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A DEM analysis of step-path failure in jointed rock slopes

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ABSTRACT

A numerical analysis of step-path failure mechanisms in rock slopes is provided based upon simulations performed using a discrete element method specifically enhanced for the modeling of jointed rock masses. Fracturing of the intact rock as well as yielding within discontinuities can be simulated to determine the failure surface without any a priori assumption on its location. For both coplanar and non-coplanar sets of discontinuities, failure is the result of the propagation of tensile microcracks that develop in the rock bridges from the tips of pre-existing discontinuity planes in a way similar to wing cracks extensions that can eventually coalesce to form extended step-path failure surfaces. Sensitivity analyses are performed to better understand the critical mechanisms that lead to slope failure and to discriminate between the respective roles played by intact rock and planes of weakness at the onset of failure. For a randomly distributed set of joints that share the same preferential orientation, failure is shown to be dependent on the frictional strength mobilized on the joint surfaces. The results confirm the critical need for a comprehensive and extensive characterization of both mechanical and geometrical properties of discontinuities when assessing the stability of a rock mass.

1. Introduction

Numerical modeling is now widely used in civil and mining engineering to assess stability of rock slopes for safety and economic purposes. However, conventional continuum or classical discontinuum methods experience some limitations to realistically simulate the progressive failure of jointed rock slopes [1,2]. The ability to describe kinematic release through fracturing is a key issue in rock slope stability analysis that cannot be addressed by conventional numerical models. Indeed, assumptions of fully persistent discontinuity sets are only valid in cases where small rock volumes are concerned in the failure process. Moreover, translational rock slope failures generally involve combined failure mechanisms where a complex interaction occurs between pre-existing discontinuities and intact rock bridges whose respective strengths are not necessarily mobilized simultaneously [3–7]. It is therefore critical to consider not only sliding and opening along pre-existing discontinuities but also the possibility of rock bridge failure when assessing the stability of a rock mass.

In slope stability analysis, the objective is to determine the critical factors that control failure to evaluate and anticipate post-failure consequences. In addition to the rock mass strength, these critical factors include the persistence and spacing of the discontinuities as well as their hydro-mechanical properties (cohesion, frictional strength, stiffness, dilation, conductivity, etc.). For several years now, a subsequent effort has been made toward the development of numerical methods able to

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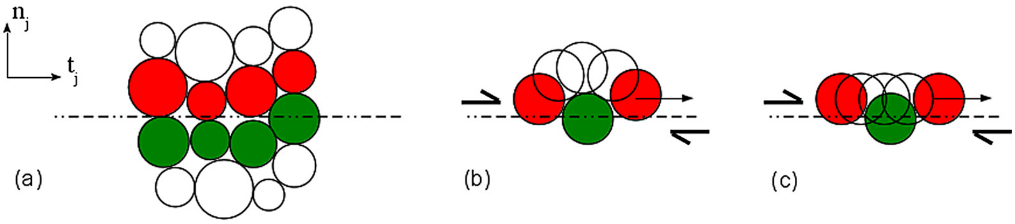

Fig. 1. (Color online.) Illustration of the plane contact logic. (a) A plane segment representing a discontinuity (or joint) overlaid on the discrete elements set. (b) Displacements induced by shearing along a discontinuity plane using the classic contact logic. (c) Displacements induced by shearing along a discontinuity plane using the modified contact logic: the normal and tangential directions to the contact are defined by the joint orientation (n_j, t_j) and not by the particles' contact geometry.

reproduce the progressive failure mechanisms occurring in jointed rock slopes [1,8–10], but it is only recently that complete formulations capable of describing crack initiation and propagation in 3D have been proposed [11–13].

The work presented here is devoted to the application of one of these recently developed numerical approaches to the study of rock slope stability, emphasizing cases where failure occurs through the combination of shearing along discontinuity surfaces and fracturing of the intact rock matrix, the so-called "step-path" failure mode. The formulation of the method is an offspring from the discrete element method which provides the capability of simulating brittle fracture propagation through breakage of the cohesive bonds defined between the particles making up the intact part of the material. As an upgrade to previous attempts made to simulate rock slopes failure using a particulate mechanics approach [8], the method has been recently enhanced with a dedicated feature that provides an efficient and constitutive manner to describe pre-existing fractures and which has proven to capture accurately progressive failure mechanisms in both intact and jointed rock [12,14,15].

In order to identify the parameters likely to play a decisive role in the development of step-path failure surfaces and subsequent translational slope movements, several rock slope configurations involving different joint set patterns were simulated. After a brief description of the model formulation, referenced case studies involving a unique rock bridge are examined in the framework of fracture mechanics with reference to previous works [5]. A sensibility analysis is then proposed in order to emphasize the effects the geometry and the mechanical properties of a given pre-existing joint set can have on slope stability. Finally, the failure mechanisms of a rock slope associated with a more realistic fracture network configuration involving several joint sets are discussed on the basis of the model's predictions.

2. Formulation of the method

The proposed method is implemented into the YADE Open DEM platform [16–18], an extendable open-source framework for numerical modeling based on the discrete element method (DEM). As initially proposed by Cundall and Strack [19], the simulated medium is represented as an assemblage of rigid particles (also called discrete elements) in interaction with each other through force-displacement laws that can be adapted in accordance to the material to be modeled. In the present work, particles are bonded together following a linear elastic–plastic law which has proven to be well adapted to simulate cohesive-frictional materials [14]. As for classical DEM, the algorithm involves two steps. First, according to the loading imposed on the numerical assembly, forces are computed between discrete elements (DE) in interaction with each other. Then, Newton's second law is used to determine, for each DE, the resulting acceleration, which is then time integrated to find the new element positions. This process is thus repeated iteratively according to the prescribed loading path. Because of its formulation, the method can simulate highly nonlinear behaviors characteristic of brittle materials as a result of local bond breakage in both tensile and shear failure modes. In order to better simulate rock-like behaviors, YADE's formulation has been recently upgraded with a specific feature dedicated to render material texture [14]. Specifically, it has been shown that, by controlling the density of contacts per particle, the degree of interlocking of the DE constituting the numerical medium could be adjusted to mimic the microstructure of the material to model. By doing so, the simulated behavior can be accurately adjusted to reproduce the characteristic features of brittle rock, i.e. a high value of the tensile strength to compressive strength ratio and a non-linear failure envelope, which is not possible with classical DEM formulation (see [14] for details).

In addition, the code has been enhanced to take explicitly into account pre-existing discontinuities (or joints) into its formulation [12,15]. Inspired from the smooth-joint contact logic developed by Cundall and co-authors for the development of the Synthetic Rock Mass [20], discontinuities are considered as planar surfaces which can be overlaid on the discrete element set. The interaction forces between DE located on each side of a discontinuity surface can thus be identified and reoriented depending on the normal and tangential directions of the plane as illustrated in Fig. 1.

Using this specifically adapted contact logic, the structural effect induced by discontinuities on the fabric of the medium can be explicitly accounted for, ensuring furthermore a constitutive behavior of the simulated joint surface as demonstrated in [12]. Indeed, contrary to the classic contact logic, the enhanced scheme enables to simulate a behavior that is not dependent on the resolution or roughness of the joint surface which emerges from the spherical shape of the DE. The interface behavior is implemented according to the Mohr–Coulomb theory. The cohesion C, tensile strength T and friction