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Probabilistic block theory analysis for a rock slope at an open pit mine in USA

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ABSTRACT

A new formulation is given to conduct a probabilistic block theory analysis. A new computer code (PBTAC) is developed to perform both deterministic and probabilistic block theory analysis. The variability of the discontinuity orientation and shear strength is incorporated in the probabilistic block theory analysis. Discontinuity orientation is treated as a bivariate random variable including the correlation that exists between the dip angle and dip direction. PBTAC code was applied to perform both deterministic and probabilistic block theory analyses for a part of an open pit mine in USA. Needed geological and geotechnical data for the analyses were obtained from field and laboratory investigations. The variability of the discontinuity orientations resulted in important differences between the probabilistic and deterministic block theory analyses results. The results confirmed that the design value selected for the maximum safe slope angle (MSSA) for a particular region in the open pit mine based on the deterministic block theory analysis can be on the unsafe side. In summary, the results showed clearly the superiority of probabilistic block theory analysis over the deterministic block theory analysis in obtaining additional important information with respect to designing rock slopes. The calculated values agree very well with the existing almost stable bench face angles reported by the mining company.

1. Introduction

Open-pit mining is one of the most important technologies for extracting mineral resources from the earth's crust. Production rates of open pits have progressively grown over the last 100 years and they will continue to grow in the future [1]. The ultimate slopes of an open pit mine are generally excavated to the steepest possible angles because the economic consequences of the excavation angles are significant [2]. For large scale open pits, changes in slope angle by approximately 2–3° may correspond to hundreds of millions of dollars in project value [3]. However, steeper slope angles result in higher probabilities of slope failure. Therefore, it is critical to calculate the maximum safe slope angles (MSSA) and also to estimate probabilities of slope failure with respect to different cut slope dip angles.

The open pit mine slope stability is one of the geotechnical subjects dominated by variability and uncertainty because the slopes are composed of natural heterogeneous materials containing a large number of discontinuities. In discontinuous hard rock masses, the variability and uncertainty of rock slope stability analyses mainly arise from discontinuity geometry and discontinuity strength. Application of probabilistic analysis has provided an objective tool to quantify and model variability and uncertainty [4,5]. The first two types of probabilistic analyses to rock slope stability have been applied using either kinematic or limit equilibrium analysis [6–10].

The block theory, introduced by Shi [11,12] and Goodman and Shi [13], is a very useful technique to investigate possible failure modes of rock blocks and to determine MSSA for rock slopes [14,15]. The block theory considers block formation by discontinuity planes along with a cut slope, without assuming presence of lateral release planes as in kinematic analysis. Therefore, the results coming from the block theory analysis can be considered to be closer to the reality than that coming from kinematic analysis [14,15]. However, the block theory is usually used to perform deterministic analysis using single fixed values (typically mean values) to represent orientation of discontinuity sets and strength parameters [14–19]. The deterministic block theory analysis is usually conducted using the stereographic projection method. In performing analysis for a field rock slope stability problem, it is tedious and very time consuming to use the stereographic

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Nomenclature

BP	block pyramid
PBTAC	Probabilistic Block Theory Analysis Code
CSDD	cut slope dip direction
DP	Devonian Popovich
DRC	Devonian Rodeo Creek
EP	excavation pyramid
I	total number of discontinuity cell combinations
J_i	total number of key blocks for discontinuity cell combination i
JP	Joint Pyramids
K	number of possible ϕ intervals
m	cut slope dip angle
MSSA	maximum safe slope angle
n	total number of all blocks formed by all discontinuity combinations considering the total repeat number
n_{ijms}	number of MSSA between 0 and m of key block j of discontinuity cell combination i with respect to failure mode s
n_{ims}	number of MSSA between 0 and m of all key blocks of discontinuity cell combination i with respect to failure mode s
n_{ms}	total number of MSSA between 0 and m of all key blocks for all discontinuity cell combinations considering the TRN with respect to failure mode s
$P_{ms}(\alpha, \varphi_k)$	instability cumulative probability of the slope with CSDD = α and $\varphi = \varphi_k$ with respect to failure mode s
$P_{ms}(\alpha)$	instability cumulative probability of the slope with CSDD = α with respect to failure mode s including the distribution of friction angle
RN	repeat number
s	failure mode
S1	sliding along the discontinuity plane from set 1
S2	sliding along the discontinuity plane from set 2
S3	sliding along the discontinuity plane from set 3
S12	sliding along the line of intersection of two discontinuities from sets 1 and 2
S13	sliding along the line of intersection of two discontinuities from sets 1 and 3
S23	sliding along the line of intersection of two discontinuities from sets 2 and 3
SP	space pyramid
TRN	total repeat number
TRN_i	TRN of discontinuity cell combination i
α	value of cut slope dip direction
ϕ	friction angle
δ	a random number between −1 and 1

projection method to perform a probabilistic block theory analysis because a probabilistic analysis requires changing the discontinuity orientation combinations as well as changing the discontinuity strength. The vector based method is more suitable to perform probabilistic block theory analysis.

A few studies have been conducted to estimate key block formation probabilities and likelihood of key block failure [20–22]. In the paper by Hatzor [20], first a joint combination probability is calculated using joint set normal vectors and corresponding linear frequencies. Then a block failure likelihood probability is calculated using the product of the following three independent parameters: (a) the aforementioned joint combination probability, (b) a block instability parameter which is a function of net sliding force and (c) a shape parameter. The methodology has been applied to joint orientation data sampled from side walls of two pilot tunnels. Joint friction angle has been treated as a deterministic parameter in the calculations. Successes and failures of the approach obtained from the results are discussed in the paper. Chen et al. [21] have applied first-order second-moment technique along with the reliability index to calculate removability of a rock block and its failure probability. Beta and Fisher distributions have been used to represent the variability of the dip angle and dip direction of joints. The dip angle and dip direction have been treated as uncorrelated parameters (even though theoretically not justifiable) to simplify the analysis in using the beta distribution to represent each of the two parameters. Joint friction angle is considered as a deterministic parameter in the study. Monte-Carlo simulations also have been conducted to compare the results with the aforementioned approach. A hanging wall case study had shown that with the same mean values of the random variables the block removable probabilities differ significantly if the dispersions of the random variables are different. Chen [22] in another study has performed a probabilistic key block analysis to evaluate stability of a mine ventilation shaft constructed in a granitic rock mass. The variability of the dip angle, dip direction and friction angle has been modeled using a beta distribution. Key block failure probabilities, the probabilistic distribution of factor of safety and the probabilistic distribution of potential maximum key block volumes have been calculated in the study. The results have indicated that although the safety factor calculated based on the mean values of the variables was above 1.0 for the stability of the most critical key block, the block had a considerable probability of failure with a significant rock volume due to variations in discontinuity orientations and rock properties.

In this paper an entirely different type of probabilistic block theory analysis, compared to the ones discussed above, is presented for a part of the rock mass (see Fig. 1) that exists in an open pit mine in USA. In the analysis, the joint orientation has been considered as a bivariate random variable including the correlation that exists between the joint dip angle and dip direction angle. Also the variability of the discontinuity shear strength is incorporated in the analysis. To accomplish the task, first the data available on geology and discontinuity orientations measured through manual

Fig. 1. Aerial view of the open pit mine and the location of the studied slope (from google earth).