

Influence of Fracture Characteristics and the Use of Network Connectivity Index on Synthetic Rock Mass Strength Characterisation of Moderately Jointed Granite in Hong Kong

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ABSTRACT

Studies by Elmo & Stead (2010) and Stavrou et al. (2019) demonstrated that rock mass strength can be quantitatively characterised and directly linked to fracture characteristics. However, to date, rock mass classification and strength characterisation processes remain largely inductive, relying on empirical methods. It has been identified that this process is influenced by subjectivity and engineering judgement. With the rise of computing power and numerical modelling tools, engineers tend to apply and extend the use of rock mass classification system to determine rock mass strength and parameters in more advanced analyses. Typically, assessment of rock mass strength is undertaken by correlating different rock mass classification systems with the Hoek-Brown criterion for engineering and design purposes. Fracture characteristics; in terms of intensity and trace lengths, are rarely analysed in detail. This study addresses this gap by evaluating the influence of fracture characteristics on rock mass strength. The focus is on the assessment of unconfined compressive strength (UCS) of moderately jointed granite, based on actual tunnel face mapping records. Virtual large scale UCS tests on Synthetic Rock Masses (SRM), which consist of Voronoi Grain-Based Models (GBM) and explicit fractures, are undertaken to determine the rock mass strengths. The results indicate that fracture characteristics poses significant influence on the SRM strengths and demonstrate that rock mass strength characterisation can be directly assessed through the Network Connectivity Index (NCI, Elmo et al. (2021), which considers explicit assessment of fracture intensity & trace lengths. Through clear correlations between rock mass strength and NCI values, this paper demonstrates that NCI provides a more robust and objective alternative to the commonly used Q'-GSI correlations in deriving rock mass strength. The findings demonstrate the importance of integrating detailed fracture assessment into rock mass classification and mapping processes, to improve reliability of rock mass strength and parameters prediction for engineering purposes.

1 INTRODUCTION

Putting a number to geology in assessing rock mass strength and behaviour is considered an important step by engineers for rock engineering and design purposes. This certainly requires rigorous assessment to characterise rock mass condition and to determine appropriate rock mass parameters that can reflect its behaviour. This is particular important given the increasing reliance on numerical modelling in rock engineering projects. Errors in parameter input may affect engineering solutions in both safety and economical spectrum. In moderately jointed, strong rock mass like Hong Kong granite; rock mass characterisation and parameters determination present a significant challenge, which may not be able to be addressed solely based on conventional method.

Based on Middleton Mine data and through a series of numerical analyses adopting Discrete Fracture Network (DFN) and Finite-Discrete Element Method (FDEM), Elmo & Stead (2010) has demonstrated that existing natural fractures (discontinuities) control the potential failure modes and peak strengths of moderately jointed, slender, hard rock mine pillars in low confinement conditions. Their study showed that pillars with higher areal fracture intensity (P_{2l} = total fracture lengths / mapping window area) exhibited lower axial strengths. The strengths of slender pillars are also significantly influenced by the orientation of the discontinuities relative to the loading direction, particularly when inclined discontinuities are present. The FDEM results further indicated that P_{2l} values could serve as an indicator of the structural character of the

rock mass and reliable measure of rock mass strength within the GSI approach. In separate works, Stavrou et al. (2019) also demonstrated the importance of fracture intensity in the moderately jointed rock with incomplete discontinuities in understanding the complete rock mass failure mode in this situation. Their numerical analysis of the large-scale Uniaxial Compressive Strength (UCS) tests demonstrated that there is a progressive strength reduction with increasing fracture intensity & persistence and decreasing fracture strength. These findings emphasise the importance of collecting detailed fracture data during site investigation and face mapping. Detailed assessment of natural fractures (e.g., discontinuities, joints) provides a more objective and quantitative approach to determining rock mass strength determination, it is directly linked to fracture characteristics. This method provides greater reliability compared to indirect assessments and secondary indicators, such as RQD or block size estimation.

Building on the extensive analyses by Elmo & Stead (2010), Elmo et al. (2021) introduced Network Connectivity Index (NCI) as a more quantitative and objective alternative for rock mass classification; based on as-mapped fracture intensity and density, and intersection density observed in rock masses. The NCI serves as an analogue to the blockiness descriptors in other systems, e.g. RQD/ J_n in the Q-system, joint spacing in the RMR system, and the vertical axis in the GSI system. By relying on directly mapped fracture data, the need for interpretation and subjective judgment associated with empirical methods can be minimised and reliability of rock mass characterisation process can be improved.

The paper investigates the effect of fracture characteristics and the applicability of NCI method in the rock mass strength characterisation process through a series of virtual large scale Unconfined Compressive Strength (UCS) tests on Synthetic Rock Masses (SRM) of moderately jointed granite based on actual tunnel face mapping data. The results of the study indicate that NCI offers a more robust approach to rock mass strength characterisation process, indicated by clear correlation between NCI and SRM strengths (thus, interpreted GSI values). The paper also highlights the limitations of conventional method relying on Q'-GSI correlations for estimating rock mass strength. The absence of a correlation between as-mapped Q' values and SRM strengths demonstrates the disconnect in the rock mass characterisation process and the influence of subjective interpretation, raising concerns about the reliability of traditional approaches and emphasising the need for an alternative approach.

2 VIRTUAL UCS TEST ON MODERATELY JOINTED GRANITE

2.1 Assessed Rock Mass Conditions

The study in this paper focuses on typical moderately jointed granite in Hong Kong and the adopted conditions are based on actual tunnel face mapping results on site. The representative data are obtained from a 100-m stretch of tunnelling, excavated with Drill & Blast (D&B) method with typical advance length of 5 m. This results to twenty (20) tunnel faces and mapping records, shown in Figure 1. The span and the height of the tunnel is 16.7 m and 11.4 m, respectively. Table 1 provides the results of geotechnical mapping on site and the resulting Q-values of each face.

2.2 Calibration of the Grain Based Model (GBM) and Natural Fracture (Joint) Shear Strength

Virtual UCS tests are undertaken adopting the SRM model based on the as-mapped conditions, assuming pillar scenario with a width-to-height ratio of 0.4. The pillar size shown as blue in Figure 1 is 4 x 10 m (width x height). This condition is chosen since it is essentially consistent with standard laboratory UCS samples of which the results are utilised to determine σ_{ci} of the Hoek-Brown criterion, one of the first few steps and a key element to derive rock mass strength. Also, in such slender pillars, failure is predominantly controlled by naturally occurring discontinuities, in contrast to wider pillars, where failures are more complex with a combination of brittle and shearing processes (Elmo & Stead, 2010). The virtual UCS tests for this study are carried out using UDEC ver. 6.0 (Itasca, 2019). For the SRMs, the intact rock is modelled as Voronoi Grain-Based Model (GBM), and the mechanical behaviour and presence of fractures are explicitly represented.

The GBM aims to model the intact rock conditions using 2D voronoi tessellations (random poly-crystals) to simulate crack damage development through initiation and propagation of micro fractures along the grain boundaries (Ghazvinian et al., 2014). To allow for failure to occur only at contacts between the grains, elastic grains are assumed (Itasca, 2011). The grain size is 250 mm, and the grain contacts are modelled using simple

Coulomb slip joint model. Iterative processes in determining micro properties according to Potyondy & Cundall (2004) are adopted until the desired macro properties are achieved. In addition to this, the micro properties are also determined to simulate Cohesion-Weakening-Friction-Strengthening (CWFS) behaviour. Published lab-scale UCS data by Wan (2018) has been used as a benchmark. For further virtual analyses of the SRMs, the intact rock strength and σ_{ci} in such large rock pillar is assumed to be the same as the lab-scale UCS result reported by Wan (2018), with no correction due to size-effect.

Table 2 presents the calibrated parameters of GBM. The virtual UCS test set up as well as the failed state and associated crack coalescence are presented in Figure 2. Figure 3(a) shows a reasonably good agreement between the stress-strain curve of the intact pillar and the curve obtained by Wan (2018) using PFC. The CWFS behaviour can be observed in Figure 3(b), particularly where the crack initiation and crack coalescence occur. The stress level for Crack Initiation level and Crack Damage are consistent with typical brittle rocks.

Table 1 Mapping Records of the Tunnel Faces

Models	RQD	Jn	Jr	Ja	Jw	SRF	Q
Model 01	90.0	6.0	1.5	1.5	1	1	15.00
Model 02	90.0	6.0	1.5	1.5	1	1	15.00
Model 03	95.0	6.0	1.5	1.5	1	1	15.83
Model 04	95.0	6.0	1.5	1.5	1	1	15.83
Model 05	90.0	6.0	1.5	1.5	1	1	15.00
Model 06	95.0	9.0	1.5	1.5	1	1	10.56
Model 07	95.0	6.0	1.5	1.5	1	1	15.83
Model 08	95.0	6.0	1.5	1.5	1	1	15.83
Model 09	95.0	6.0	1.5	1.5	1	1	15.83
Model 10	95.0	6.0	1.5	1.5	1	1	15.83
Model 11	100.0	6.0	1.5	1.5	1	1	16.67
Model 12	100.0	12.0	1.5	1.5	1	1	8.33
Model 13	100.0	6.0	1.5	1.5	1	1	16.67
Model 14	95.0	6.0	1.5	1.5	1	1	15.83
Model 15	85.0	12.0	1.5	1.5	1	1	7.08
Model 16	90.0	12.0	1.5	1.5	1	1	7.50
Model 17	90.0	12.0	1.5	1.5	1	1	7.50
Model 18	95.0	12.0	1.5	1.5	1	1	7.92
Model 19	100.0	6.0	1.5	1.5	1	1	16.67
Model 20	100.0	6.0	1.5	1.5	1	1	16.67

Table 2 Calibrated Parameters of the GBM in This Study

Micro Parameters (Grain Contacts)								Grain Parameters	
kn [GPa/m]	ks [GPa/m]	c_p [MPa]	c_r [MPa]	T_p [MPa]	T_r [MPa]	ϕ_p [°]	ϕ_r [°]	E [GPa]	ν
4,000	3,000	123	0	18	0	5	10	24	0.2
Laboratory Macro Properties (Wan, 2018)									
UCS [MPa]								189.42	
Young's Modulus [GPa]								22.0	

Natural fractures (joints) based on mapping records are explicitly modelled in the subsequent virtual tests on the SRMs. The adopted shear strength of the fractures is derived considering various Direct Shear (DS) tests around the tunnels. Back-analyses of the lab-scale DS tests are performed to determine the parameters. Continuously-Yielding-Joint Model (CYJM) (Cundall & Hart, 1984) is adopted to simulate fracture behaviour under DS tests. The CYJM is considered more realistic than the standard Mohr-Coulomb joint model, as it considers some nonlinear behavior observed in physical tests. Table 3 summarises the calibrated parameters. Figure 4 presents both the comparisons between stress-displacement curves obtained from the model and lab-

scale DS tests (a), and comparisons between shear strength envelopes of the model and various shear strengths from lab tests (b).

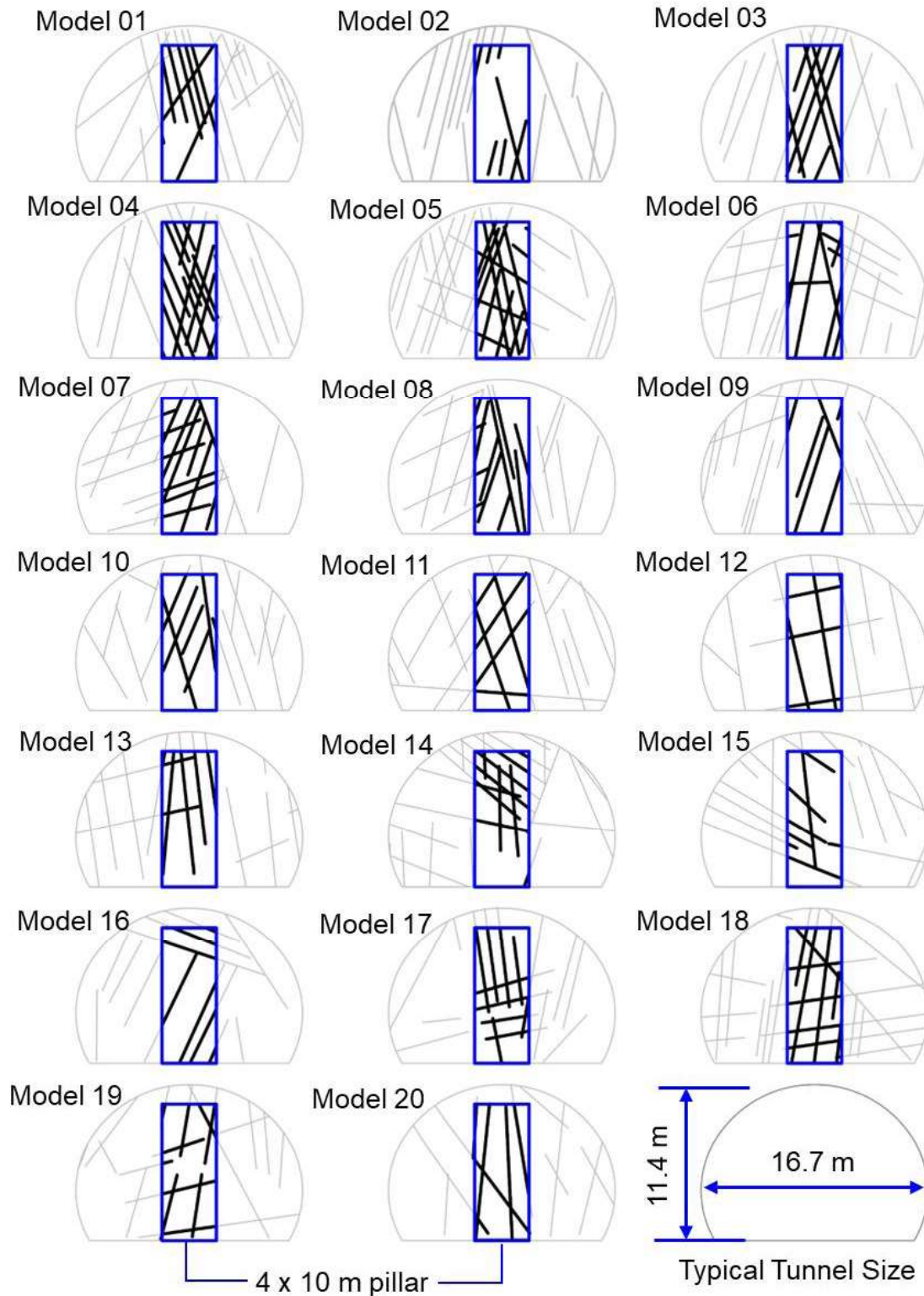


Figure 1: As-Mapped Tunnel Face and Adopted SRMs for Virtual UCS Tests (Highlighted in Blue)

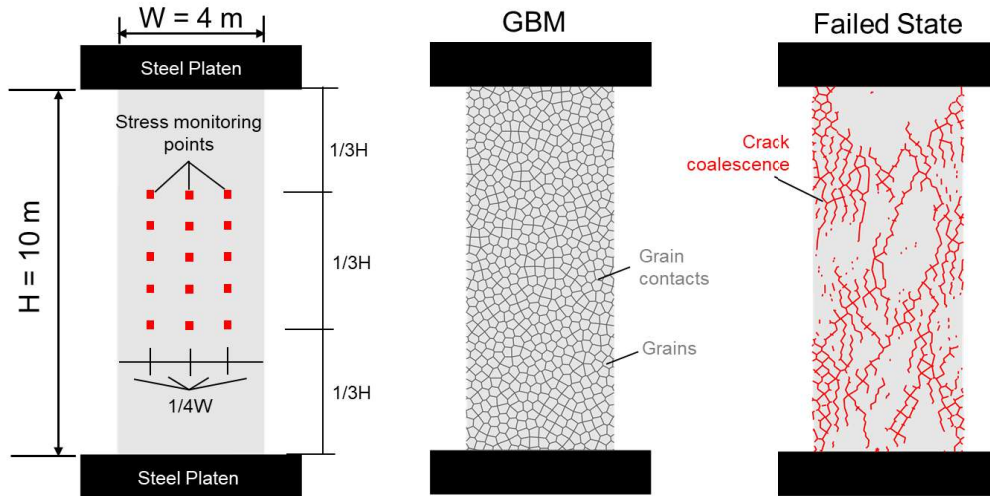


Figure 2: Virtual UCS Test Setup, the GBM and the Failed State of Intact Rock Pillar for Calibration

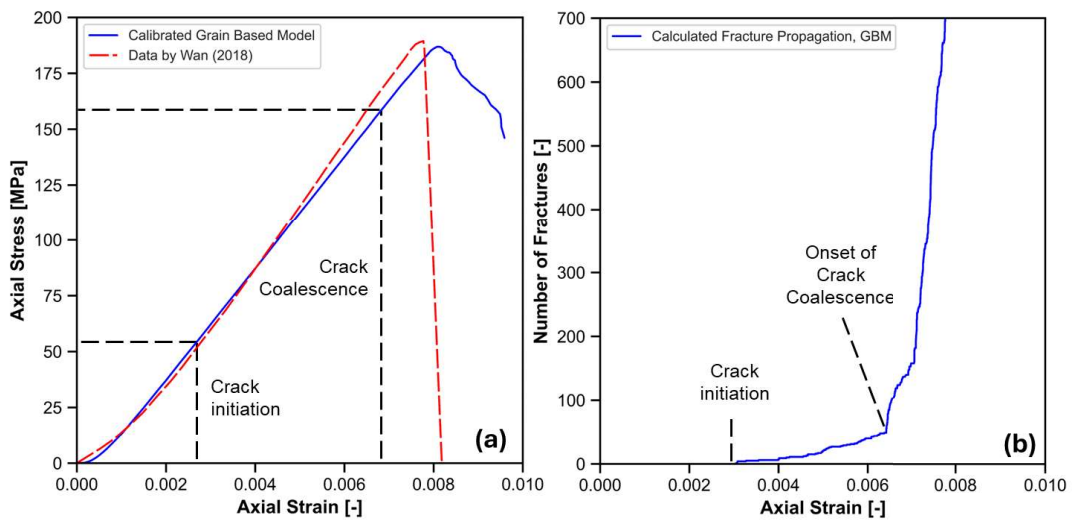


Figure 3: Stress-Strain & Fracture Propagation Plots of the Calibrated GBM (Intact Rock Pillar)

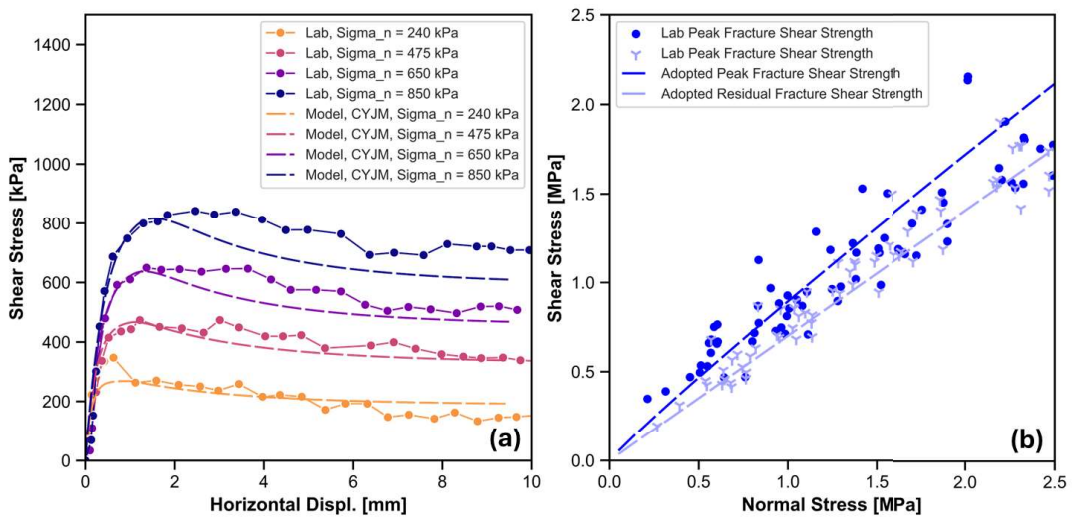


Figure 4: Fracture Shear Strength Calibration (a) and Adopted Peak and Residual Fracture Shear Strength (b)

Table 3 Calibrated CYJM Parameters for Fracture Shear Strength

kn [MPa/m]	ks [MPa/m]	c_p [MPa]	c_r [MPa]	ϕ_i [$^\circ$]	ϕ_r [$^\circ$]	roughness [m]
20,000	2,000	0	0	48	35	0.003

2.3 Virtual UCS Test Results and Comparisons with Rock Mass Quality Ratings

Following the calibrations, large scale UCS tests on 20 SRMs with explicit as-mapped fractures based on mapping results are undertaken, as discussed in Section 2.1. The sample is loaded at a rate of 50 mm/s in unconfined conditions. Both axial strain and peak unconfined axial stresses of the SRMs (UCSrm) are monitored and assessed. Upon obtaining the peak rock mass strengths, back-analysis is carried out to determine the associated GSI values for each SRM model. It should be noted that this process involves direct conversion from the obtained peak axial stress to associated GSI values, and no interpretation or engineering judgement is involved.

Figure 5 shows the post-peak conditions of the pillars and the resulting crack coalescence after virtual tests. This figure highlights the variability in failure modes across different SRM samples, which manifests as splitting (e.g. Model 13), shearing (e.g. Model 08), or combination of both (e.g. Model 02). However, it can be observed that majority of the failure modes are mostly driven by the natural fractures, which can be primarily attributed to the distribution, orientation, and intensity of natural fractures. Figure 6(a) summarises all the estimated rock mass strengths (UCSrm) from the virtual tests, including the interpreted GSI values; and Figure 6(b) presents the typical stress-strain curves of different SRMs with different interpreted GSI values. The use of NCI for rock mass strength characterisation are subsequently evaluated below.

3 INVESTIGATING THE INFLUENCE OF FRACTURE CHARACTERISTICS AND POTENTIAL USE OF THE NETWORK CONNECTIVITY INDEX (ELMO ET AL., 2021)

The Discrete Fracture Network (DFN) method is widely used for modelling rock masses, as it explicitly represents geological fractures, allowing for the estimation of potential block sizes within the rock mass. Miyoshi et al. (2018) demonstrated the application of DFN and block size analysis in estimating the blockiness axis of the GSI system (vertical axis). Haryono et al. (2024) demonstrated that it is possible to adopt DFN in the early design stage to estimate rock mass condition in terms of its fracture intensity and block sizes, and their study highlighted the benefits of DFN in improving reliability and enhancing the rock mass characterization process for underground engineering projects. Fracture intensity plays a crucial role in DFN modelling, as it directly influences the blockiness of a rock mass and, consequently, its mechanical behaviour. Fracture intensity is expressed as P_{ij} , where i refers to the dimension of the measurement region and j refers to the dimension of the sampling region (Dershowitz, 1998). For a 2D mapping region, P_{21} refers to areal fracture intensity that represents the summation of fracture lengths per sampling area.

By explicitly assessing the fractures and characterising UCSrm from Figure 6(a) based on P_{21} , inverse relationship between fracture intensity and the rock mass strength can be observed, as shown in Figure 7. Higher P_{21} , indicating higher degree of jointing, leads to lower rock mass strength and These results demonstrate the effect of rock mass fracture characteristic to the rock mass strength, similar to the findings by Elmo & Stead (2010). These findings will certainly benefit rock mass characterisation process on site as it eliminates the need for estimating RQD or block size, which involves convoluted processes. However, the resulting P_{21} -UCSrm relationship presented herein are based on specific load setup relative to the fracture orientations for this study. Elmo & Stead (2010) have demonstrated that rock mass behaviour is influenced by the relative orientation of the fracture and applied load. Rotation of loading axis relative to the general fracture orientation will change the failure modes and estimated UCSrm. Therefore, relying solely on P_{21} values is not ideal.

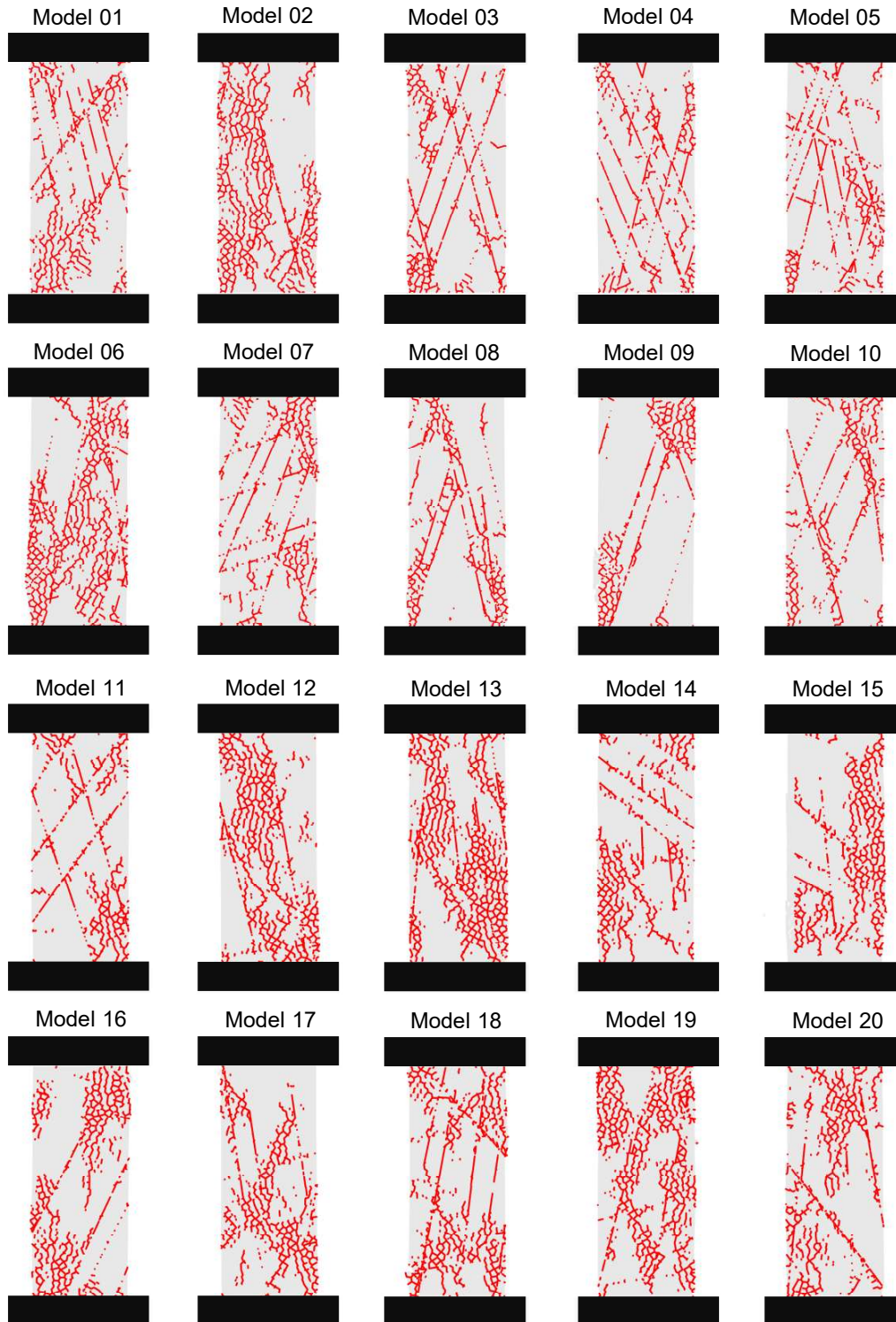


Figure 5: Crack Coalescence Observed in Post-Peak Condition After Virtual UCS Tests

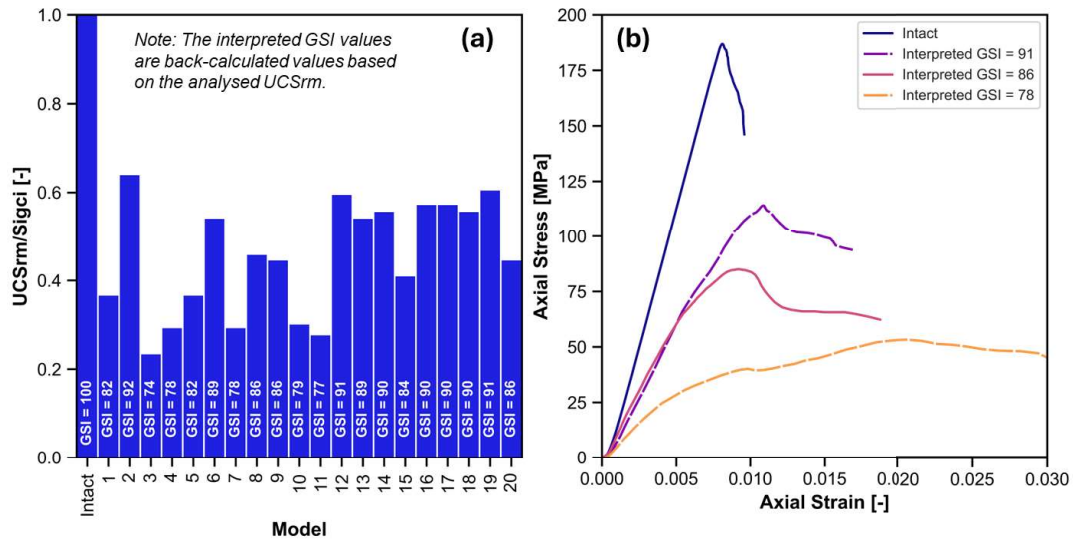


Figure 6: Estimated Strengths of All SRMs and Typical Stress-Strain Curves for Different SRMs with Different Interpreted GSI

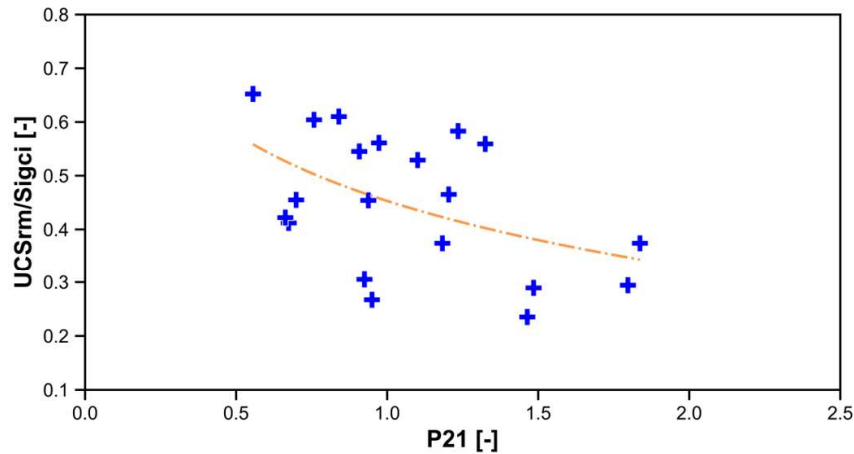


Figure 7: Relationship Between P_{21} and SRM Strengths

Xu et al. (2006), Alghalandis et al. (2015), and Sharif et al. (2019) highlighted the importance of considering fracture connectivity and intersections for rock mass characterisation. Based on this, Elmo et al. (2021) proposed to use the Network Connectivity Index in 2D (NCI_{2D}) for rock mass characterisation. NCI_{2D} in 3D space (NCI_{3D}) has been conceptualised by Elmo (2023), however it is not discussed in this paper. NCI_{2D} relies on three basic parameters, including P_{21} , P_{20} , and I_{20} ; where P_{20} , and I_{20} are the areal fracture density and areal fracture intersection, respectively. The determination of this parameters is shown in Figure 8. The term ‘X’ refers to the number of fracture intersections at different locations. The NCI_{2D} serves as an analogue to the blockiness descriptors in other systems, e.g. RQD/Jn in the Q-system, spacing in the RMR system, and the vertical axis in the GSI system., scale, size effects, and loading orientation are accounted in the NCI.

Combining the virtual test results, the back-calculated GSI, and the assessed NCI_{2D} , allows us to correlate GSI and NCI, as shown in Figure 9(a). The relationship demonstrates the effectiveness of using NCI for rock mass characterisation. The determination of the associated GSI ranges of a mapped face condition can be directly determined by collecting detailed fracture data and deriving the NCI values. Given the interpreted GSI values, a range of UCS_{rm} for certain rock mass condition can also be directly determined, as shown in Figure 9(b). This approach is considered more objective and simplifies the classification process while reducing reliance on subjective & convoluted interpretation. It also enhances consistency and reliability in rock mass strength estimation.

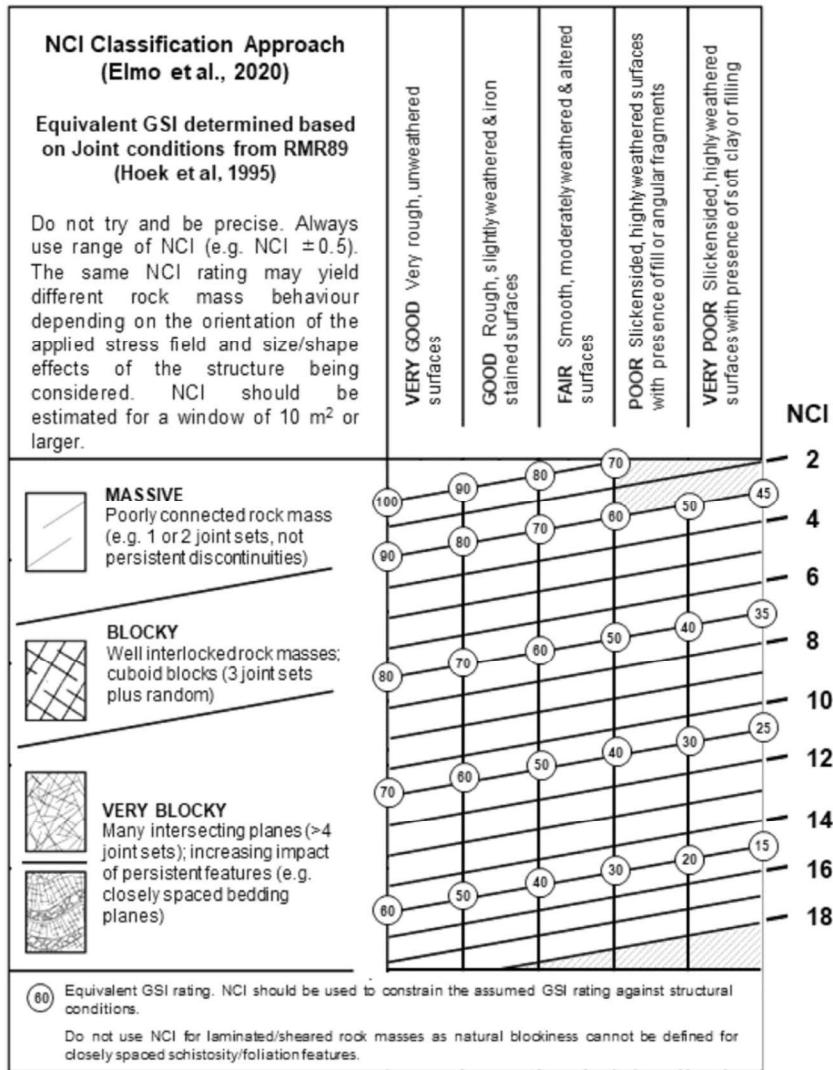
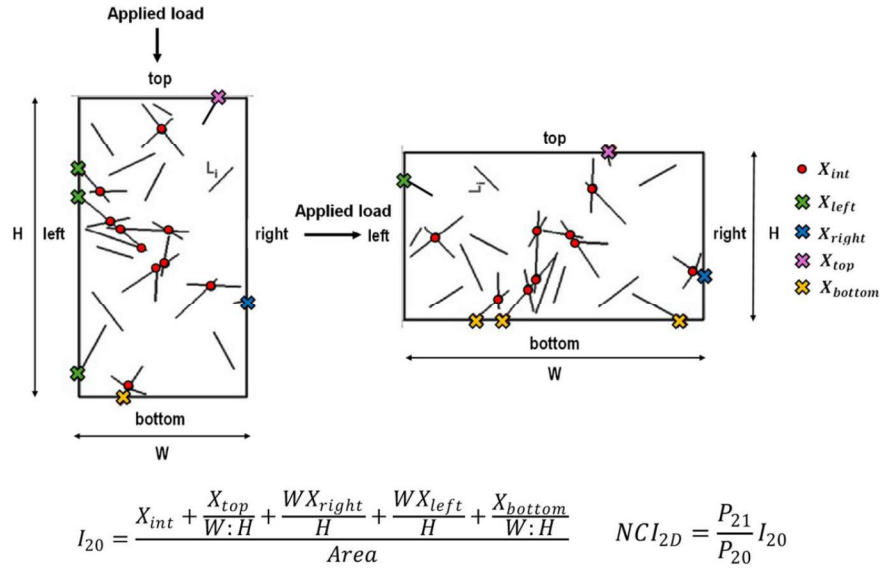


Figure 8: the Network Connectivity Index in 2D (NCI_{2D}) (Elmo et al., 2021)

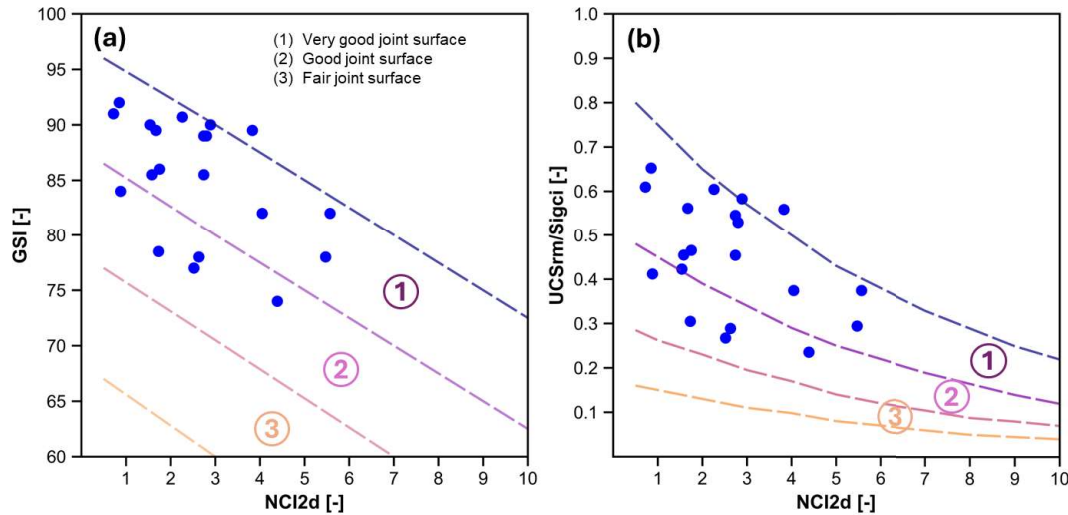


Figure 9: Relationship Between NCI_{2D} and GSI, and Between NCI_{2D} and Rock Mass Strengths

4 COMPARISON WITH CONVENTIONAL ROCK MASS CHARACTERISATION APPROACH IN DETERMINING ROCK MASS STRENGTH

Traditionally, typical underground engineering projects in Hong Kong adopt Q-values and Q-GSI conversion to determine rock mass parameters and strength for various analyses including numerical modelling. The correlation $GSI=9\ln Q'+44$ (Hoek, 1994) remains widely adopted, while for Hong Kong’s volcanic rocks, Wu et al. (2025) recently proposed $GSI=15\ln Q'+42$. While both systems are based on similar descriptors; i.e. blockiness and joint conditions; their underlying concept, essence, geological database, parameters and ratings differ (Yang et al., 2022). Q-system (Barton et al., 1974) was specifically developed as a rock mass characterisation and tunnel support design tool. Unlike the Q-system, GSI was originally to link the constants m and s of the Hoek-Brown failure criterion to rock mass conditions observed on site, and to determine representative Hoek-Brown parameters (Hoek, 1994; Hoek & Brown, 2018). The GSI system was developed without considering Rock Quality Designation (RQD) and place a greater emphasis on assessment of the lithology, structure, and condition of discontinuity surfaces obtained from visual examination. The heart of the GSI system is careful engineering geology description, which is essentially qualitative (Marinos et al, 2005). Despite the widespread adoption of Q-GSI conversions, there is no established equivalency criterion to validate their accuracy. Quoting Yang et al. (2022), “Classification systems are not universal, and their validity should not be set as default in every new project. Furthermore, empirical correlations potentially introduce more human and parameter uncertainties in the design process.”. Given these concerns, the assumption that the conventional classification ratings and conversions can be directly linked to rock mass physical properties, may be misleading and may influence the outcomes significantly.

Figure 10(a) demonstrates a counterintuitive trend and disconnect between as-mapped Q-values (Table 1) and rock mass strengths obtained from the virtual tests on the SRM models. It is naturally expected that lower Q-values are associated with lower rock mass strength due to increasing blockiness, however, the opposite trend emerges. This issue may stem from the inductive nature of the classification process and the influence personnel judgement during mapping, resulting in subjective results. Based on the parameters presented in Table 1, the main issues possibly arise the determination of the blockiness parameters (RQD/J_n). This has been highlighted by others, e.g. Erharter (2024). Additionally, many have pointed out several limitations of the use of RQD in rock mass characterisation, e.g Pells et al. (2017); which might further contribute to the inconsistencies. This underscores the setbacks of the conventional process and raises concerns about the reliability of Q'-GSI approach in determining rock mass strength. Figure 10(b) illustrates the limitations of this method and demonstrates inconsistencies in the estimated rock mass strengths. Regardless which correlation is adopted, notably, deviation in UCS_{rm} values for a certain GSI deviate by more than 50%. It can also be observed that the trend in rock mass strength classified based on Q'-GSI approach differ significantly from the theoretical line. In contrast, Figure 9 and process outlined in Section 3 provides more robust and objective framework for rock mass characterisation.

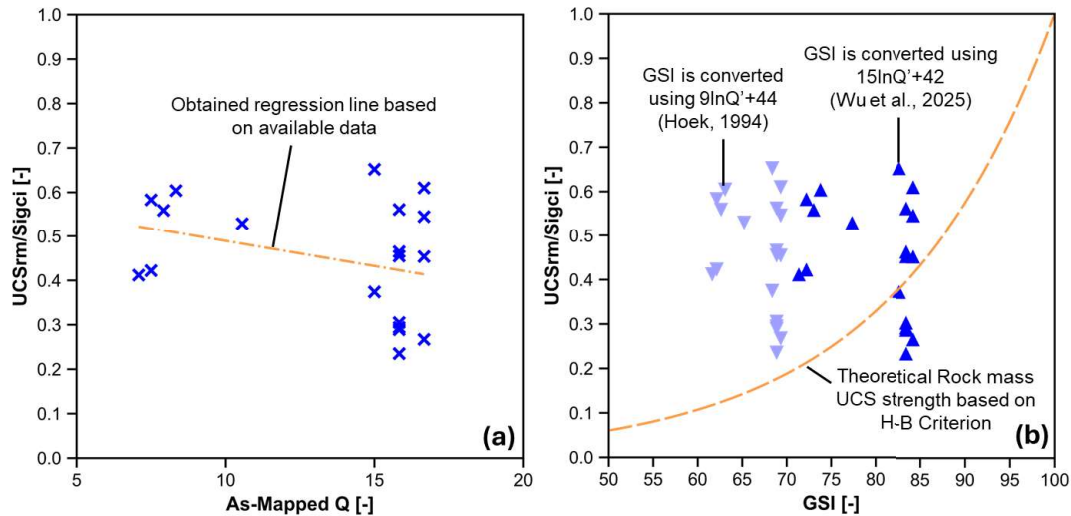


Figure 10: Counterintuitive Relationship Between Analysed SRM Strengths & Rock Mass Ratings (Q & GSI)

5 CONCLUSION

Through a series of virtual UCS tests on Synthetic Rock Masses (SRM) that incorporate actual as-mapped rock conditions, this study demonstrates that rock mass strength is fundamentally influenced by fracture characteristics. The results of this study confirm that rock mass strength can be reliably characterised using fracture-based descriptors. This is demonstrated by clear trend and correlations between P_{2l} , NCI (Elmo et al, 2021), and rock mass strengths described above. By integrating detailed assessment of fracture intensity, density, and connectivity; it is possible to establish a more objective and quantitative rock mass characterisation framework. The determination of GSI and associated rock mass strength through NCI method becomes more straightforward and robust; improving reliability in workflow and minimising the influence of convoluted and inductive process.

In contrast, this paper also demonstrates the limitations of traditional rock mass strength characterisation relying on Q'-GSI conversion. Despite its convenience, its dependence on subjective interpretation and engineering judgment coupled with input uncertainties, increases the risk of inaccurately determining rock mass parameters. The absence of clear trend and the disconnect between the analysed SRM strengths and as-mapped rock mass ratings, including the converted GSI, highlights the concerns about the reliability of Q'-GSI approach in determining rock mass strength. As the equivalency criterion between the two systems is not well established, this paper argues that rock mass classification and strength determination process should avoid the conventional approach (correlations between rock mass systems) as their application could affect engineering outcomes significantly. Ultimately, it should be recognised that different classification systems are established based on different concepts, parameters and ratings. Kaiser (2019) noted that these systems should be used independently of each other and not based upon correlations derived under different geological conditions.

It should be noted that this study focuses on uniaxial problems. For underground engineering projects, stress path around underground openings is more complex and rock mass strength is influenced by different stress in minor and major principal stress directions. Further studies are required to account for this condition.

REFERENCES

- Alghalandis, Y.F., Dowd, P.A. and Xu, C., 2015. Connectivity field: a measure for characterising fracture networks. *Mathematical Geosciences*, 47(1), pp.63-83.
- Barton, N., Lien, R. and Lunde, J.J.R.M., 1974. Engineering classification of rock masses for the design of tunnel support. *Rock mechanics*, 6, pp.189-236.
- Barton, N.R., 1988. Rock mass classification and tunnel reinforcement using the Q-system. In: Kirkaldie L. (ed.) *Rock Classification Systems for Engineering Purposes*, ASTM STP 984. American Society for Testing and Materials, Philadelphia, PA, 59-88.

- Barton, N.R., 2015. Forty years with the Q-system – lessons and development. Keynote Lecture, Underground Design and Construction Projects, Hong Kong Institute of Materials, Minerals & Mining.
- Cundall, P. A., and Hart., R.D., 1984. Analysis of block test no. 1 inelastic rock Mass behavior: phase 2 – a characterization of joint behavior (final report). Itasca Consulting Group Report, Rockwell Hanford Operations, Subcontract SA-957.
- Dershowitz, W.S., 1998. FracMan interactive discrete fracture feature data analysis, geometric modelling and exploration simulation. User Documentation.
- Elmo, D. and Stead, D., 2010. An integrated numerical modelling–discrete fracture network approach applied to the characterisation of rock mass strength of naturally fractured pillars. *Rock Mechanics and Rock Engineering*, 43, pp.3-19.
- Elmo, D., Yang, B., Stead, D. and Rogers, S., 2021. A discrete fracture network approach to rock mass classification. In *Challenges and Innovations in Geomechanics: Proceedings of the 16th International Conference of IACMAG-Volume 1 16* (pp. 854-861). Springer International Publishing.
- Elmo, D., 2023. The Bologna Interpretation of Rock Bridges. *Geosciences*, 13(2), pp.33–33.
- Erharter, G.H., 2024. Rock mass structure characterization considering finite and folded discontinuities: A parametric study. *Rock Mechanics and Rock Engineering*, 57(7), pp.5229-5249.
- Ghazvinian, E., Diederichs, M.S. and Quey, R., 2014. 3D random Voronoi grain-based models for simulation of brittle rock damage and fabric-guided micro-fracturing. *Journal of Rock Mechanics and Geotechnical Engineering*, 6(6), pp.506-521.
- Haryono, I.S., Rogers, S.F., Barrett, S.V.L. and McQueen, L.B., 2024. Improved reliability in rock mass characterisation for underground support design–Discrete fracture network model and site observation. *Tunnelling and Underground Space Technology*, 147, p.105740.
- Hoek, E. 1994. Strength of rock and rock masses. *ISRM News Journal*, 2, 4–16.
- Hoek, E., Carranza-Torres, C. and Corkum, B., 2002. Hoek-Brown failure criterion-2002 edition. *Proceedings of NARMS-Tac*, 1(1), pp.267-273.
- Hoek, E. and Brown, E.T., 2019. The Hoek–Brown failure criterion and GSI–2018 edition. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(3), pp.445-463.
- Itasca Consulting Group, Inc. (2019) UDEC — Universal Distinct Element Code, Ver. 6.0. Minneapolis: Itasca.
- Itasca, 2011. Long-term geomechanical stability analysis: OPG’s deep geological repository for low & intermediate level waste. Technical Report, NWMO DGR-TR-2011-17.
- Kaiser, P.K., 2019. From common to best practices in underground rock engineering. *Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019)*. CRC Press, Boca Raton, FL, 141–182.
- Miyoshi, T., Elmo, D. and Rogers, S., 2018. Influence of data analysis when exploiting DFN model representation in the application of rock mass classification systems. *Journal of Rock Mechanics and Geotechnical Engineering*, 10(6), pp.1046-1062.
- Pells, P.J., Bieniawski, Z.T., Hencher, S.R. and Pells, S.E., 2017. Rock quality designation (RQD): time to rest in peace. *Canadian Geotechnical Journal*, 54(6), pp.825-834.
- Potyondy, D.O. and Cundall, P.A., 2004. A bonded-particle model for rock. *International journal of rock mechanics and mining sciences*, 41(8), pp.1329-1364.
- Sharif, L.K., Elmo, D. and Stead, D., 2019. Improving DFN-geomechanical model integration using a novel automated approach. *Computers and Geotechnics*, 105, pp.228-248.
- Stavrou, A., Vazaios, I., Murphy, W. and Vlachopoulos, N., 2019. Refined approaches for estimating the strength of rock blocks. *Geotechnical and Geological Engineering*, 37, pp.5409-5439.
- Yang, B., Mitelman, A., Elmo, D. and Stead, D., 2022., Why the future of rock mass classification systems requires revisiting their empirical past. *Quarterly Journal of Engineering Geology and Hydrogeology*, 55(1), pp.qjeh2021-039.
- Wan, H.L.A, 2018. Numerical Simulation of UCS Test of Rocks Based on PFC3D Modelling. MSc. Thesis. The University of Hong Kong.
- Wu, P.K.K., Chan, C.T.H. and Tsui, R.W.S., 2024. A review of the Q-system and the GSI based on recent tunnel and cavern projects in Hong Kong. *Rock Mechanics and Rock Engineering*, pp.1-13.
- Xu, C., Dowd, P.A., Mardia, K.V. and Fowell, R.J., 2006. A connectivity index for discrete fracture networks. *Mathematical geology*, 38, pp.611-634.