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Use of an integrated finite/discrete element method-discrete fracture network approach to characterize surface subsidence associated with sub-level caving

Pooya Hamdi[a,*], Doug Stead[b], Davide Elmo[c], Jimmy Töyrä[d]

[a] Golder Associates Ltd., Vancouver, Canada
[b] Resource Geotechnics Research Group, Simon Fraser University, Burnaby, Canada
[c] Institute of Mining Engineering, University of British Columbia, Vancouver, Canada
[d] LKAB Mine, Kiruna, Sweden

ABSTRACT

The LKAB Kiruna sub-level cave mine, located in Kiruna, Sweden, is one of the most well studied sub-level cave mines. Due to proximity of the city to the hanging wall, the mine has developed a comprehensive surface deformation monitoring program which is perhaps unparalleled in the mining industry. This surface monitoring scheme provides an excellent data source with which to constrain numerical modelling. In this study, a finite/discrete element modelling approach coupled with a discrete fracture network (FDEM-DFN) is utilized to analyse the Kiruna hanging wall surface subsidence with an emphasis on investigating the influence of discontinuity persistence and spacing. The FDEM-DFN data interpretation uses a variety of novel approaches including time-displacement hanging wall deformation characterization, numerical inverse velocity analysis and virtual hanging wall inclinometer simulation to improve our understanding of the extent and mechanism of hanging wall failure with mine advance. The simulated displacements correspond closely to the actual field data, illustrating the ability of the proposed approach to reproduce sub-level cave behaviour. Three distinct time-displacement phases namely: regressive, progressive and steady state are observed in the FDEM-DFN models. The paper also reviews the potential application of the inverse velocity method and virtual inclinometers in characterizing sub-surface brittle failure associated with sub-level caving.

1. Introduction

Sub-level caving is a cost-efficient mining method that enables a high degree of mechanization and automation.[1] Mining using this method induces a large area of deformation on the hanging wall with a more limited area of damage on the footwall. Various parameters influence the observed hanging wall surface subsidence including depth of active mining, geometry and dip of the orebody, the mechanical properties of the intact rock and characteristics of pre-existing discontinuities and geological structures. In general, mining using the sub-level caving method induces two types of ground surface deformation zones: (i) discontinuous and (ii) continuous.[2] A discontinuous deformation zone is characterized by formation of visible cracks on the ground surface and large horizontal and vertical deformations. Surface disturbances such as tension cracks, topographic steps and chimney caves are normally observed in this zone. The disturbance is more extensive in the hanging wall, although the footwall is also affected by the mining activity. A continuous deformation zone is characterized by uniform settlement and lowering of the ground surface which can only be detected by periodic monitoring with, in general, no visible surface cracks.

Characterization of the extent of these deformation zones is important both for the continuity and safety of the mine operation as well as the environmental impact assessment. The extent of the discontinuous and continuous deformation zones is generally characterized, as shown in Fig. 1, by two parameters: the break angle and the limit angle. The break angle is defined as the angle measured from horizontal of a line drawn from the active mining level to the outermost visible crack on the ground surface and the limit angle is the angle to the extent of continuous deformation zone.

The Kiruna mine is a sub-level cave mine located west of Kiruna city in northern Sweden. Due to proximity of the city to the hanging wall, the mine has developed an intensive surface deformation monitoring program which is perhaps without parallel in the mining industry. This

* Correspondence to: 2920 Virtual Way #200, Vancouver, BC, Canada V5M 0C4.
E-mail address: Phamdi@golder.com (P. Hamdi).

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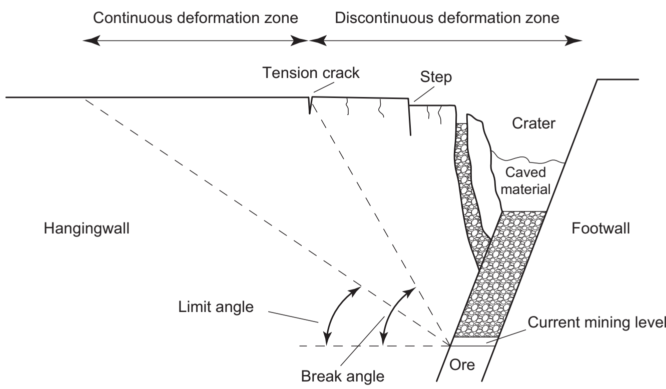

Fig. 1. Surface subsidence induced by sub-level caving (modified after[2]).

surface monitoring campaign provides an excellent data source with which to constrain/calibrate numerical analyses of the hanging wall subsidence. In this study, the combined finite/discrete element method (FDEM) code ELFEN[3] is employed to simulate the hanging wall surface subsidence observed at the Kiruna mine. Discrete fracture network (DFN) models created based on the borehole data and the discontinuity mapping are integrated into the FDEM geomechanical modelling. A series of numerical analyses with an emphasis on the influence of discontinuity persistence and spacing are undertaken, and the results are calibrated with the surface deformation monitoring instrumentation implemented at the Kiruna mine.

2. Empirical and analytical approaches to analyse hanging wall surface subsidence

Different empirical and analytical methods have been used to predict the magnitude of the break angle and characterize the failure mechanism involved in block and sub-level cave mining. Probably the most commonly used empirical method for estimating block caving parameters in cave mining is Laubscher's method. Laubscher[4] proposed a design chart that relates the predicted cave angle to the MRMR (Mining Rock Mass Rating), density of the caved material, height of the caved rock and mine geometry. Analytical solutions commonly based on the limit equilibrium method have also been developed to predict the surface subsidence associated with caving. Hoek[5] proposed a limit equilibrium analysis for predicting the sequence of progressive hanging wall failure. In this method the failure mechanism, which is a combination of tension cracking and shear failure, is controlled by the strength of rock mass, geological structures and in-situ stress conditions. Other researchers[6,7] have also proposed modified analytical solutions based on Hoek's method incorporating additional parameters such as surface traction and different mining geometries. While these approaches have been successfully applied in various case studies, analytical and empirical approaches are often limited by the requirement for important assumptions including rock homogeneity and isotropy. Heslop and Laubscher[8] indicated that geological structures are the main controlling factors in hanging wall failure. In complex mine environments where simple assumptions are no longer appropriate numerical methods have been increasingly adopted.

3. Numerical modelling of caving mechanisms

Recent developments in numerical techniques have demonstrated significant potential for furthering our understanding of the mechanisms/processes involved in rock engineering problems. From a computational perspective, numerical modelling of sub-level caving can be classified into three categories: (i) continuum approaches such as the finite element method (FEM) and the finite difference method (FDM), (ii) discontinuum approaches such as the distinct element method (DEM) and the discontinuous deformation analysis (DDA) and (iii) combined/hybrid methods such as the finite/discrete element method (FDEM). In continuum approaches the rock mass, which is an assemblage of intact rock and discontinuities, is modelled implicitly using rock mass classification or empirical methods by downgrading the strength of intact rock due to the presence of discontinuities. In discontinuum and hybrid numerical methods however, discontinuities are represented explicitly providing a more realistic representation of the rock mass.

The application of continuum numerical modelling in analysing hanging wall surface subsidence has been the subject of extensive research. Sainsbury et al.[9] examined the influence of rock mass strength anisotropy and discontinuity orientations on caving response using the ubiquitous jointed rock mass (UJRM) technique in FLAC3D[10] and concluded that variations in the discontinuity orientations have a significant effect on cave shape and the rate of cave propagation. Villegas and Nordlund[11] proposed a novel approach to model the sequence of sub-level cave mining using the FEM code Phase2[12] which artificially considers both the air gap and caved material. It was concluded that their proposed approach was able to represent the general behaviour of the observed rock mass.

The main limitation of continuum approaches in analysing hanging wall surface subsidence is that continuum analysis does not allow the detachment of individual blocks and hence, large block displacements cannot be modelled and the true kinematics of failure are not followed. Considering that sub-level cave mining comprises large movements, a more appropriate approach to model the caving behaviour is to use a numerical approach that is able to model large displacements. Discontinuum and combined FDEM methods are able to simulate both block translational and rotational movements and large displacements. These methods have been successfully used to model surface subsidence associated with cave mining. Villegas and Nordlund[13] used the particle flow code PFC2D to reproduce surface subsidence at the Kiruna sub-level cave mine in Sweden. Using an FDEM-DFN approach, Vyazmensky et al.[14] analysed a series of conceptual models to investigate the influence of intact rock bridges and discontinuity orientation on the break angle and cave propagation in block caving and concluded that discontinuity orientation and persistence play an important role on the extent of the caved-induced failure surface.

Zavodni[15] indicated the importance of developing kinematic release, internal distortion, dilation and fracturing to realistically simulate progressive failure in rock engineering. One major advantage of the combined FDEM method is an ability to simulate the transition from a continuum to a discontinuum state by explicitly simulating fracturing and fragmentation processes. In this approach, intact rock blocks can both fracture and fragment in addition to being deformed. This is particularly important in sub-level caving since the failure process involves intensive fragmentation. Two approaches can be used in the combined finite/discrete element method (FDEM) to represent the rock mass: i) an implicit approach or equivalent continuum method, and ii) an explicit approach incorporating a discrete fracture network (DFN).

In the implicit or equivalent continuum approach the rock mass is represented as a continuum medium with reduced intact rock properties to account for the presence of discontinuities. The equivalent continuum properties can be established in the model using conventional rock mass classification systems such as the Rock Mass Rating (RMR) / Geological Strength Index (GSI) or using a more advanced technique incorporating a synthetic rock mass (SRM) approach.

The synthetic rock mass approach is being increasingly used to analyse large scale problems. The SRM approach, first proposed by Pierce et al.[16] uses a bonded particle model (BPM) in PFC3D[17] incorporating a discrete fracture network (DFN). The SRM method is based on the generation of a three-dimensional synthetic rock mass sample that simulates the rock mass as an assembly of bonded spheres (intact rock) with a discrete fracture network (DFN). The main objective of an SRM model is to construct an "equivalent continuum