International Journal of Rock Mechanics and Mining Sciences 106 (2018) 165–175

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Numerical investigation of the development of the excavation damaged zone around a deep polymetallic ore mine

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ARTICLE INFO

Keywords:
Brittle-ductile behavior
Constitutive model
Deep mine
Hard rock
Numerical modeling
In situ stresses

ABSTRACT

This paper deals with the development of a non-linear constitutive model of a rock mass and its application to predict the extension of the excavation damaged zone (EDZ) around openings. A comparison of the model results with the simulations of triaxial compression tests shows a good agreement between predictions and theoretical values of peak and residual strengths as well as a good reproduction of the transition between brittle failure and ductile response. The relevance of the proposed model to evaluate the potential failure around stopes of the Garpenberg mine was examined. The comparison of the results proved satisfactory and highlighted the interest of considering a more realistic mechanical behavior of hard rock masses in rock engineering compared with the elastic perfectly plastic models generally used in numerical modeling of underground deep mines. Finally, a 3D simulation of the complete mine geometry was carried out in order to model the first phases of stope mining operations. The predicted stresses were compared with the continuous measurements of induced in situ stresses recorded by stress cells at different points around the stope. The predictions of the proposed constitutive model provided a much better agreement with stress measurements than those obtained with elastic perfectly plastic models.

1. Introduction

Damage by micro-cracking is the main dissipation process associated with inelastic behavior and failure in most brittle materials such as rocks, concrete and ceramic composites. Under high in situ stresses and highly anisotropic stress ratio conditions, an excavation damaged zone (EDZ) may develop around underground openings excavated in brittle rocks. The failure mechanisms involved in the development of this damaged zone, namely the initiation, growth and coalescence of cracks and fractures, are directly related to the constitutive behavior of the rock mass. Experimental studies on brittle rocks have shown that there are many different mechanisms by which cracks can initiate and grow under compressive stresses (e.g.[1–3]). These mechanisms include sliding along pre-existing cracks and grain boundaries, pore crushing, elastic mismatch between mineral grains and dislocation movements. Over the past decade, several constitutive models have been developed to provide a more realistic description of damage processes in brittle rocks in relation to experimental observations (e.g.[4,5]). In other words, these constitutive models are aimed to better predict the global behavior of geo-environmental structures (storage, civil, petroleum and mining engineering).

In the framework of the European project I^{2}Mine, INERIS developed an innovative methodology to better understand the behavior of the rock mass resulting from the mining processes.[6] This methodology was applied on the Garpenberg deep mine in Sweden. This polymetallic ore mine operated by Boliden Mines, is exploited between depths 1100 and 1300 m according to the sub-level stoping method with paste filling (Fig. 1). Several seismic sensors and CSIRO HI stress measurement cells (comprising 12 strain gauges) were installed in a deep area of the mine to monitor the evolution of stresses induced by mining operations and compare it with the recorded induced seismic activity.[7]

The objective of this paper is to present a non-linear constitutive model of a rock mass and its application to the understanding of the mechanical behavior of underground works in the Garpenberg mine. This model has the advantage of being relatively simple since based on the Hoek and Brown criterion widely used in rock engineering but sufficient powerful to simulate the brittle failure mechanisms and damage of geomaterials. The study includes the numerical modeling of different stages of underground works. As a first approach and in order to grasp the key mechanisms of failure, we examine 2D models that consider the anisotropic initial state of stresses and the stope geometries

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https://doi.org/10.1016/j.ijrmms.2018.04.028
Received 28 March 2017; Received in revised form 16 January 2018; Accepted 10 April 2018

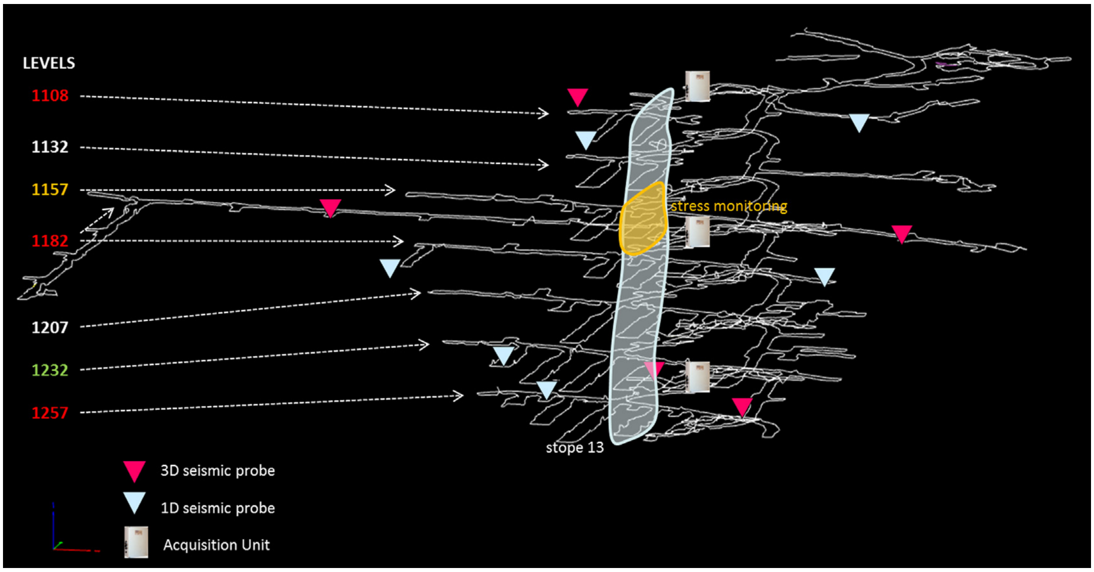

Fig. 1. Experimental set-up (stress and microseismic measurements) in the Swedish mine Garpenberg: operating plan and location of the pilot area.

representative of a pilot area in the Garpenberg mine (Fig. 1). The goal of this 2D modeling is to show the potential of the new proposed constitutive model to predict induced stresses and plasticity distribution around Garpenberg mine openings. Secondly, a full 3D large-scale model is performed with four different materials: ore, limestone, weakness zones and backfill material; the induced stresses are numerically evaluated and compared to the continuous in situ stress measurements performed at different points around openings using CSIRO HI cells. The goal of this 3D modeling is to underline the essential roles of the lithology and of the ore behavior to gain better correlation between measured and computed stresses. More precisely, the purpose of this paper is to present: (a) a numerical implementation of an elastoplastic model obeying the Hoek–Brown criterion. This model considers the transition from brittle failure to ductile behavior depending on the mean stress, as observed on most rock samples. The initiation and growth of cracks for brittle rocks are modeled by a softening behavior in the post-peak in the framework of plasticity theory; (b) the simulation of triaxial compression tests as model verification. Finally, the numerical modeling provides the localization of the EDZ and the potential instability areas in the vicinity of stopes located around the pilot area of the mine works at the Garpenberg mine (Boliden Mines). The obtained results are punctually validated by the local in-situ stress measurements.

2. Mechanical model formulation

The mechanical behavior of geomaterials is widely varied and depends mainly on the confining stress (or mean stress) and the loading paths. At low stress confining levels, rocks break by the creation of one or more shear planes or bands accompanied by a strain-softening behavior characterized by microcracks dilatancy and grains rotation at the microscopic scale. Under high mean stresses, rocks undergo a hardening behavior which is microscopically associated with volumetric strains. More precisely, for most geomaterials subjected to triaxial compressions under low to moderate confining pressures, the following characteristics of stress-strain curves are typically observed[8,9]: (a) a linear isotropic elastic behavior after a short non-linear phase corresponding to the closure of initial pores and microcracks (b) a strain-hardening in the pre-peak region corresponding to the initiation and growth of microcracks modeled generally by the plasticity theory or the damage mechanics through the concept of effective stress and the hypothesis of strain equivalence (c) a strain-softening after reaching the peak strength (failure) associated with a progressive loss in material cohesion and a decrease in strength (d) a phase where the rock strength remains practically constant. Regarding the elasto-brittle materials where the initial microcracks closure and the growth of microcracks in the pre-peak domain can be neglected in a first approximation (as it is the typical case of hard rock masses studied herein at the Garpenberg mine), we will consider an isotropic elastic linear behavior before the peak.

The Hoek-Brown failure criterion is widely used in the field of rock mechanics and rock engineering. Its limitations and simplifying assumptions are well known and were largely documented.[10] In this study, this criterion was generalized in terms of the three stress invariants. One of the most important limitations of the Hoek-Brown criterion is its non-dependency on the intermediate principal stress σ_2. Subsequent experimental studies have since suggested that the intermediate principal stress has a substantial influence on the rock strength.[11,12] This has led to the development of several 3D versions of the Hoek–Brown failure criterion.[13–16]

It is well known that the three principal stresses σ_1, σ_2 and σ_3 (compressive stresses being taken as negative and $\sigma_1 > \sigma_2 > \sigma_3$) can alternatively be expressed in terms of mean stress (p), generalized deviatoric stress (q) and Lode's angle (θ) and vice versa:

$$\begin{cases} \sigma_1 = \frac{2q}{3} sin\left(\theta + \frac{2\pi}{3}\right) + p \\ \sigma_2 = \frac{2q}{3} sin(\theta) + p \\ \sigma_3 = \frac{2q}{3} sin\left(\theta - \frac{2\pi}{3}\right) + p \end{cases} \tag{1}$$

where $p = \frac{tr(\underline{\sigma})}{3}$, $q = \sqrt{3J_2} = \sqrt{\frac{3}{2}\underline{S} : \underline{S}}$ and $-\frac{\pi}{6} \le \theta = \frac{1}{3} Arcsin\left(\frac{-3\sqrt{3}}{2}\frac{J_3}{{J_2}^{3/2}}\right) \le \frac{\pi}{6}$ with $\underline{S} = \underline{\sigma} - p\underline{\delta} J_2 = \frac{tr(\underline{S}^2)}{2} = \frac{1}{2}\underline{S} : \underline{S}$ and $J_3 = \frac{tr(\underline{S}^3)}{3}$.

$\underline{\sigma}$ is the stress tensor, tr($\underline{x}$) denotes the trace of the tensor $\underline{x}$, J_2 and J_3 are the second and third deviatoric stress invariants respectively and $\underline{\delta}$ is the Kronecker tensor.

Relations (1) allow to express the classical Hoek-Brown criterion in the 3D-stresses space (p, q, θ). After some manipulations, the following generalized yield function (F_s) is proposed on the basis of[16]:

$$F_s = \frac{4}{3}\frac{\cos^2\theta}{\sigma_c} q^2 - m\left(\frac{\cos\theta}{\sqrt{3}} - \frac{\sin\theta}{3}\right) q + mp - s\sigma_c \tag{2}$$

where σ_c is the uniaxial compressive strength of the intact rock, m and s represent the rheological behavior parameters.

The significance and quantification of m and s differ from the well-known dimensionless empirical parameters of Hoek-Brown which