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Prediction of mining-induced surface subsidence and ground movements at a Canadian diamond mine using an elastoplastic finite element model

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ABSTRACT

A full three dimensional elastoplastic finite element model of Diavik Diamond Mine is developed to predict surface-induced ground movement due to underground blasthole stoping activities. A mesh convergence study has been conducted to reach to an optimum meshing scenario when further mesh refinements produce a negligible change in the results. This way the calculation cost and time has been managed successfully. Furthermore, sequences of the excavation/backfilling in the model are defined according to the mine production plan; however, some simplifications in the shape of the stopes have been made. Consequently, the developed finite element model simulates the complete stress-strain path through the entire excavation and backfilling simulation steps in full three dimensional space. The model is calibrated using two extensometers installed on the back of two secondary undercut drifts in one of the Kimberlite pipes. The results of the calibrated model are validated using pit surface prism monitoring system data. The average relative error between the measured data and FE model predictions is 7.95%. It is shown that the numerical predictions of the mining-induced surface subsidence, due to the blasthole stoping mining method, matched well with the Gaussian distribution. A significant increase, approximately by 44%, to the amount of the induced settlements on the surface occurred as the mining activities reaches near surface ground levels. Finally, the comparison between the predicted results of the finite element model and monitoring data showed that the predictive capacity of the numerical model is a valuable tool for stability and design analysis of underground mines.

1. Introduction

Subsidence is the downward settlement of the ground surface. Mining-induced surface subsidence is a phenomenon that occurs due to the underground extraction of an orebody. Open pit and underground mining operations cause stress redistribution; consequently, this causes some induced displacements on the ground surface.

According to the elasticity theory, any excavation at any depth and extend can cause movement on the ground surface. This means that all underground mining methods can cause surface subsidence. According to Pariseau,[1] the most common reasons of surface subsidence are: (i) redistribution of the stresses due to mining activities, and (ii) de-watering of the ground during mining activities which cause lowering of the groundwater tables.

Prediction of the surface subsidence profile and its magnitude is a critical task for rock mechanics engineers, and it is crucial for planning underground mining operations. A comprehensive review of the methods to determine mining-induced surface subsidence is given by Brady and Brown.[2] Several empirical, numerical, observational, graphical, profile function, influence function and physical methods to predict subsidence parameters have been developed by various researchers.[3–14]

Overall, methods for prediction of mining-induced surface subsidence can be classified into four main categories: (i) empirical methods, (ii) analytical methods, (iii) numerical methods, and (iv) hybrid methods. Empirical methods (i.e. profile functions, influence functions, graphical methods) are based on the back analysis of field data; for instance, Woo et al.[15] developed a comprehensive database of block cave mining and mining-induced surface subsidence to guide empirical relationships between caving depth and its impact on surface movements. Consequently, empirical methods can be used only where a large database of measured field data is available. Analytical methods are based on applying mathematical solutions derived from first principles to predict how the rock mass will behave when an excavation is made within it[16]; for example using elasticity theory, Salamon[17] derived analytical solution to calculate displacements and stresses induced on the surface due to longwall mining in coal. Numerical methods can be used to model elastoplastic, non-linear, and post-yield

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behavior of rock mass and include the effects of in-situ stresses and geological features on the mining-induced surface subsidence. The current approach is to use the hybrid methods, which is the combination of the analytical or numerical methods with back analysis of field data.

To meet the objective of this paper, finite element method (FEM) is used for numerical analysis due to its recognition as a tool to solve rock mechanics and geomechanical problems. It has the ability to deal with material heterogeneity, non-linearity, complex-boundary conditions, in-situ stresses and gravity.

To predict the induced surface subsidence due to underground mining activity at Diavik Diamond Mine, a fully three-dimensional elastoplastic finite element (FE) model was established. The initial results of the model were calibrated using two underground calibration points. Finally, the calibrated model was used to predict the induced settlement profile for the surface of the N9290 bench located in the A154 pit at Diavik Mine. Results of the developed FE model were verified by comparing the outputs of the constructed FE model with available pit monitoring data.

2. Diavik Diamond Mine

Diavik Diamond Mine is located on a 20-km^2 island in Lac de Gras, approximately 300 km northeast of Yellowknife, Northwest Territories.[19] Diavik reserves are contained in four diamond-bearing Kimberlite pipes named A154 North, A154 South, A418 and A21. The host rock is granite. All four pipes were located under the waters of Lac de Gras. To enable open pit mining, first the water was removed, and dikes were constructed to drain the water and prepare the surface for open pit mining. In 2002, the first dike around the A154 North and A154 South pipes was completed. Consequently, open pit mining operations started in 2003. In 2007, construction of the second dike around the A418 pipe was completed. In 2010, open pit mining of the two A154 pipes was completed and development of the underground mine commenced.

As it can be seen from Fig. 1, the mine is surrounded with water. Consequently, prediction of any surface subsidence in this mine is vital. Any mining-induced instability on surface can jeopardise the stability of the dikes surrounding the mine. If these dikes fail, the mine will be flooded. The focus of this paper is on prediction of mining-induced surface subsidence due to underground mining at A154 North Kimberlite pipe.

2.1. Mining method

Extraction of the ore at Diavik began with open pit mining. In late 2012, the transition from open pit to underground mining had been completed and Diavik became an underground mine. Two underground mining methods, sublevel longhole retreat (SLR) and blasthole stoping (BHS), were used. A154 South and A418 pipes are mined by SLR. BHS is used in A154 North pipe. The research area of this paper is focused on A154 North Pipe.

The BHS mining method is being used in the A154 North pipe at Diavik Mine. The planned BHS include primary and secondary stopes. The preliminary design calls for all of the stopes to have 7.5 m widths, strike lengths of about 100 m and heights of approximately 30 m sill to sill. Cemented rockfill (CRF) is being used to backfill the excavated stopes.

BHS generally involves two sublevels and a certain amount of preparation of the stope before actual production can proceed. One sublevel is used for drilling (overcut) and another sublevel is used for production (undercut). According to Hustrulid and Bullock,[18] the BHS method is the best option when the ore body has the following characteristics: (i) the dip of ore body is steep (which is the case in most Canadian underground diamond mines), (ii) the ore and host rock are competent (in diamond mines the host rock is often granite), (iii) the ore boundaries are regular, and (iv) strong hanging wall and foot wall present.

Production in BHS is performed in a primary/secondary manner. First, the primary stopes are excavated. After the primary stopes are completely excavated and backfilled, excavation of the secondary stopes are initiated. After completing the mining of one level, the operation moves to the next mining level. The dimensions of the stopes are usually large in the vertical direction. Therefore, the assessment of the stability of these stopes is a critical task for geomechanical mine designers.

3. Methodology

3.1. Model geometry

A full three dimensional (3D) finite element analysis model of the mine, as shown in Fig. 2, is constructed using Abaqus.[20] Two simple representative geometries of the open pits, A154 and A148, are included in the model. The analysis domain dimensions are 2.2 km by 2.2 km and maximum depth of the model is 800 m. The domain dimensions are sufficient to eliminate the influence of the boundaries on the model. On the vertical boundary of the model, horizontal restraints (on both *X* and *Y* directions) are applied. Encastre boundary conditions are applied at the bottom of the model (Encastre means completely fixed in all directions).

To accurately calculate the initial state of the stresses, both open pits are included in the model. This allows the model to calculate the initial geostatic state of the stresses in the first step of the simulation. Moreover, including both pits allows the model to account for the zone

Fig. 1. Aerial image of Diavik Diamond Mine (courtesy of Diavik Diamond Mine).

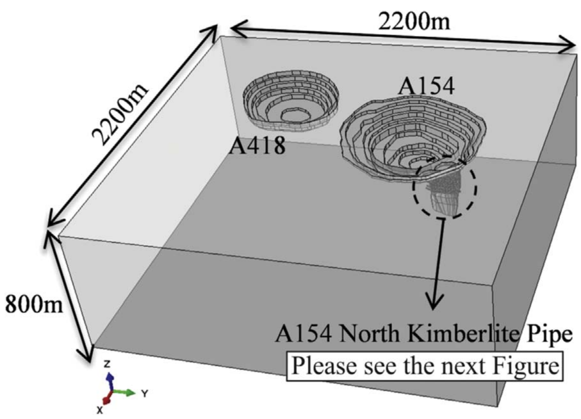

Fig. 2. Full 3D model of the mine in Abaqus.