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Numerical modeling of influence parameters in cavabililty of rock mass in block caving mines

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ABSTRACT

The prediction of rock mass cavability is needed in the design of block caves to estimate the undercut size required to achieve continuous caving. The cavability of the rock mass will control mine design and economic issues for a given geological environment and is a fundamental issue in establishing a successful block caving mine. With recent interest in applying caving techniques to stronger rock masses, the reliable prediction of rock mass cavability is becoming increasingly important. The two most universally applied methods for cavability prediction are the empirical stability graph approach developed by Laubscher and numerical methods. Empirical approaches developed to predict rock mass cavability have been based on the assessment of rock mass conditions using recognized rock mass classification schemes. Rock mass classification is the first stage in empirical approaches to predicting rock mass cavability. The numerical approaches also commonly utilize rock mass classification schemes to assign rock mass properties and apply failure criteria within the models. A reliable prediction of cavability of rock mass depends on the accurate identification of the influence parameters in rock mass cavability. The cavability of a rock mass is based on many factors such as natural and induced factors, affect the caving performance. In this paper the effect of seven parameters, the compressive strength of intact rock (UCS), joint orientation, joint persistence, joint density (P_{32}), joint friction, confined stress and hydraulic radius (HR), is investigated using numerical technique named the Synthetic Rock Mass (SRM). The SRM is a numerical modeling technique which combines the Bonded Particle Model (PFC) for intact rock and Discrete Fracture Network (DFN) simulation. To assess the influence of each parameter in numerical modeling, the value of one parameter is changing while the values of other six parameters are fixed. It is found that in-situ stress and hydraulic radius are the most effective parameters in cavability of rock mass in block caving mines.

1. Introduction

Block caving is a method that is completely based on the principles of caving. This method is based on the assumption that ore fractures and breaks by itself, due to the presence of internal stresses and forces caused by the weight of the ore body and also the downward movement of the broken rocks.[1] The deposit is divided into large blocks, usually square in shape. Each block is undercut completely by a horizontal slot. Gravity forces due to the presence of millions of tons of ore and waste, being in the block and above and around the block, act on the rock masses, and successive fracturing occurs in this way, affecting the entire block in a gradual manner. The travelling ore is broken when the rock pressure rises at block bottom. It is crushed to a degree of fragmentation that allows removal through draw points or any other types of arrangement.[2]

Understanding the initiation and propagation of caving and its successful characterization is the first stage in developing a reliable method for assessing and predicting rock mass cavability.[3] The most used methods for prediction of block caving cavability are empirical and numerical methods. The use of empirical methods to estimate cave propagation behavior has been, and still is, widespread. The common used method for predicting cavability was developed by Laubscher.[1,4–6] The proposed method is based on a set of caving case histories. The most data is derived from low strength rock mass of kimberlitic deposits in South Africa.

There are numerous numerical modeling methods (boundary element, finite element, finite difference, distinct element and hybrid) and approaches available for performing stress and deformation analysis in geomechanics. In his review of cave mining practices, Brown reasons that numerical modeling investigates cave initiation and propagation behavior more precisely and fundamentally than empirical (or analytical) methods, since it may have advantages in cases where current experience is lacking.[7]

Palma and Agarwal developed the first two-dimensional elastic

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finite element model to study cave propagation behavior at the El Teniente Mine in Chile.[8] During this study, they recognized the need to consider the fracture network and the effect of major stress direction in relation to the undercut dimensions on the cave propagation behavior.[8] Barla introduced a softening material model to represent the degradation of the in-situ rock mass strength to a bulked and weakened state during cave propagation.[9]

During the International Caving Study (ICS 1997–2004), Flores and Karzulovic considered the influence of depth, stress, large-scale discontinuities, rock mass strength and groundwater on cavability through a generalized sensitivity analysis with a two-dimensional finite element method (FEM) code.[10]

Two dimensional distinct element models (DEM) were developed by Lorig et al.[11] within the PFC^{2D} (particle flow code) code to present a better understanding of the jointed rock mass and a reclaimed cave back form in block caving mines. Lorig performed sensitivity simulations in axis-symmetric models in a research including a more accurate representation of the three-dimensional shape of the propagating cave and surrounding induced stress field. A cylindrical undercut located at increasing depths was considered.[12]

Gilbride[13] and Sharrock[14] used a three-dimensional DEM approach to model the mechanisms of caving for large-scale subsidence analysis. Gilbride calibrated a large-scale rock mass reaction via rock mass simulations in a laboratory and used the results in a large-scale model. Beck[15] developed a methodology for the assessment of cave propagation behavior using the numerical modeling package Abaqus.[16] Pine[17] and Vyazmensky[18] used ELFEN (the combined finite element and discrete element) code to insert physical fractures into a continuum finite element mesh. Paluszny and Zimmerman[19] assessed primary fragmentation in block caving mines using a finite-element method. In this study the growth of fractures around an undercut of a block cave is simulated. Although many conceptual block cave models have been documented,[17,18,20] these approaches have not been validated against observed behavior at an existing mine.

In this paper, by using the PFC^{3D} software, a large block caving mine is modeled. Then, by coupling this model with a discrete fracture network, the influence of six parameters, the compressive strength of intact rock, joint orientation, joint persistence, joint density (P_{32}), joint friction and hydraulic radius (HR), is assessed on the cavability of rock mass. Finally, by sensitivity analysis, the most effective parameters are introduced.

2. Block caving mining method

Block caving is an underground mass production system of ore extraction which, under favorable conditions, gives lower mining costs than any other underground method. However, it requires relatively large capital expenditure in terms of preliminary development and infrastructure establishment. Block caving is suited to massive orebodies with a well-disseminated grade.[21] Additional features necessary for block caving are a well-developed fracture system within the orebody and a capping material that is weak enough to cave along with the orebody.[22]

Block caving is a system of underground mining that removes support from under an orebody. The principal concept behind caving is to undercut the rock mass causing it to cave or unravel naturally to form broken material rather than using blasting to fragment the in-situ rock mass. The removal of support results in the propagation of new fractures, and opens existing fractures within the rock mass.[3]

2.1. Cavability of rock mass

Cavability refers to the capability of an in-situ rock mass to unravel when undercut, and considers all three stages of caving: initiation, propagation and continuous caving.[23] The cavability of an orebody is strongly influenced by the natural properties of the rock mass and is also enhanced by induced features that are directly attributable to the mining process.[3] Estimation the cavability of a rock mass is an area of primary significance in block cave design.[11] The cavability of a rock mass is based on various factors; however, it is usually assumed that any rock mass will cave if a large enough area is undercut.[24] The challenge is to reliably predict the undercut area required to achieve continuous caving. This is particularly important with mass caving systems where the orebody footprint limits the maximum size of the undercut.

The reliable prediction of cavability is critical in determining the undercut dimensions required to initiate and continuously cave an orebody. The cavability of rock mass will control mine design and economic issues for a given geological environment, and is a fundamental issue in establishing a successful block caving mine.[25] Therefore, the cavability of a rock mass and the conditions required to achieve cave initiation and continuous propagation must be determined as initial inputs into mine design. The cavability and resulting fragmentation of the ore zone, host rock and cap rock must be determined when evaluating the applicability of block caving as a mining method.[26] Cavability of an orebody is a critical consideration in the feasibility stages of a caving operation, not only in terms of overall mine ability, but also in blasting, fragmentation, crushing and grade recovery.[24]

3. Synthetic rock mass (SRM)

The SRM method is based on the generation and test of three dimensional numerical (synthetic) rock mass samples. This method combined two techniques: the Bonded Particle Model (BMP) for intact rock, proposed by Potyondy and Cundall[27] and Discrete Fracture Network (DFN) modeling which represent the in-situ joint fabric of rock. In the SRM model each single joint is simulated explicitly. This feature provides using of the Smooth-Joint Contact Model (SJM). This new technique of joint representation in PFC^{3D} has made it possible to extend the approach of Park[28] to volumes of rock at the scale of 10–100 m, containing thousands of non-persistent joints.

3.1. Particle flow code in three dimensions (PFC^{3D})

Distinct element modeling for micromechanical assessment of geomaterials and particulate systems in three dimensions PFC^{3D} (Particle Flow Code in 3 Dimensions) is a discontinuum code used in analysis, testing, and research in any area where the interaction of many discrete objects presenting large-strain and/or fracturing is required. Since PFC^{3D} is not designed to examine a specific type of problem, its range extends to any analysis that examines the dynamic behavior of a particulate system.[29]

In PFC^{3D}, materials may be modeled as either bonded (cemented) or unbounded (granular) assemblies of particles. Though the code uses spherical particles by default, particle shape may be defined in a PFC^{3D} model through the use of the built-in clump logic. PFC^{3D} uses an explicit solution scheme that provide stable solutions to unstable processes. It can explain non-linear behavior and localization with an accuracy that cannot be matched by common finite element programs.[29]

4. Numerical simulation

The particle flow code PFC^{3D} is used to develop the numerical environment. In this software, the micro properties of material are necessary to construct the model.

The first step in numerical modeling by PFC^{3D} is determining the micro-characterization of materials. Table 1 presents a summary of the micro-parameters of the contact and parallel bond model for the first constructed model.