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Initialization of highly heterogeneous virgin stress fields within the numerical modeling of large-scale mines

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ABSTRACT

The objective of the present paper is to propose a methodology to numerically simulate (i.e., initialize) the pre-mining stress field in complex but rather frequent situations in which the classical overburden-weight assumption and existing stress measurements are in disagreement and where the stresses strongly vary from one zone to another, even at constant depth. This methodology is illustrated by the case of a deep mine in France that exploits a 10°-dipping coal seam, in which numerous stress measurements were carried out. Virgin principal stresses in this mine have been shown to be highly heterogeneous and anisotropic. To correctly reproduce such a challenging initial stress state in a numerical model and to be able to later calculate mining-induced stresses, five distinct methods (M#1 to M#5) are successively presented and compared, along with their advantages and drawbacks. All of them are based on “fixed” boundary conditions, with null normal displacements on all lateral boundaries except on the top one, which is considered as a free surface of the Earth coinciding with the natural flat topography. The initial conditions of the model assume that the pre-mining stress components linearly depend on the Cartesian coordinates x, y and z (depth), and the Simplex Method is used to calculate the linear coefficients by minimizing the squared difference between the measured stresses and their simulated values. We show that the use of 3D stress gradients produces more realistic results than a 1D vertical stress gradient.

1. Introduction

Numerical modeling is an effective tool in rock mechanics to describe the rock mass behavior before and during underground mining operations, which is a key issue for stability assessment and rock burst prevention, for example. Nevertheless, to perform a reliable stress state computation while mining is underway, a coherent initial stress state must be first built up within the model that agrees with in-situ measurements, if available, and/or with other assumptions regarding the overburden weight[1] and horizontal-to-vertical stress ratios[2–5] or stress orientations.[6]

This stress-initialization step is sometimes neglected, even though it may strongly influence the calculated stress changes, especially in the case of non-elastic rock mass behavior. Various authors have already tackled the issue of initializing the stress field in their numerical models. For example, Baryshnikov and Gabkhova[7] utilized a 2D numerical model for the Aikhal open-pit mine to test the influence of the vertical-to-horizontal stress ratio on the results of the numerical modeling. They used two distinct models to initialize the virgin stress state. In the first model, the horizontal stress was equal to the vertical stress (the weight of the overburden), and in the second model, the horizontal stress is a function of the vertical stress and Poisson' ratio. Other researchers[8–13] used the horizontal-to-vertical stress ratio to initialize the stress state.

McKinnon[14] proposed a calculation-based method to determine the boundary tractions to be applied in a model based on six locations of stress measurement. Unit normal and shear tractions are applied to the model boundaries, and the response is computed at the location of the measurement points in the model. McKinnon concluded that this method would not be effective in the case of heterogeneous rock mass because the stress distribution will not depend on rock stiffness. To obtain an appropriate methodology for heterogeneous rock masses, McKinnon[15] established a back analysis for more than 40 points of in-situ stress measurements by assuming that i) the rock mass behavior is heterogeneous, ii) the horizontal and vertical stresses are principal stresses at the boundaries of the numerical model and iii) virgin stresses are constituted by tectonic and gravitational stress components. This method produced the

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same principal stress values as those measured. However, the limitation of this method is that the computed far-field tectonic stress tensors for different structural domains had different orientations than those measured, which is not compatible with the anisotropic stress field with high principal stresses orientation in respect to the North direction.

Bewick et al.[16] used fixed boundaries at a great distance from the area of interest. They found that this method is acceptable if the rock mass is homogeneous with little or no variation in the material stiffness. Thus, they used another condition, i.e., the displacement-boundary condition, by compressing the model until it had been strained sufficiently to produce a global stress field with magnitudes similar to those anticipated in the area being modeled. When the stress state within the model sufficiently matched the measured stress state in the field, the boundaries of the model were fixed prior to continuing with the rest of the simulation in the normal manner.

Perman et al.[17] compared the calibrated stress field with the measured in-situ stress values in the case of the Malmberget Mine in Sweden by assuming that the vertical stresses are equal to the overburden weight and that the horizontal stresses are functions of the vertical stress. However, this method will not be appropriate in the case of the existing difference between the measured vertical stress and overburden weight; moreover, the shear stresses could not be equilibrated initially within the model.

Obara et al.[18] proposed a procedure for back-analyzing the regional strain and stress fields with a 3D boundary element method based on the measured local stresses reported by Li et al.[19] Then, they estimated the stress state at the level of mine excavation by performing a 3D finite element analysis using boundary conditions from the analyzed regional strain and stress fields. In horizontal strata, Esterhuizen et al.[20] supposed that the depth of the overburden determines the pre-mining vertical stress and that the horizontal stress is not only depth dependent but also influenced by a tectonic component. However, their method is not applicable in the case of an inclined mining seam with an anisotropic stress field.

Shnorhokian et al.[21] proposed two approaches to initialize the stress state in their model in the case of a heterogeneous rock mass at the Garson Mine in Sudbury, Ontario. In the first one, all model boundaries are fixed; the vertical stress results from the overburden weight, while the horizontal stresses are linear functions of depth. The second approach is the boundary traction model, which is based on applying stresses at all model boundaries. The authors observed that unlike field measurements, the first method generates uniform pre-mining stress gradients across heterogeneous geological units at a given depth, while the boundary traction method was able to produce pre-mining stresses correlated to rock mass mechanical properties (e.g., stiffer geological units carry higher stresses than the others). On the other hand, the disadvantage of applying stresses at the boundary of the model is that doing so produces displacement at the model boundary, which in turn will have an effect on stress redistribution after mining. Table 1 summarizes the different methodologies used to reproduce the initial stress field.

In this paper, we successively present and then compare five distinct methods (M#1 to M#5) used to numerically simulate (i.e., initialize) the pre-mining stress field. All of them are based on "fixed" boundary conditions, with null normal displacements on all lateral boundaries as well as the bottom one, except on the top one, which is considered as a free surface of the Earth, coinciding with the natural flat topography. The initial conditions of the model assume that the stress components linearly depend on the Cartesian coordinates x, y and z (depth), and the Simplex Method is used to calculate the linear coefficients of stress gradients by minimizing the squared differences between the predicted stress values from the numerical model σ_n and the measured stress

Table 1
Summary of different methodologies used to reproduce the virgin stress field.

Numerical model	Vertical stress	Horizontal stresses	Boundary condition	Calibration method	Rock mass	Ref.
Discrete element	Unit value	Unit value	Free	Measured stress points	Homogeneous	[?14?]
Discrete element	Unit value	Unit value	Free	Measured stress points	Heterogeneous	[?15?]
Discrete element Finite element	Constant value	Constant value	Free	Measured stress points	Homogeneous with little or no variation in the material stiffness	[?16?]
Finite difference	Overburden weight	Constant function of the vertical stress	Free	In-situ stress measurements	Heterogeneous	[?17?]
Finite element	Overburden weight	Constant function of the vertical stress	Free	Measured principal stress	Homogeneous	[?18?]
Boundary element	Overburden weight	Constant function of the vertical stress	Free	Measured principal stress	Homogeneous	[?19?]
Finite difference	Overburden weight	Function of vertical stress and modulus of elasticity[5]	Fix	With the coal pillar strength	Heterogeneous	[?20?]
Finite difference	Overburden weight	Constant function of the vertical stress	Fix	Principal stresses at some points	Heterogeneous	[?21?]
Finite difference	Constant at certain level value with gradient in the vertical direction	Constant at certain level value with gradient in the vertical direction	Free	Principal stresses at some points	Heterogeneous	[?21?]

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