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A numerical modeling approach for estimating the rock mass post-peak deformation modulus near a mine drift

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1 INTRODUCTION

The selection of a numerical method and a particular software tool is often dictated by a series of technical and practical trade-offs. The choice for a particular numerical method is based on its capacity to represent the problem boundary conditions, the material behavior, and the pertinent rock mass failure mechanisms. It follows that there could be more than one numerical method suitable for a particular problem. Irrespective of the choice of numerical model, there are considerable challenges in selecting appropriate input parameters. The situation is further compounded by the absence of appropriate techniques to determine large scale rock mass properties. The absence of applicable data is often conveniently overlooked and large-scale material properties are extrapolated from laboratory tests or derived from empirical correlations. This approach is sometimes justified, given that the selected input model properties are revised during the calibration process.

Of particular interest in this investigation is the way the Young's modulus (E) is estimated and introduced in a numerical model. In a laboratory setting, E is determined from the stress-strain curve of an intact rock specimen and is defined as the ratio of the change in axial stress to the change in axial strain. Fairhurst and Hudson (1999) note that although E is usually associated with the pre-peak portion of the stress-strain curve, it can also be determined in the post-peak region, and that it degrades gradually with increasing damage. The in-situ determination of E can be made through field tests, but they are generally time consuming and expensive, and their reliability is sometimes questionable (Hoek & Diederichs 2006). Consequently, there is a tendency to rely on empirical relationships whereby the in-situ rock mass deformation modulus is estimated based on rock mass classification systems. The reliability of any of these relationships is outside the scope of this paper.

The development of excavations results in a disturbance of the rock mass that can be conceptually divided into a fracture zone, plastic zone and elastic zone. The rock mass behavior can be significantly different in these zones. There is no consistent approach on how these variations are accounted for in numerical models. The most usual approach is to introduce a degradation or strength reduction logic in the post-peak region of the stress-strain curve (e.g. Fang & Harrison 2001). It is interesting to note that the deformation modulus is not usually modified during the numerical modelling process. It is possible that in certain cases this residual or post-peak deformation modulus may have a significant influence on the simulated rock mass behavior. Irrespective of its theoretical implications, there are significant practical limitations on how to capture the in-situ post-peak deformation modulus.

This paper introduces a numerical modelling approach to estimate the post-peak, or residual, rock mass deformation modulus. For this purpose, a continuum model was used to capture the results of a previously calibrated discontinuum model to arrive at the post-peak deformation modulus of a rock mass near an instrumented section of a mine drift. Given that the objective was to address some of the practical implications in determining the deformation modulus, a conscious decision was made to expand on a well-documented case study from an underground hard rock mine.

2 CASE STUDY

3DEC (Itasca 2016) was used to simulate an instrumented section of a drift at the George Fisher mine, Mount Isa, Australia. The details of this case study have been provided by Bahrani & Hadjigeorgiou (2018). The original objective was to gain an understanding of the behavior of ground support in response to the excavation of nearby stopes. The *3DEC* models were calibrated based on instrumentation data from the monitoring program conducted at the North site of the mine, as described by Sweby et al. (2016). Bahrani & Hadjigeorgiou (2018) considered several simplifications when constructing the *3DEC* models by focusing on the stopes close to the instrumented section of the drift. Furthermore, a simplified geometry was used for the drifts and stopes as shown in Figure 1a. Four excavations stages were used in the numerical simulations. Stage 1 introduced the drifts and stopes prior to instrumentation (stopes in grey color in Fig. 1a). Subsequently, reinforcement elements were introduced into the model to simulate the instrumented cables and rebar rock bolts at the North site (Fig. 1b). The displacements were then reset to zero, and Stopes 21, 23 and 29 (Fig. 1a) were excavated sequentially from Stage 2 to 4.

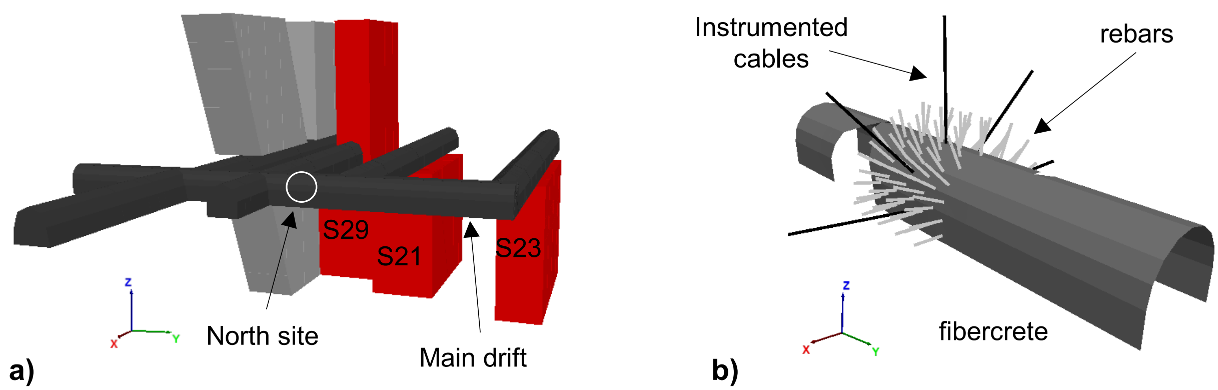

Figure 1. a) *3DEC* model showing the main drift and the stopes excavated prior to (in gray) and following (in red) the instrumentation at the North site; b); liner and cable elements used to simulate fibercrete, rock bolts and instrumented cables at the North site.

Both continuum and discontinuum models in *3DEC* were used for the analysis of this case study. A 24 m × 24 m × 8 m block was used to represent the rock mass near the instrumented section of the drift at the North site (top image in Fig. 2). In the continuum model, the rock mass in this block was simulated with very small zones using a ubiquitous-joint (UJ) constitutive model (left images in Fig. 2). In the discontinuum model, three joint sets were used to explicitly simulate the bedding planes, joints and intact rocks with Mohr-Coulomb properties (right images in Fig. 2). Both models were calibrated against drift convergence monitored using tape extensometer and rock mass deformation monitored using instrumented cables, following the excavation of Stope 29. It was found that the continuum model could only be calibrated by using strength properties much lower than estimated values from empirical approaches (GSI system). This model suggested extensive yielding of the rock mass surrounding the drift. As this was inconsistent with field observations, such extensive yielding predicted by the continuum model was deemed not representative. The discontinuum model provided more realistic results in terms of the extent of yielded zone than the continuum model.

Figure 3 illustrates the displacement profiles measured along the sidewall cables following the excavation of Stope 29, and those obtained from the calibrated discontinuum model. This figure demonstrates that the results of discontinuum model match reasonably well with the deformation measured along the instrumented cables. Table 1 summarizes the block and contact properties obtained from the calibration of the discontinuum model.

Table 1. Properties of calibrated *3DEC* discontinuum model.

Block (rock block) properties	Young's modulus (GPa)	76
	Poisson's ratio	0.31
	Cohesion (MPa)	8
	Tensile strength (MPa)	0.5
	Friction angle (°)	39
	Dilation angle (°)	19
Contact (joints) properties	Normal stiffness (GPa/m)	1.5
	Shear stiffness (GPa/m)	1
	Cohesion (MPa)	1
	Tensile strength (MPa)	0.01
	Friction angle (°)	30
	Dilation angle (°)	15

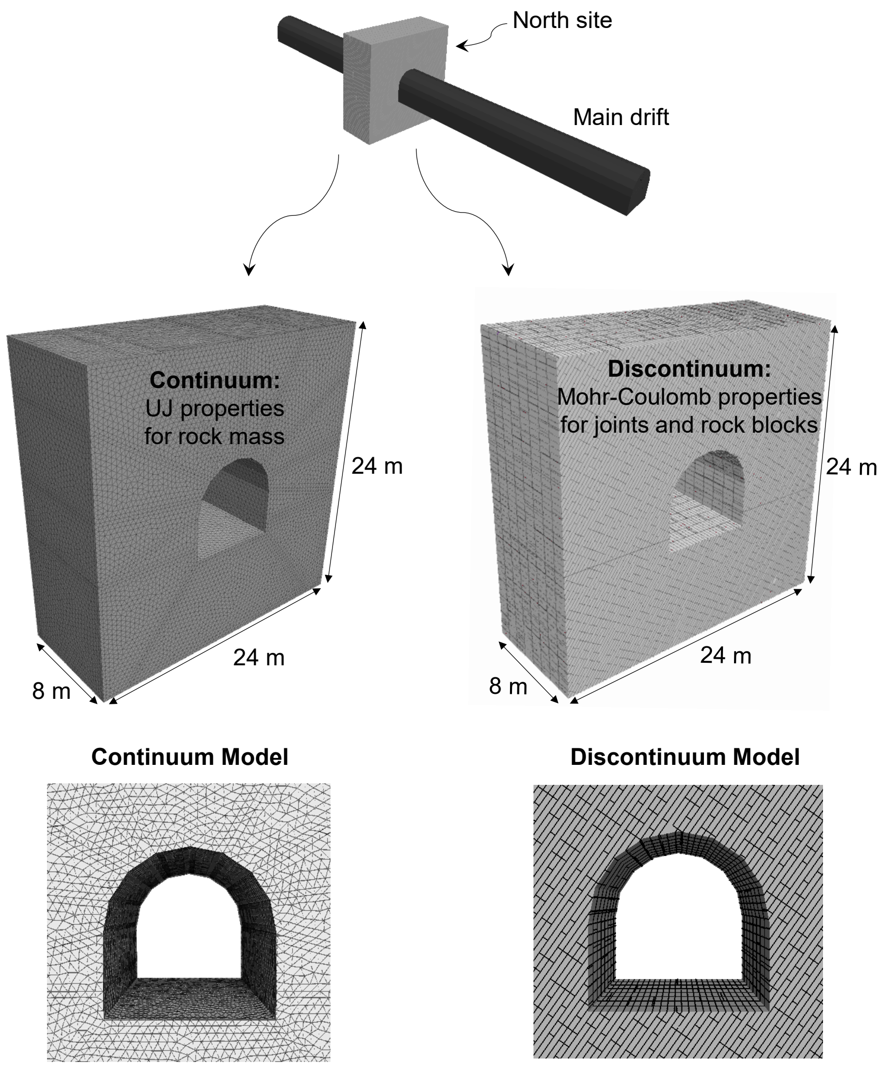

Figure 2. Main drift and block simulating the rock mass at the North site with small zones in continuum model (left) and three joint sets in discontinuum model (right).

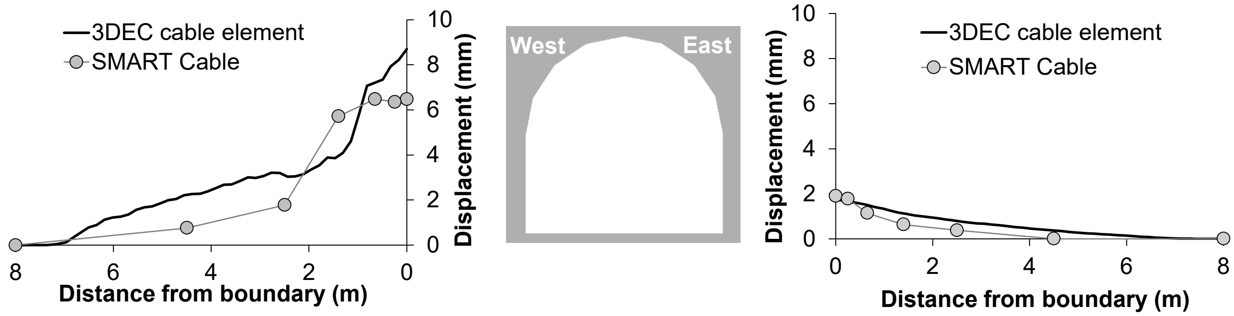

Figure 3. Comparison between axial displacements measured along sidewall cables and those from discontinuum model on: a) west; and b) east sides of the drift at the North site.

3 BACK ANALYSIS OF ROCK MASS RESIDUAL DEFORMATION MODULUS

The results of the calibrated discontinuum model showed that the excavation of the drift (i.e. excavation stage 1) resulted in yielding of the surrounding rock mass (Fig. 4). The simulated yielding corresponds to shearing and/or opening of joints as well as fracturing of the rock blocks. Following this stage, and prior to the excavation of Stopes 21, 23 and 29, the instrumented cables were installed. In effect, the rock mass surrounding the drift was at its post-peak state when the instrumented cables were installed, and monitoring began. Following the excavation of Stope 29, yielding of joints and rock blocks propagated further away from the drift. The calibration of the discontinuum model required adjusting the block and joint deformation properties to better capture the recorded behavior following the excavation of Stope 29. Therefore, the properties of the calibrated model correspond to the rock mass at its post-peak state. This implies that the block elastic modulus and joint stiffness values in Table 1 are in fact the post-peak deformation properties of the jointed rock mass.

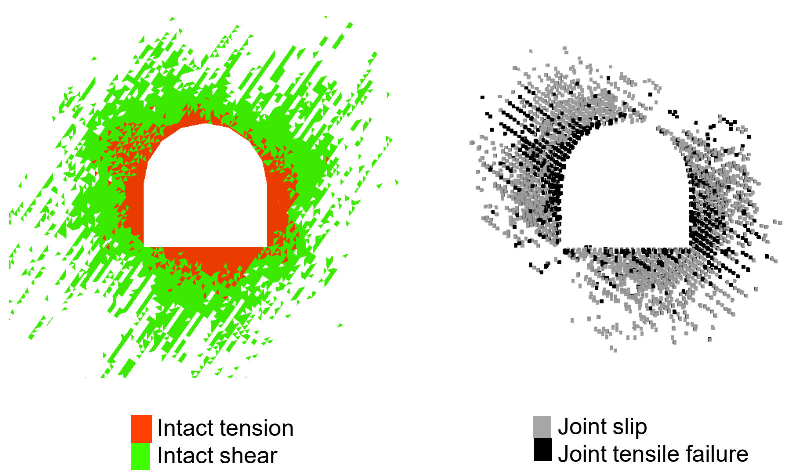

Figure 4. Extent of rock block (left) and joint (right) yielding from calibrated discontinuum model following the excavation of drift.

Further simulations were conducted to explore the possibility of estimating the deformation modulus of the rock mass at its post-peak state from the calibrated discontinuum model. Numerical simulations were conducted using both continuum and discontinuum models to arrive at an estimate for this parameter. For this purpose, an elastic discontinuum model was used to simulate the excavation of the drift with elastic properties for both joints and blocks (i.e. block Young's modulus and Poisson's ratio of 76 GPa and 0.3, and joint normal and shear stiffness values of 1 GPa and 0.5 GPa). This provided the displacement field due to the redistribution of elastic stresses in response to the drift excavation. Figure 5a shows the displacement contours surrounding the drift. The maximum displacement, approximately 0.2 m, occurs near the upper left and lower right walls of the drift. The extent of displacement with magnitudes greater than zero is roughly 4 m from the drift wall.

In the next step, an elastic continuum model with the same geometry and in situ stress field as the elastic discontinuum model was constructed in order to back calculate the rock mass deformation modulus near the drift. This was done by adjusting the elastic modulus in the continuum model until the displacement field due to the excavation of the drift matched that obtained from the elastic discontinuum model. Two criteria were used for this purpose: 1) displacement magnitude at the drift boundary; and 2) extent of rock mass displacement with magnitudes greater than zero. It was found that an elastic modulus of 2 GPa in the continuum model would result in rock mass displacement with an extent comparable to that of the elastic discontinuum model (compare Fig. 5a and Fig. 5b). The continuum model underestimates the displacement magnitude near the drift boundary. Consequently, the elastic modulus was reduced until the displacement magnitude at the drift boundary matched that of the elastic discontinuum model. An elastic modulus of 0.8 GPa was obtained from this process (compare Fig. 5a and Fig. 5c).

The results of the proposed numerical modeling approach suggest that the post-peak deformation modulus of the rock mass near the drift at the North site of the George Fisher mine is about 0.8 GPa. The rock mass post-peak deformation modulus increases to about 2 GPa at about 4 m from the drift boundary due the decrease in the density of joint and block yielding with increasing confinement.

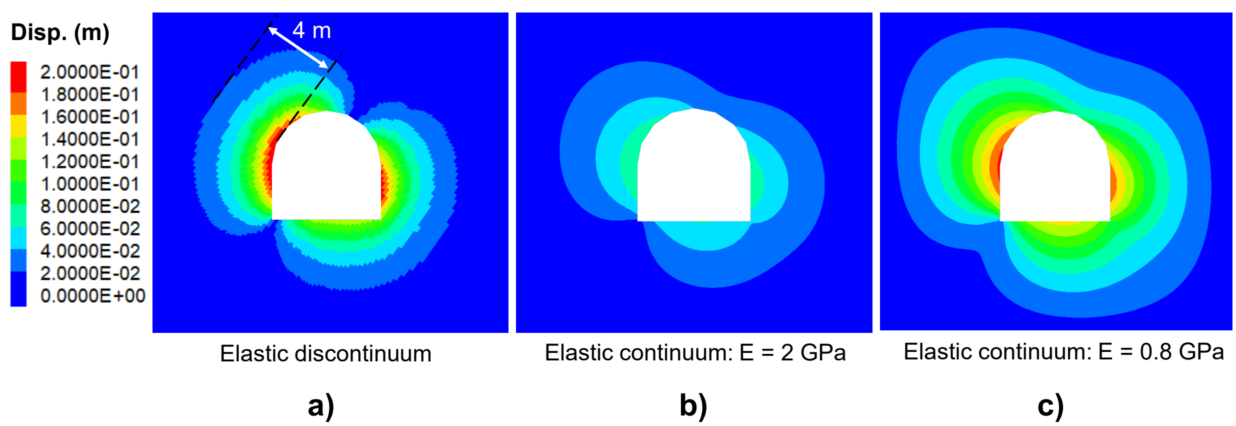

Figure 5. Displacement contours in: a) elastic discontinuum model; b) elastic continuum model with E = 2 GPa; and c) elastic continuum model with E = 0.8 GPa.

4 PATH FORWARD

The results of numerical investigation suggest an avenue of further research for a more realistic simulation of rock mass degradation and deformation around underground excavations using both continuum and discontinuum models. In continuum models, a post-peak deformation modulus parameter related to the plastic shear strain can be introduced. The post-peak deformation modulus is used when yielding occurs (i.e. peak strength exceeded) and when after yielding, the rock mass is subjected to a change in the loading condition (i.e. rock mass unloading/re-loading). In discontinuum models, where rock blocks and joints are explicitly simulated, the post-peak deformation response of the rock mass can be controlled by introducing residual shear stiffness and normal stiffness for joints and defining a post-peak deformation modulus for rock blocks. Although addition of these parameters increases the complexity of the calibration process, it may result in a more realistic simulation of rock mass degradation. It can potentially provide a means of capturing progressive stress fracturing and deformation of the rock mass due to changes in loading conditions caused by mining development activities.

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REFERENCES

Bahrani, N. & Hadjigeorgiou, J. 2018. Influence of stope excavation on drift convergence and support behavior - insights from 3D continuum and discontinuum models. *Rock Mechanics and Rock Engineering*, **51**: 2395-2413.

Fang, Z. & Harrison JP. 2001. A mechanical degradation index for rock. *International Journal of Rock Mechanics and Mining Sciences*, **38**: 1193-1199.

Fairhurst, C.E. & Hudson, J.A. 1999. Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences*, **36**: 279-289.

Hoek, E. & Diederichs, M.S. 2006. Empirical estimation of rock mass modulus. *International Journal of Rock Mechanics and Mining Sciences*, **41**: 3-19.

Itasca Consulting Group, Inc. 2016. *3DEC – Three-Dimensional Distinct Element Code, Ver. 5.2*. Minneapolis: Itasca.

Sweby, G., Dight, P., Potvin, Y. & Gamble, N. 2016. An instrumentation project to investigate the response of a ground support system to stoping induced deformation. In *Proceedings of the eighth international conference on ground support in mining and underground construction*, Lulea, Sweden.