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Research Paper

Key-block based analytical stability method for discontinuous rock slope subjected to toppling failure

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ABSTRACT

This study introduces a simplified semi-distinct element algorithm for discontinuous rock slopes under toppling instability assessment based on block theory. The presented algorithm is developed to investigate block, flexural and block-flexural types of toppling failures which have been coded in the Python high-level programming language. In order to investigate toppling instabilities for different modes, the three modelling steps, namely, geometrical, behavioural and mechanical simulations were conducted to appoint high-order calculation trending loops. These loops were based on the analytical description of modified second-order reliability method with first-order efficiency to determine the factor of safety values for discontinuous rock slopes. Each type of toppling failure was described based on main assumptions that were modified by geometric qualifications such as the analytical procedure, single block slip, and the Voronoi diagram algorithm for the stability analysis of the three different failure types. According to the stability assessment results of the studied slopes which were verified by the distinct numerical method via UDEC software, it has been clarified that the results obtained from the algorithm and the numerical analysis were in an appropriate trend. The used algorithm is superior in pinpointing the critical sliding zones, safety factor estimation and progressive failure analyses as compared to the numerical analyses. Moreover, the block theory based algorithm has higher processing capability and speed with respect to the numerical method.

1. Introduction

Müller [1] is the pioneer researcher who has first specified the overturning phenomenon and sliding on reservoir host rocks during the instability assessment studies of the Vaiont dam. Ashby [2] introduced a straightforward computational criterion to evaluate this kind of phenomenon and used the ‘toppling’ concept for the first time for these kinds of instabilities. Cundall [3] used a computer simulation for the description of large-scale rock block progressive movements for a specific case. Since then, a number of researchers have worked on toppling phenomenon as a case study along with the application of numerical and experimental approaches until Goodman and Bray [4] presented an exclusive quantification for toppling in rock masses. They classified toppling failure into two categories, namely, main (block, flexural, block-flexural) and secondary (head of slide toppling, toe of slide toppling, column toppling, pit crest toppling) clusters based on discontinuity network. Wyllie [5] described three historical cases for rock slope toppling failure and stability analysis based on Goodman and Bray's analytical solution. After the Goodman and Bray [4] toppling classification globalisation, a considerable number of researches worked on classification systems including block, flexural, and block-flexural toppling of various cases [6–16].

Application of several theories and computer-based technologies for the calculation of different modes of slope structural failures has led researchers to focus more on hybrid methodologies to evaluate the toppling failure mechanism. One of the most flexible theories considered in slope instability investigations is block theory. After Goodman and Shi’s block theory globalisation in 1985 [17], many scholars used the theory to investigate discontinuous rock mass instability based on rock block geometrical spatial distribution. This theory’s flexibility enabled to perform coupled stability analysis based on limit equilibrium and geometrical rock body conditions in two-dimensional (2D) and three-dimensional (3D) spaces [18–20] where the factor of safety (F.S) and probable sliding surfaces were computed from the structural displacements. In fact, by considering the formulations of the discontinuity network in rock slopes based on limit equilibrium-

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based stability relations, simplified, accurate and rapid assessment of any type of geometrical failure with higher processing capability was achieved. Of these failures, planar and wedge failures are estimated directly from the computational and projection approaches. For circular/massive or toppling failures, the use of block analysis is required for inclusion of several computational assumptions. Regarding the toppling failure modes, the block theory should be rectified for these modes. For this purpose, according to Goodman's theory, it is first necessary to investigate and identify especially the critical rock blocks which are known as ‘key blocks’ that are responsible for progressive instabilities in discontinuous rock slopes. Then, considering the type of rock blocks (geometrical rock body condition) and the failure mechanism, slope stability is evaluated by the limit equilibrium methods. In the toppling cases, application of ordinary block theory is associated with considerable computational errors (i.e., it is not possible to perform this analysis directly). Thus, after the identification of the types of rock blocks in the slope, depending on the failure mechanism, the appropriate force/moment geometrical analyses based on limit equilibrium methods are conducted to achieve proper stability. For example, in order to assess the stability of the slip phenomenon at the surface, force equilibrium is used, whereas for the rotational condition, moment equilibrium is utilised.

This study applies an algorithm for simplified stability analyses of block, flexural and block-flexural toppling failure types based on coupled block theory which has been coded in Python [21]. In this application, the equilibrium equations are utilised for sliding and toppling failure mechanisms along with using specific relations as presented in the following sections.

2. Rectified key block analysis for toppling failure

Toppling involves rock column rotation about a fixed point on a solid base which is classified as main and secondary toppling failure by Goodman and Bray [4]. The main toppling group is divided into block toppling, flexural toppling and block-flexural toppling as briefly described below and as presented by Fig. 1 [9,14].

2.1. Block toppling

Block toppling occurs in rock bodies and is related to the emplacement of two main discontinuity sets, where the main discontinuity set dips steeply into the face and the secondary discontinuity set widely divides the orthogonal discontinuity and defines the rock slab height. The short rock slabs shaping the slope toe are pushed forward by longer overturning slabs behind the loading and this toe sliding permits additional toppling for the entire mass [6]. Fig. 1(a) presents a simple block toppling failure mechanism with two different mechanisms of ‘sliding’ and ‘rotation’ which control this type of toppling [14]. The stability assessment of block toppling is presented by Eqs. (1) and (2) as follows [9]:

$$P_{n-1}^{toppling} = \frac{\left(P_n(M_n - \Delta x \tan \phi_d) + \frac{W_n}{2}(y_n \sin \psi_p - \Delta x \cos \psi_p)\right)}{L_n} \tag{1}$$

$$P_{n-1}^{sliding} = P_n - \left(\frac{W_n\,[\cos \psi_p \tan \phi_p - \sin \psi_p]}{(1 - \tan \phi_p \tan \phi_d)}\right) \tag{2}$$

where, P and M are sliding/toppling forces and moments in the n^{th} block, W is block weight and Δx_n is the n^{th} rock slab thickness. In block toppling, if sliding occurs in the first block and slab toppling occurs in the other block, the first block is considered as the key block for mass movement.

The first step in key block based stability analysis is to rectify the rock block geometrical condition based on Goodman's procedure [17] and then to identify the key-blocks to solve the stability equation (i.e.,

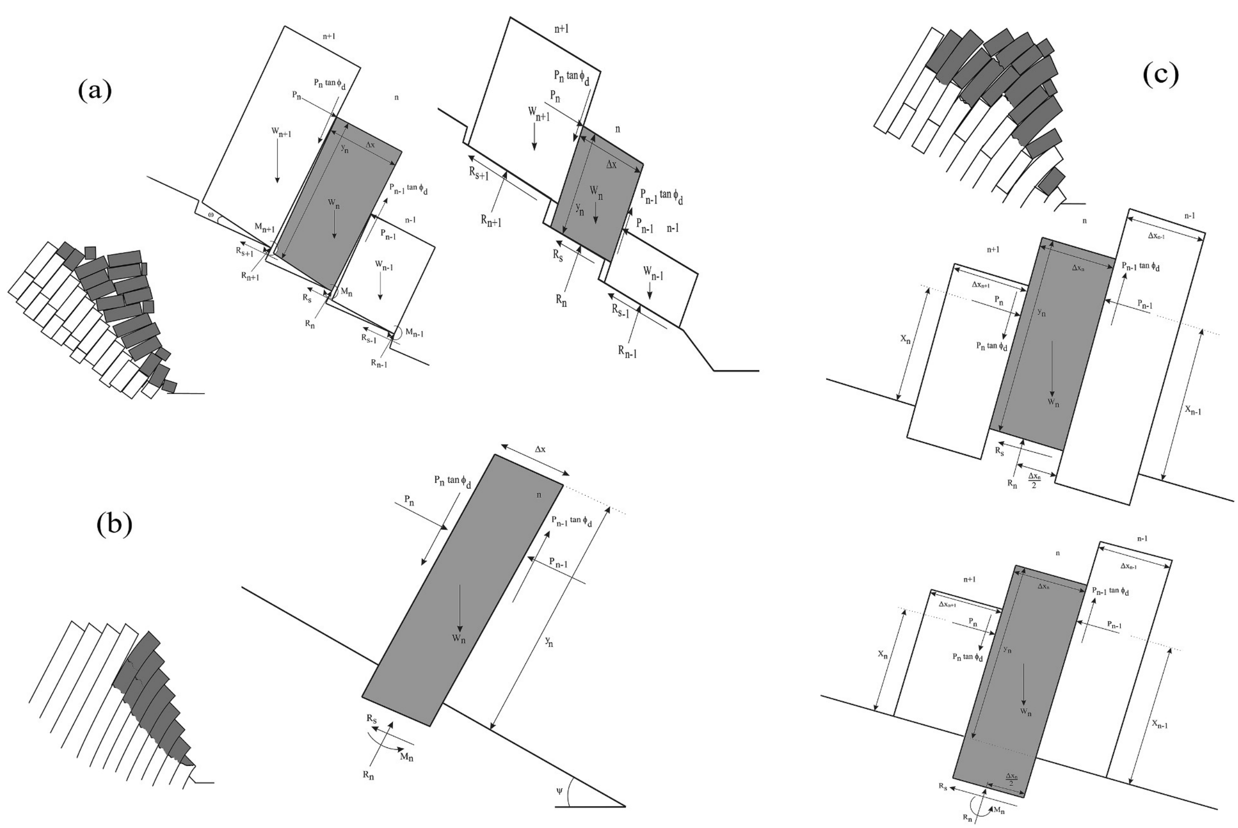

Fig. 1. Toppling failure mechanisms: (a) block toppling, (b) flexural toppling, (c) block-flexural toppling [6,14].