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An equivalent discontinuous modeling method of jointed rock masses for DEM simulation of mining-induced rock movements

Bayisa Regassa[a,b], Nengxiong Xu[a,*], Gang Mei[a]

[a] School of Engineering and Technology, China University of Geosciences (Beijing), 100083 Beijing, China
[b] School of Earth Sciences, Addis Ababa University, Ethiopia

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ABSTRACT

The Discrete Element Method (DEM) is of obvious and inherent advantages in simulating large displacements and discontinuous deformations of rock masses, and thus is suitable to simulate the mining-induced rock movements. However, when the region of the DEM calculation model is large, for example, when both the length and width of the research area are larger than several hundreds of meters, the rock mass in the model range often contains a large number of actual joints. If the calculation model is built according to the distribution of the actual joints, the calculation model of DEM will consist of a large number of blocks, which would lead to the impossibility of numerical calculations. To address this problem, an Equivalent Discontinuous Modeling Method (EDMM) of jointed rock masses for DEM simulation of mining-induced rock movements is proposed in this paper. In this method, an actual geological body with a complex joint system will be simplified into an Equivalent Discontinuous Model (EDM), which is a DEM calculation model with a simple hypothesis joint system. The approach for determining the mechanical parameters, i.e., the cohesive strength (C), the internal friction angle (ϕ), the joint normal stiffness (JKN), and the joint shear stiffness (JKS), of the hypothetical joints of the EDM is the core of the proposed EDMM. The main procedure of the proposed EDMM is composed of: (1) for each subarea of an EDM, building a group of Equivalent Discontinuous Cube Models (EDCMs) that are of different joint spacings; (2) determining the joint mechanical parameters of each EDCM based on the mechanical properties of the actual rock masses of the subarea; (3) establishing the relationships between the joint spacings and joint mechanical parameters for each subarea of EDM; and (4) determining the mechanical parameters of the hypothesis joints in each subarea of the EDM according to these relationships. By exploiting the EDM, the DEM numerical simulation is performed to simulate the mining-induced rock movements and failures. To demonstrate the applicability, the proposed EDMM was employed to simulate the rock movements and failures triggered by mining under the western open-pit final slope of Yanqianshan iron mine.

1. Introduction

Underground mining can cause rock mass movement and failure, such as the caving of the roof, surface subsidence, and sliding of side walls.[1–4] A reliable prediction of the movement and failure conditions of the rock masses surrounding underground mining area would be useful to develop a safe mining layout design and select a suitable mining parameters and supporting system.[5] It thus needs to investigate and predict the movement and failure condition of the rock mass surrounding the mining area before and during the mining processes.

Currently, there are extensive studies that have been carried out using different methods to predict the movement pattern and failure condition of jointed rock masses that induced by mining activities. The empirical approach is one of the methods that used to predict the rock mass movement pattern and failure condition in the mining area.[6] However, its adequacy is limited when it deals with the complex geological formation as it suffered from the numbers of simplification. The numerical modeling is one of the powerful methods to simulate the movement and failure condition of rock masses surrounding the mining area due to its capability of considering different mechanical and geometrical features of the joints and intact rock properties.[7]

The continuum-based numerical modeling methods, such as Finite Element Method (FEM) and Finite Difference Method (FDM), are widely used to analyze and predict the movement and failure of the rock mass surrounding the mining area.[8–13] In these kinds of numerical modeling methods, the discontinuous jointed rock masses are treated as continuous ones using the Equivalent Continuous Method (ECM).[14–16] However, when using these continuum-based numerical modeling

* Corresponding author.
E-mail address: xunengxiong@cugb.edu.cn (N. Xu).

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methods, it is quite difficult to model some complex underground mining-induced rock mass behaviors, such as the fracture opening, block rotation, and large displacement.

Discrete Element Method (DEM) is a discontinuum-based numerical modeling method which is commonly focused on fractured or particulate geological media.[17,18] It is a powerful numerical modeling technique to simulate discontinuous rock masses movement and failure. It is inherently capable of simulating the large displacements of individual blocks, block rotation, fracture opening, complete detachments; and it can recognize new contacts automatically as the simulation progresses.[19] Therefore, there are extensive studies conducted using DEM to simulate the mechanical activities of jointed rock masses.[1,7,20–24]

The adequacy of DEM modeling results depends heavily on the accuracy of in-situ rock mass fractures information such as the fractures system geometry and fractures mechanical parameters.[19] For a specific mining area, there are a large number of joints, with various joint spacing at different sections of mining domain. The DEM can adequately simulate this mining area if it accurately considers these actual complex rock mass features. However, if all actual joints are added in the DEM calculation model as they are in the field, it will result in excessive numbers of blocks in the DEM calculation model, which can cause the calculation difficulty.[24,25]

To solve this problem, Xu et al.[24] proposed a numerical modeling method which involves two main steps: first, the rock masses in the research area are simplified as an equivalent jointed rock mass model; then, a back analysis method is used to invert the mechanical parameters of the model. This method did not consider the influence of joint spacing on joint mechanical parameters in the equivalent model. To improve the method in Xu et al.[24], an Equivalent Discontinuous Modeling Method (EDMM) is proposed in this paper. In this method, a complex discontinuous geological body is simplified to be an Equivalent Discontinuous Model (EDM); then, the relationships between joint spacings and joint mechanical parameters are established for determining the joint mechanical parameters for each subarea of EDM; finally, the DEM numerical simulation is performed to simulate the mining-induced rock movements and failures.

2. Methodology

2.1. Outline and basic concepts of the proposed method

(1) *Outline of the proposed method*

In this paper, the Equivalent Discontinuous Modeling Method (EDMM) is specifically proposed to reduce the number of actual joints developed in the rock mass by simplifying a large number actual joint sets into a significantly small number of hypothetical joint sets.

The proposed EDMM is composed of four main procedures: (I) building an EDM of the study area; (II) establishing the relationships between joint spacings and joint mechanical parameters for each subarea of the EDM; (III) determining the joint mechanical parameters for the EDM; and (IV) conducting the DEM numerical simulation using 3DEC code[19] to analyze the rock movement and failure in the study area.

To avoid confusion and for the sake of convenience, we refer the *Actual Geological Body* in the study area as AGB, and its corresponding equivalent discontinuous model as EDM. Any EDM is the equivalent model of a given AGB.

(2) *Features of the EDM*

An EDM is a calculation model that simplified from the AGB of the research area. The main features of an EDM are as follow.

(I) An EDM includes several groups of hypothetical joints and the joint groups should be formed based on the simplification of the dominant joint groups distributed in the AGB of the study area. The occurrence of each joints group is determined based on the mean occurrence of one dominant joint group in the AGB.

(II) All joints in one joint group are parallel to each other, and each

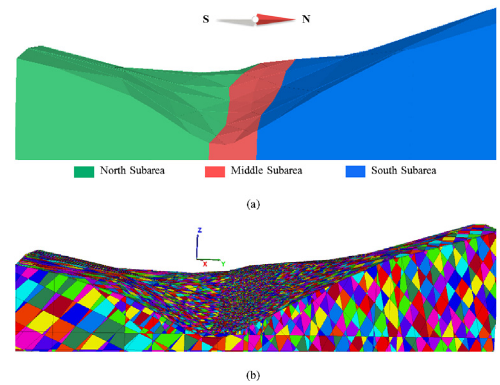

Fig. 1. (a) A 3D geological model of the study area and (b) An EDM of the study area.

joint is simplified as an infinite plane cutting through the EDM.

(III) The joint spacing of any two adjacent joints in the joint group is determined according to the possible disturbance of the rock masses. That means, in the area with strong rock masses disturbance the joint spacing is small, while in weakly disturbed area the joint spacing is large.

(IV) An EDM is divided into a series of blocks by the joints, and each block was treated as a rigid body.

2.2. Process of the proposed method

(1) *Building an EDM*

The sub procedures for building an EDM are as follows: (I) building an actual geological model of the study area using the geological modeling technology[35] according to the actual geological conditions (Fig. 1(a)); (II) determining the dominant joint groups distributed in the study area and the joint spacings of any two adjacent hypothetical joints to create a hypothetical joints system; (III) adding the created hypothetical joints system into the geological model using the DEM modeling function provided by the numerical software 3DEC[19] and cut the geological model into a number of rock blocks to form an EDM (Fig. 1(b)).

(2) *Determining the mechanical parameters of the EDM*

In the EDM, all blocks are assumed as rigid bodies; therefore, it only needs to determine the mechanical parameters of the joints. Since the joints in an EDM are hypothetical, the mechanical properties of these joints are different from that of actual joints distributed in the AGB of the study area.

To determine its joints mechanical properties, the EDM was first divided into different subareas based on their geological formation. Each subarea can be treated as a homogeneous rock mass formation. However, to reduce the number of joints in an EDM, relatively small joint spacings are arranged in the zones that are significantly affected by the underground mining, while the relatively large joint spacings are arranged in the zones that are less affected by the underground mining. Accordingly, in one subarea of an EDM, the joint spacing is possible to vary from a section to another section. However, the rock masses mechanical properties cannot be changed in one subarea, as it is a homogeneous rock mass.

Hence, to obtain uniform rock mass mechanical properties throughout the domain of a subarea, the effect of joint spacing variation is compensated by the changeable joint mechanical properties in the subarea. Thus, the different joint spacings in one subarea of an EDM do not indicate the variation of rock mass mechanical parameters in a given subarea. Small joint spacing was arranged for the highly disturbed rock mass region to allow the more free movement of rock blocks in that region.

To determine the mechanical properties of joints with different joint

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