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Application of the discrete element method for modeling of rock crack propagation and coalescence in the step-path failure mechanism

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ABSTRACT

The present study evaluates the discrete element method (DEM) as a tool for understanding the step-path failure mechanism in fractured rock masses. Initially, the study simulates crack propagation and coalescence in biaxial and triaxial laboratory tests. The results of this analysis show that the DEM accurately represents these processes in comparison to other studies in the technical literature. The crack propagation and coalescence processes are important in the step-path failure mechanism for slopes. Simple examples of this mechanism were modeled, and their results were compared with those of the analytical model proposed by Jennings (1970). Among the possibilities suggested by Jennings, modeling with DEM did not provide a good approximation for the case of co-planar cracks, for which failures in the intact rock bridges should only be caused by shear forces. In modeling with DEM, tensile failures occur within the sliding block, generating forces that are not considered in the Jennings model. The non-coplanar crack condition provided a better approximation, since the Jennings model formulation for this case includes the tensile failure of the rock. The main advantage of the DEM over other computational tools is its micromechanical representation of discontinuous media, which permits a better understanding of the step-path failure mechanism. However, good calibration of the macroscopic parameters of the rock and its discontinuities is necessary to obtain good results.

1. Introduction

The stability of a rock slope is highly dependent on the configuration and spatial distribution of its discontinuities and the maximum height of the slope (Read and Stacey, 2009). The stability of small slopes is controlled by discontinuities, and the most common failure modes are planar, in wedge, and toppling, which can be evaluated using limit equilibrium methods (Hoek and Bray, 1981). However, when the height of a slope becomes much larger than the persistence of its discontinuities, ruptures also involve intact rock in failure mechanisms that are generally little understood (Hustrulid et al., 2000). The relative motion on the discontinuities leads to their propagation through the intact rocks, creating new fractures in the rock matrix.

Of the different failure mechanisms described by Sjöberg (1996), the step-path type is probably the most important for evaluation in high slopes. In this mechanism, the overall rupture surface is formed by the union of several pre-existing discontinuities that propagate by a process called coalescence. These processes are also observed on the microscale. Griffith (1924) (in Whittaker et al., 1992) noted that crack propagation under compressive conditions is caused by tensile stresses that act near the tips of pre-existing cracks. Under these conditions, propagation is initiated, forming primary tensile cracks that propagate in the direction of the applied load (wing cracks - Horii and Nemat-Nasser (1985); Ashby and Hallam (1986); Einstein and Dershowitz (1990) amongst others). In studies performed by Park and Bobet (2009) on gypsite specimens subjected to uniaxial compression, up to three types of fractures propagated as a result of the applied load (Fig. 1): primary cracks generated by tension (Mode I), which initiated at the edges of the crack and contained no pulverized material, and two types of secondary cracks (coplanar and oblique), which are generated by shear (Mode II) and feature pulverized material on the failure surface.

Coalescence is defined as the connection of pre-existing cracks and discontinuities in a rock material via propagation. The connection type depends on the position of the cracks and the type of propagation involved. Several authors have studied this mechanism. For example, Ghazvinian et al. (2012) analyzed the influence of the distance between two co-planar cracks in the coalescence between them using shear test results and numerical simulation using the discrete element method. Kemeny (2003, 2005) considers the time-dependent degradation of rock bridges in the same case, with analytical solutions and distinct element models. Park and Bobet (2009) reported various types of coalescence observed in a gypsite sample subjected to compression (Fig. 2). Wong and Einstein (2008) used a marble sample and studied

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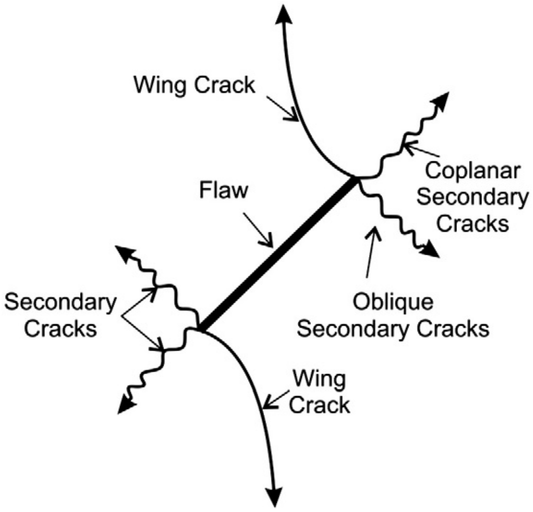

Fig. 1. Propagation of a crack subjected to compression (Park and Bobet, 2009).

the propagation and coalescence of two parallel cracks on the macroscopic and microscopic scales, noting that the microscopic cracks advanced by propagation through crystals in the material. Mughieda and Karasneh (2006) used a synthetic sample composed of silica, sand and cement to observe the variation of the coalescence mechanism as a function of the separation of the cracks, and they concluded that the type of coalescence depends on this separation. Vásárhelyi and Bobet (2000) used the code FROCK to study the propagation of cracks and coalescence from experimental analyses. Mughieda and Omar (2008) used the finite element method (FEM) to determine the stress distribution in a sample with two non-collinear cracks under uniaxial compression. These results were compared to the results of compression tests on synthetic samples made in the laboratory. The result of this analysis shows that tensile stresses acting on the rock bridge between the two cracks causes coalescence.

The same crack propagation and coalescence processes observed in laboratory specimens occur in a fractured rock slope. When the persistence of discontinuities is small as compared to the height of the slope (for example, in high slopes), the overall failure surface is formed by pre-existing discontinuities interconnected by different types of coalescence, and the types of coalescence are determined by the spatial distribution of the discontinuities. This complex failure mechanism is called step-path (Fig. 3). There are few methods for evaluation of this mechanism by determining a safety factor (SF), and they are limited to two-dimensional analyses. Jennings (1970) was the first to establish a methodology for evaluating the SF based on the limit equilibrium. Two main scenarios are considered in his work: coplanar and non-coplanar discontinuities (Fig. 4). In the case of coplanar fractures, their propagation would occur by shear of the rock matrix. The stability of the slope would depend on the shear strength of the discontinuities and the rock matrix that would form a planar failure surface. When the discontinuities are not coplanar, the stability of the resulting stepped surface is evaluated by an "equivalent" critical planar surface. On this "equivalent" surface, the strength of the pre-existing discontinuities and intact rock to tensile and shear stresses are considered. Other methods for evaluating the stability of step-path failures are statistical, such as the technique proposed by Baczynski (2000), which also determines the SF of a critical surface, and those of Einstein et al. (1983) and Miller et al. (2004), which determine the probability of slope failure.

In the present study, the step-path failure mechanism is evaluated by analyzing the propagation and coalescence of cracks with the discrete element method (DEM). This method allows a rock sample or a rock mass to be represented as a set of disk-shaped particles (in the two-dimensional case) or spheres (in the three-dimensional case), which can be joined at their points of contact. Thus, a crack can be represented as the surface where there are no bonds between particles, and its propagation can be represented by the points at which bonds are broken. These analyses will be performed by sequential modeling. Initially, small-scale models (simulations of biaxial and triaxial laboratory tests) will be used to verify the types of propagation and coalescence shown by Park and Bobet (2009). After this verification,

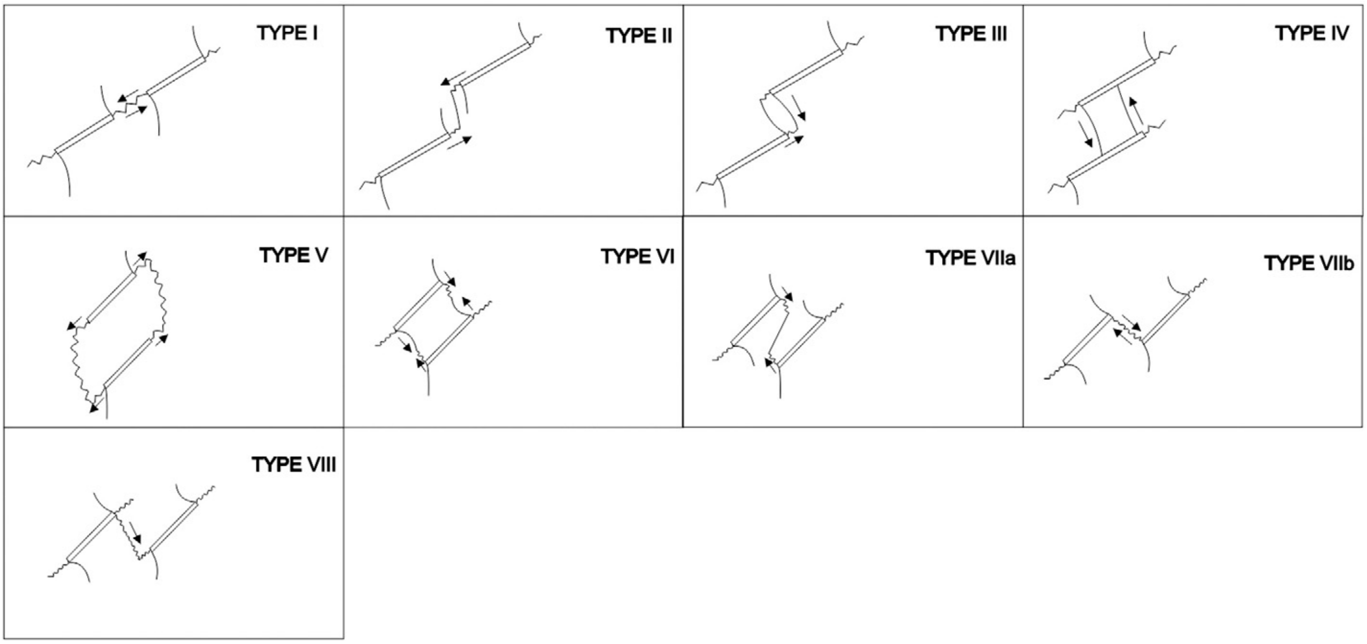

Fig. 2. Types of coalescence (Park and Bobet, 2009).