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Investigation of the effect of critical parameters affecting caveability using numerical modelling

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1 INTRODUCTION

In block caving mining, an undercut must be extended until its hydraulic radius reaches a critical value to allow cave initiation. In this process, caving propagates as a response of the rock mass to stress changes or gravity effects, while broken ore is drawn. Even though research has attempted to understand caving mechanisms (Bucky 1956, Mahtab & Dixon 1976, Panek 1981, Duplancic 2001, Brown 2002), there is still uncertainty about the caving process itself. One of the main reasons why caving geomechanics is not well understood is because it is not possible to enter a cave to measure the rock mass parameters involved in the caving process. The caving process is also a complex and open system. Consequently, there is no single solution to represent one particular case, since many combinations of parameters could result in the same rock mass response. Caving geomechanics is also a typical example of rock mechanics being a data limited problem (Starfield & Cundall 1988). Although the problem of caving geomechanics cannot be entirely physically described, it is critical to make stepwise advances towards its understanding.

The main objective of this research is to identify and define the significance of the effect of dominant parameters affecting caveability. For this purpose, a discontinuum model is used to represent and test the responses of cases described by different combinations of factors. The numerical code used in this research is *3DEC* (Itasca 2016), since it can accommodate large deformations, shearing along pre-existing joints and fracturing of intact rock. *3DEC* is used along with a Discrete Fracture Network (DFN) model.

A limitation to fully incorporate all the processes and parameters involved in a single model is the availability of computational power. The replication of a real case should represent caveability, fragmentation and gravity flow processes, which is currently impossible due to the complexity of discontinuum models and their sizes that result in excessive run times. In this study, the model is simplified as much as possible to reduce the run time, but yet remain good enough to provide realistic results to understand caveability. A simple model is also preferred because it is more complicated to evaluate the quality of a model that contains too many details. Therefore, the design of the model is driven by the questions that the model is supposed to answer, rather than by including as many details as possible (Starfield & Cundall 1988).

The next section presents the methodology of choosing the combination of parameters simulated in *3DEC* and, the third section presents the results obtained from the numerical modelling and the statistical analyses used to quantify the impact of each factor in the numerical model. Finally, the conclusions are presented.

2 DESIGN AND ANALYSIS

There is previous research that models jointed and veined rock masses using a collection of tetrahedral blocks with relatively uniform size distribution (Garza-Cruz & Pierce 2016). In this work, a DFN model is incorporated in *3DEC* to enable a study of the influence of a broader range of block shapes and sizes in the rock mass response. Given that *3DEC* does not allow the direct incorporation of non-persistent joints, fictitious joints, as presented in Figure 1, are used to represent intact rock bridges (Vergara et al. 2016). Fictitious joints, as well as the joints within the rock mass, are represented as a combination of contacts following the Coulomb Slip model. On the other hand, the blocks within the model are assumed to be isotropic, elastic and deformable. The use of deformable elastic blocks allows the direct assignment of deformability parameters if the stiffness of the contacts is significantly higher than the modulus of the zones, so that the deformation takes place at the zone level and not at the contact level. In other words, the stiffness does not need to be calibrated (Turichshev & Hadjigeorgiou 2016).

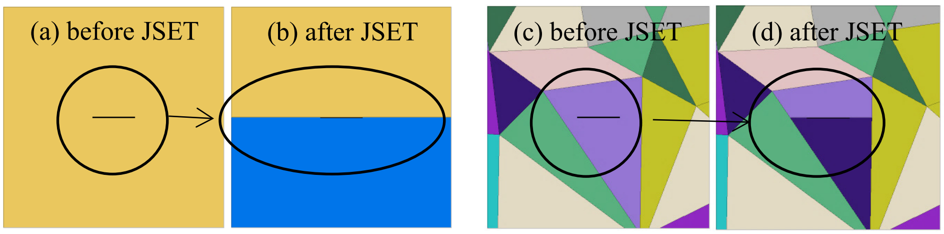

Figure 1. Effect of cutting blocks of different sizes: (a) and (b) single block cut by a single joint divided in 2, and (c) and (d) block formed by a collection of tetrahedral blocks cut by a single joint (JSET is the command that splits blocks).

Once an appropriate model has been built, models are tested changing seven parameters (Suzuki Morales & Suorineni, 2017) namely: joint orientation, joint persistence, joint intensity, intact rock properties, joint properties, field stress and diameter of a circular undercut. Given the large number of factors that are potentially critical for caveability, parameters are grouped either into two categorical or numerical subcategories that should produce different responses in the rock mass behavior under caving conditions. The choice of two levels means that the response is approximately linear over the range of the factor levels chosen. Values describing the parameters at the low (_) and high (+) levels for the seven factors are presented in Table 1. Factors are worked as coded design variables because the original units are not directly comparable. For simplicity, factors are named by a capital letter and a (_) or (+) symbol to represent the level.

A full factorial design contains all the 128 possible combinations to quantify the main effects and interaction effects. However, this number of combinations is not practical due to the long run times that each simulation takes. As an alternative, a subset of possible combinations is analyzed as part of an unbalanced design. Unbalanced designs are common when some combinations are of greater interest. In total, 102 combinations are studied at two levels from a total of 128 possible combinations.

Table 1. Summary of factors and levels evaluated in the simulations.

	Critical parameters influencing caveability	Low level (_)	High level (+)
A	Joint orientation	Configuration J_1	Configuration J_3
B	Joint persistence	Low persistence	High persistence
C	Joint intensity	$1\ m^{-1}$	$2\ m^{-1}$
D	Intact rock category	very hard	hard
E	Joints category	no filling	soft filling
F	In-situ stresses magnitude	$\sigma_1 = 30$ MPa	$\sigma_1 = 70$ MPa
G	Hydraulic radius (diameter)	1.75 m (7 m)	2.5 m (10 m)

Note: σ_3 is assumed to be $\sigma_1/1.5$ and σ_2 the average between σ_1 and σ_3.

3 RESULTS AND DISCUSSION

Figure 2 shows the contours of displacements in the z-direction from eight preliminary simulations that theoretically investigate the quality of the model. The calculations were done in 3D, but for simplicity, these results are shown in 2D cut planes. Joints forming the DFN are highlighted. It can be observed that displacements are affected by all parameters at different magnitudes. Because these cases resulted in different final displacements, all other cases were run initially for 10,000 steps in order to analyze the displacements at that stage.

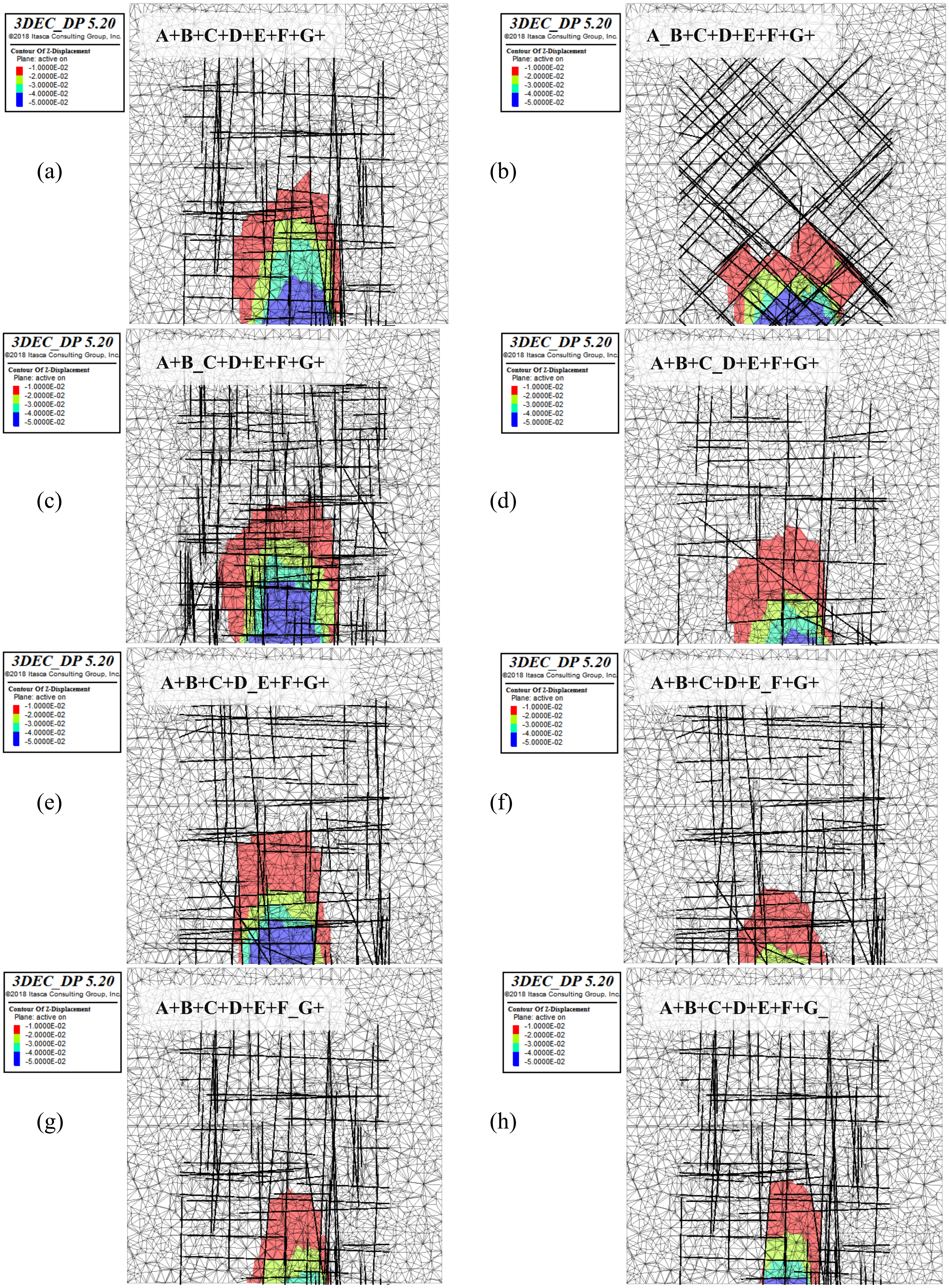

Figure 2. Displacements at the final stage for the combination containing all factors at the high level and for the combinations containing all factors at the high level except for one factor, with factors at the low (_) and high (+) levels as defined in Table 1 (The in-situ $\boldsymbol{\sigma_1}$ and $\boldsymbol{\sigma_3}$ stresses are horizontal and vertical respectively, in the cut plane presented).

Statistics is used to define in general terms how factors affect the observed response (Y). It is important to note that statistical methods cannot prove that a factor has a particular effect, but their main advantage is that they add objectivity to the decision-making process. A generalized linear model (GLM) is fitted in order to define how results effectively explain the data and to define how significant the contribution of each independent variable is to the final response. Experience show that it is more appropriate to describe data by two models. The first model describes factors to predict that responses are zero ($Y' = 0$ if $Y = 0$) or any positive value ($Y' = 1$ if $Y > 0$), and the second model describes factors that predict positive responses ($Y > 0$), where Y is a continuous variable describing the observed response and Y' is a binary variable that takes the value 0 or 1 to indicate the absence or the presence of the observed response.

The second model indicates which factors have a significant effect on the final response when the p-value obtained for that factor is less than the significance level α, which is the probability of rejecting the null hypothesis given that the null hypothesis is true. At $\alpha = 0.01$, factors significantly affecting Y are the undercut area (factor G), the joint intensity (factor C), the joint properties category (factor E), the in-situ stress magnitude (factor F), the intact rock properties (factor D) and joint persistence (factor B), and two-factor interactions C:F, C:G, E:F, E:G and F:G. The findings of this study indicate that a system approach to caveability prediction is more appropriate compared to optimizing individual factors independently.

4 CONCLUSIONS

As observed by Starfield & Cundall (1988), rock mechanics problems are data limited. In this research, limited data exists. One of the primary issues in block caving practice is the lack of understanding of the caving geomechanics. This paper is therefore based on conceptualizing the caving process to more reliably predict caveability of orebody rock masses. Thus, the investigation used generic models. The results make physical sense but need to be validated in future studies pending the availability of field data.

Modelling the complete caving process remains a challenge due to computer capacity limitations. However, numerical modelling is shown to have the ability to theoretically define the significance of the effect of parameters in the rock mass response if it is assumed that results from simulations run until a preliminary stage represents the rock mass behavior at initial caving stages. The main advantage of numerical modelling is that it can quantify the rock mass response, which is useful to investigate further the applicability of geotechnical guidelines defined by the opinion of experts. Further improvements are still required to make the model more realistic and the results practical.

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