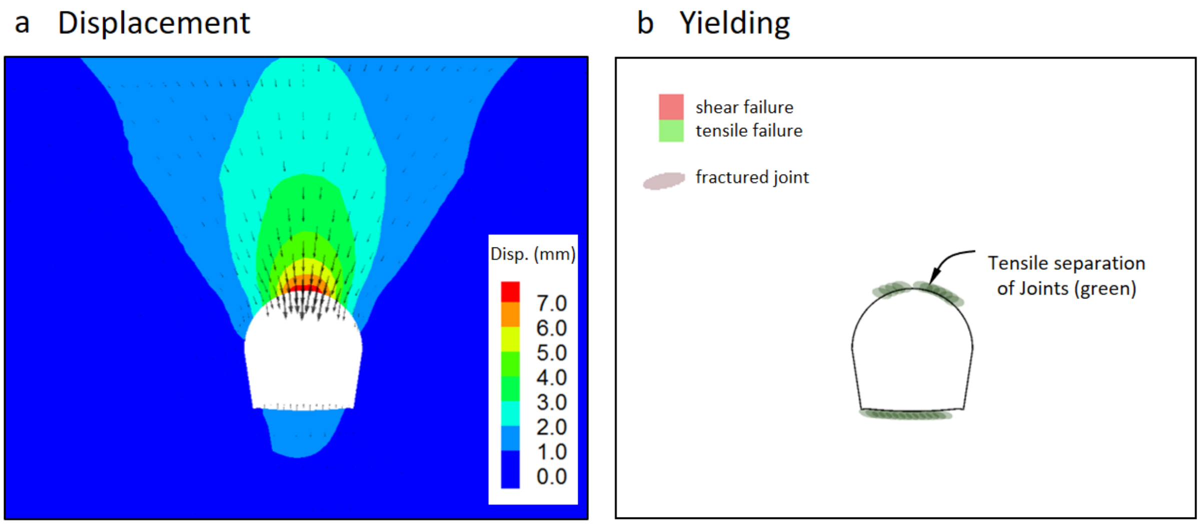

Figure 12 – Cable tunnel displacement and rock mass yielding

5. MELBOURNE UNDERGROUND RAIL LOOP, PLATE BEARING TESTS

During construction of the Melbourne Underground Rail Loop (MURL), a series of large-scale plate bearing tests were conducted to determine the load – deformation response of the Melbourne Formation. The results and interpretation of eight tests carried out at four locations in the lower tunnels near the corner of Spring Street and Victoria Parade, illustrated in Figure 13, are reported in [15]. The 914 mm diameter plates were loaded to produce bearing pressures up to 1.65 MPa.

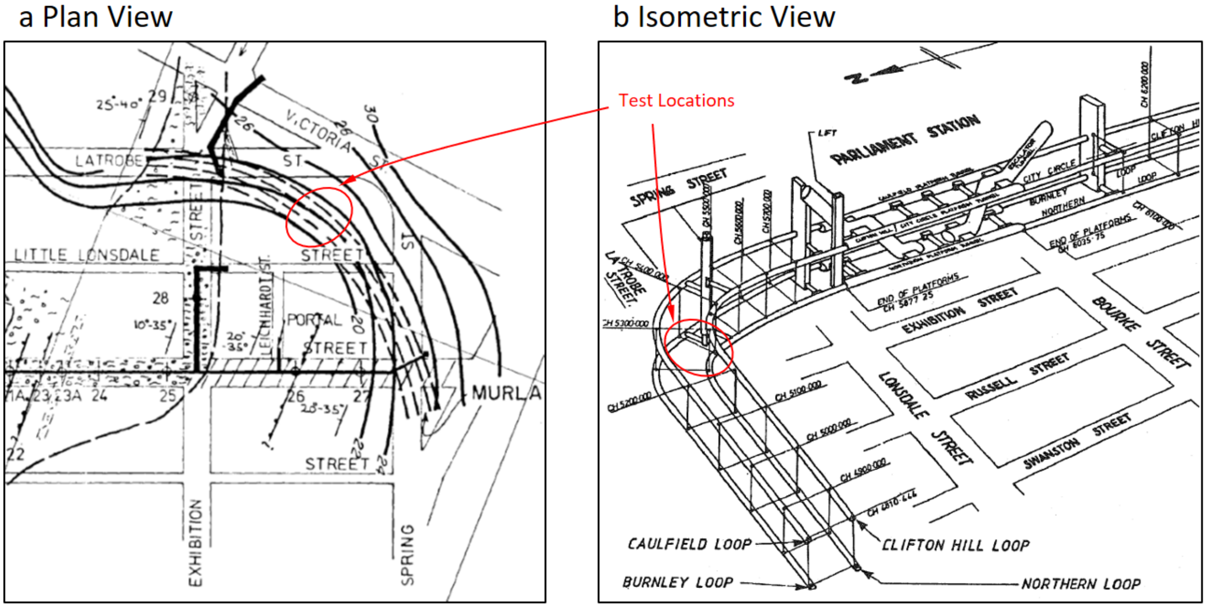

Figure 13 – a) Plan view of test location (after, [12]); b) Isometric view (after, [15])

Test Site 1 within the Burnley Loop Tunnel was situated within fresh Melbourne Formation with an intact UCS of 23 MPa. The anisotropic response of the rock mass whereby the in situ strength and modulus observed is dependent on the orientation of the bedding planes with respect to the tunnel axis is described in [15].

To validate the Melbourne Formation UJRM properties, the Test Site 1 plate loading test was recreated. Figure 14 illustrates the test arrangement and the three-dimensional model geometry. The UJRM model was used to simulate the fresh Melbourne Formation with a dip of 35^{o} and dip direction 20^{o} from the tunnel axis.

Figure 15a presents the displacement induced by the 1.65 MPa load which was applied in four loading increments. The rock mass yielding surrounding the tunnel is presented in Figure 15b. The failure mechanism is predicted to be predominantly tensile separation and shear along the bedding defects. As illustrated, the location of the disturbed zone is controlled by the orientation of the bedding fabric. [15] report that the depth of the disturbed zone at the test location was between 0.07 – 0.93 m, which is consistent with the simulated rock mass yielding.

Based upon the Boussinesq solution for the settlement of elastic masses presented in [16], the deformation moduli presented in Figure 16 have been calculated from the deformation – load response for the second, third and fourth loading increments. The model load – deformation response for the fresh and moderately weathered Melbourne Formation is observed to provide a close match to the measured response of Test Site 1.

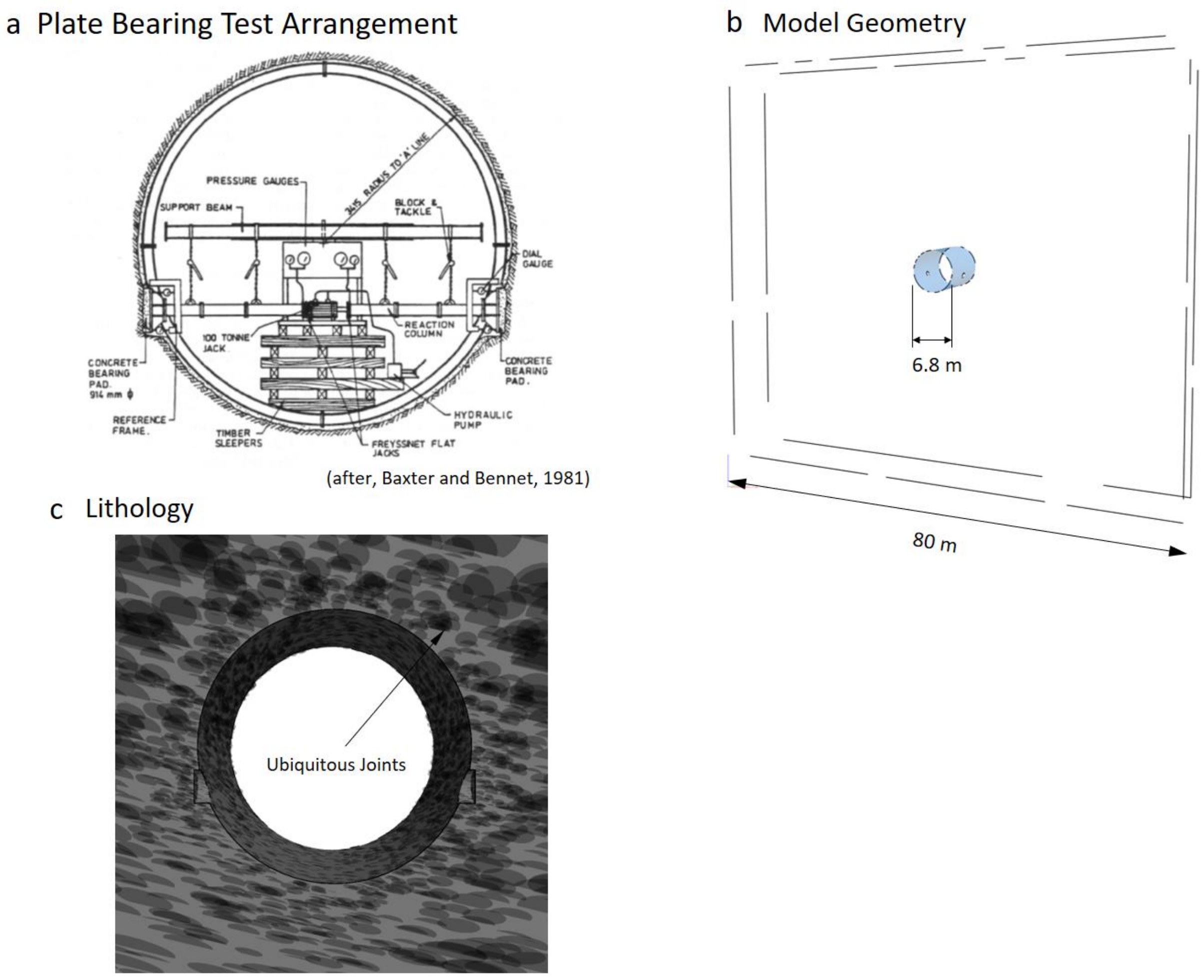

Figure 14 – Test arrangement and model geometry

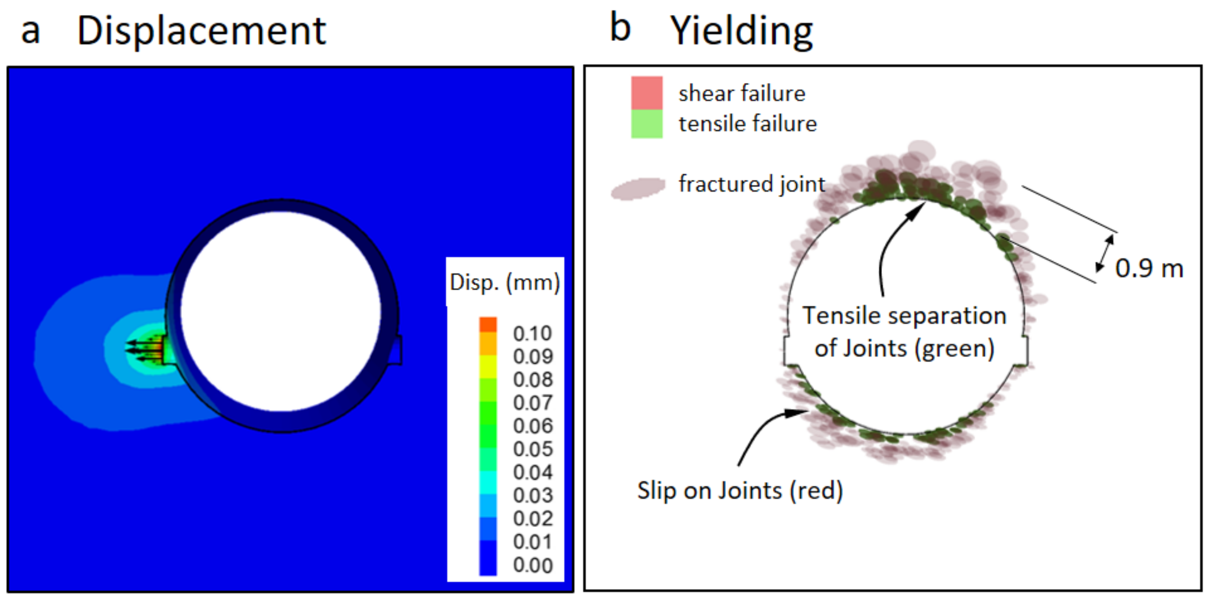

Figure 15 – a) Deformation response to plate loading; b) rock mass yielding

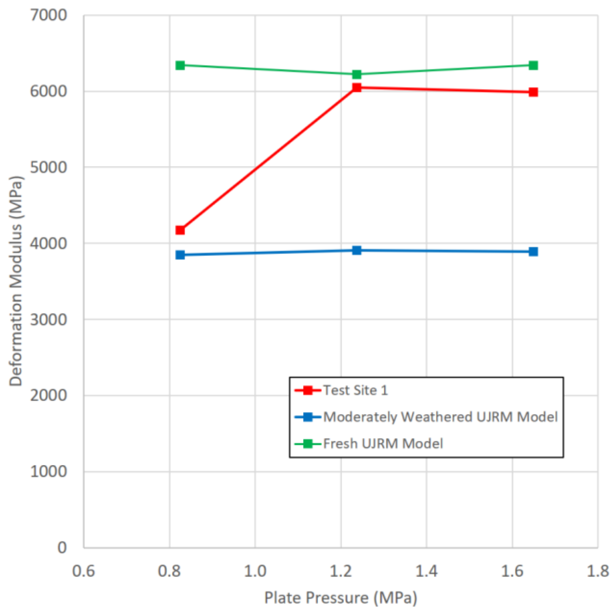

Figure 16 –Comparison of model deformation response to plate loading Test Site 1

6. CITY LINK DOMAIN TUNNEL

The 16 m wide City Link Domain Tunnel was constructed from 1996 to 2000 within the Melbourne Formation. The surface settlement monitored above the tunnel in the Kings Domain is reported in [17]. The maximum surface settlement recorded was 18 mm, while most points measured were between 3-10 mm. Approximately 16 mm convergence in the crown of the tunnel was measured.

At the monitoring location, the crown is located within highly weathered Melbourne Formation while the invert is within moderately weathered Melbourne Formation. The primary support installed at the monitoring location consisted of 350 mm shotcrete and 1.2 m spaced steel sets.

To validate the UJRM properties for moderately weathered Melbourne Formation, a model was constructed to simulate the surface settlement and tunnel convergence within the Domain Tunnel. Figure 17 illustrates the three-dimensional model geometry. The UJRM model was used to simulate the moderately weathered Melbourne Formation with a dip of 35º and dip direction 20º from the tunnel axis.

Figure 18 presents the response of the model which provides a close match to the surface settlement and tunnel convergence reported by [17].

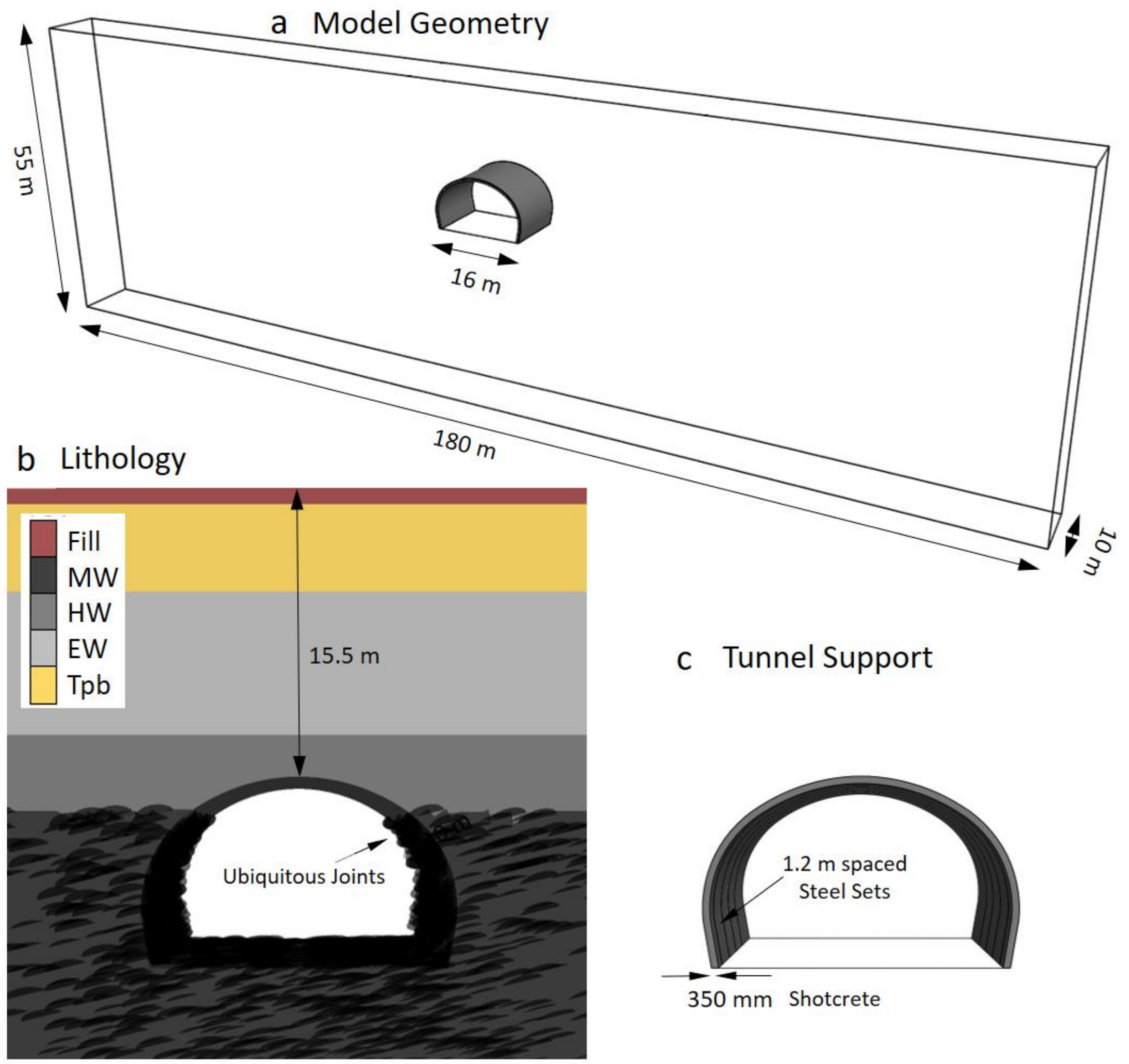

Figure 17 –Domain Tunnel model geometry

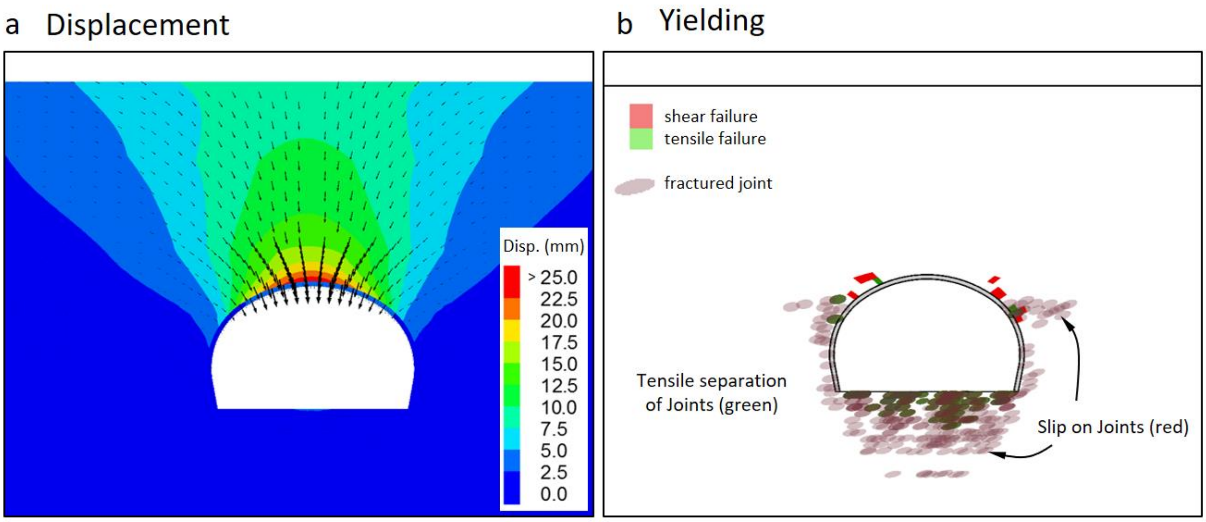

Figure 18 –Domain Tunnel model response

7. SUMMARY AND CONCLUSIONS

Discontinuum analyses will always provide the most rigorous assessment of anisotropic rock mass strength and deformation behavior. However, when large-scale analysis of anisotropic rock masses dictate the need for a continuum based Ubiquitous-Joint or Subiquitous model, careful calibration of the material response to a series of discontinuum numerical experiments provides significant insight, understanding and robust modeling results.

Calibration of UJRM properties for fresh and moderately weathered Melbourne Formation and validation of the modelling methodology against the measured and observed response of tunnel excavations throughout Melbourne provides confidence in the analysis of future tunnel excavations in the Melbourne Formation.

8. ACKNOWLEDGEMENTS

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