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PROGRESSIVE FAILURE MECHANISMS IN JOINTED ROCK: INSIGHT FROM 3D DEM MODELLING

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Abstract. Instabilities occurring in rock masses are generally related to the presence of pre-existing discontinuities and the destabilization process often related to the complex interaction between the discontinuities and the rock matrix through the progressive breakage of rock bridges. A 3D model for fractured rock is presented here. The model uses a discrete representation of the intact medium over which discontinuity planes can be overlaid to represent predefined DFNs representative of pre-existing geological structures. These structures, or joints, can then be simulated using a modified contact logic where interactions are setup depending on the orientations and mechanical properties of the joint surfaces. Uniaxial compression tests on a pre-flawed sample are simulated in order to emphasize the relevance of the model in reproducing the so-called "wing crack" extensions usually observed around penny shaped cracks. The model capabilities in terms of crack propagation and coalescence are then discussed on the basis of simulations performed at the scale of a jointed rock slope, with an emphasis on its capability to reproduce one of the key mechanisms usually involved in the development of progressive failure surfaces, the so-called step-path failure mode.

1 INTRODUCTION

Instabilities occurring in rock slopes are generally related to the presence of pre-existing discontinuities and the limit equilibrium method involving a representation of the slope as a set of rigid blocks remains the most commonly adopted approach to assess its potential failure [1]. However, back analyses have shown that for numerous cases, non persistent discontinuities (or joints) are involved in the failure process, with the breakage of rock bridges between those joints being mainly at the origin of the rock mass destabilization [1,2,3]. Thus, if in most cases, progressive failure mechanisms of rock bridges lead to global failure, a model for studying rock slope stability should encompass the nucleation or activation of cracks within the rock, the possible coalescence of which would then lead to the creation of critical failure surfaces.

Different techniques have been developed to deal with sets of non persistent discontinuities. For example, using stochastic techniques, Einstein et al. [4] made an attempt at relating rock mass stability with persistence in the geometry and spatial variability of discontinuities. However, this approach was based on the limit equilibrium analysis and therefore, remained limited in reproducing and understanding the progressive nature of slope failure. More recently, numerical methods have led to significant enhancements in rock slope stability analysis, which can take into account complex but realistic features (e.g., Discrete Fracture Network, anisotropy, 3D effects, non-linear behaviour, etc…). If classical continuous or discrete approaches in their initial formulation do not seem adapted to describe the progressive failure mechanisms in jointed rock, several attempts have been made to extend their capabilities. For example, Wang et al. [5] demonstrated that the application of a particle flow code can provide valuable insight into the stability analysis of heavily jointed rock slopes. Eberhardt et al. [2] showed that a coupled FEM/DEM formulation [6] can reproduce observed failure mechanisms by taking advantage of both continuous and discrete approaches (case study: 1991 Randa rockslide). However, to our knowledge, all these previous studies were performed in 2D. A step further is therefore to use 3D models which can reproduce the complex combination of intact material fracturing and yielding within discontinuity planes.

Using a discrete approach, a 3D simulator for jointed rock slopes which accepts Discrete Fracture Networks (DFN) has been recently developed by Itasca [7]. Based upon a similar approach, a 3D model implemented into YADE Open-DEM [8] is presented in this paper. The model uses a discrete representation of the intact rock mass, in which DFNs can be plugged in a straightforward way as a set of planes representing discontinuities (joints).

In this paper, it is shown that the model can reproduce typical progressive failure mechanisms as they have been observed both in the laboratory and at the scale of a rock slope. Simulations are presented to show how non persistent discontinuities can interact and induce fracturing within a rock mass.

2 MODEL DESCRIPTION

The numerical formulation of YADE is given in Kozicky and Donze [8]. It is an extensible open-source framework for discrete numerical modelling, focused on the Discrete Element Method. The algorithm used in YADE involves two steps. In the first one, interaction forces are computed when elements slightly interpenetrate each other. In the second step, Newton 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 repeated until the simulation is finished. The dynamic formulation allows the model to follow highly nonlinear behaviour characteristic of brittle material as a result of local interaction link breakage in both tensile and shear failure modes.

2.1 Intact Rock

The experimental results obtained by Sulem and Ouffroukh [9] on Fontainebleau sandstone provide a characteristic and well referenced data set for an intact brittle rock behaviour and it has been used here to setup the mechanical properties of the intact part of the model. Average values of 5 GPa for Young's modulus E, 0.25 for Poisson's ratio ν, 41.3° for the internal friction angle Φ and 15.5 MPa for the cohesion C were obtained by Sulem and Ouffroukh [9] based on a series of drained triaxial tests. The calibration procedure of the discrete model was thus performed in order to reproduce within a best agreement the macroscopic behaviour of this sandstone. The triaxial curves and rupture envelop predicted by the model are presented in Figure 1.

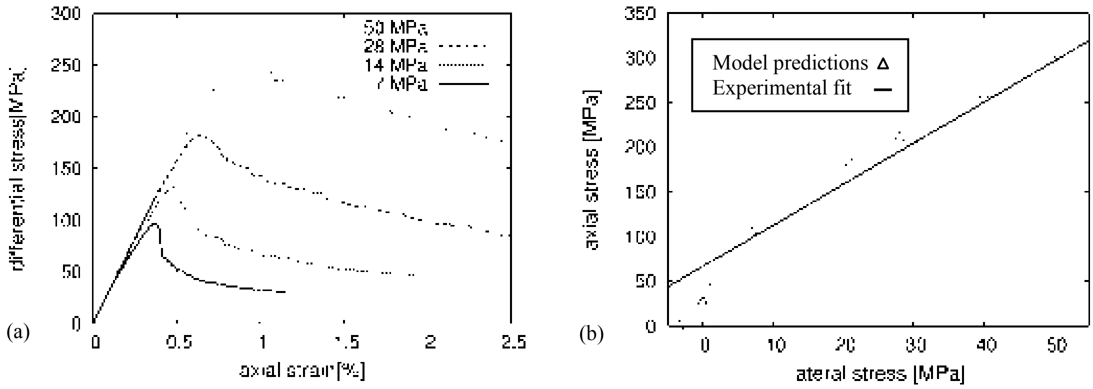

Figure 1: Stress Strain curves (a) and rupture envelop (b) obtained from triaxial and uniaxial test simulations performed on the model calibrated to simulate Fontainebleau sandstone after [9].

2.2 Discontinuities

In order to model discontinuities in the DEM, a specific contact formulation, related to the work made by Cundall and co-authors for the development of the Synthetic Rock Mass [10], has been implemented into YADE Open DEM. This joint contact logic is based on the identification and reorientation of each DE interaction which crosses the plane representing the discontinuity surface (Figure 2). With this joint contact logic the discontinuities structural effects on the fabric of the medium can be accounted for and any dependence of the joint behaviour on the DE distribution size is avoided. For instance, using the classical contact logic, the shear resistance is higher when less DEs are involved in the joint due to the interlocking of the DEs (Figure 2a). Indeed, the degree of interlocking and the associated roughness increases when the ratio between the size of the DE and the effective joint surface decreases. The resulting shear strength of the joint is therefore dependent on the resolution of the model. On the contrary, the enhanced contact logic provides a constitutive behaviour of the joint model which is fully controlled and determined by its local mechanical properties and which does not depend on the resolution of the model as illustrated in Figure 2b for a case without any cohesion for which perfect elastic-plastic behaviour is expected. In addition to the possibility to introduce cohesion in the joint model, dilation can also be accounted for in order to match the actual properties of the simulated joint in a more realistic manner.

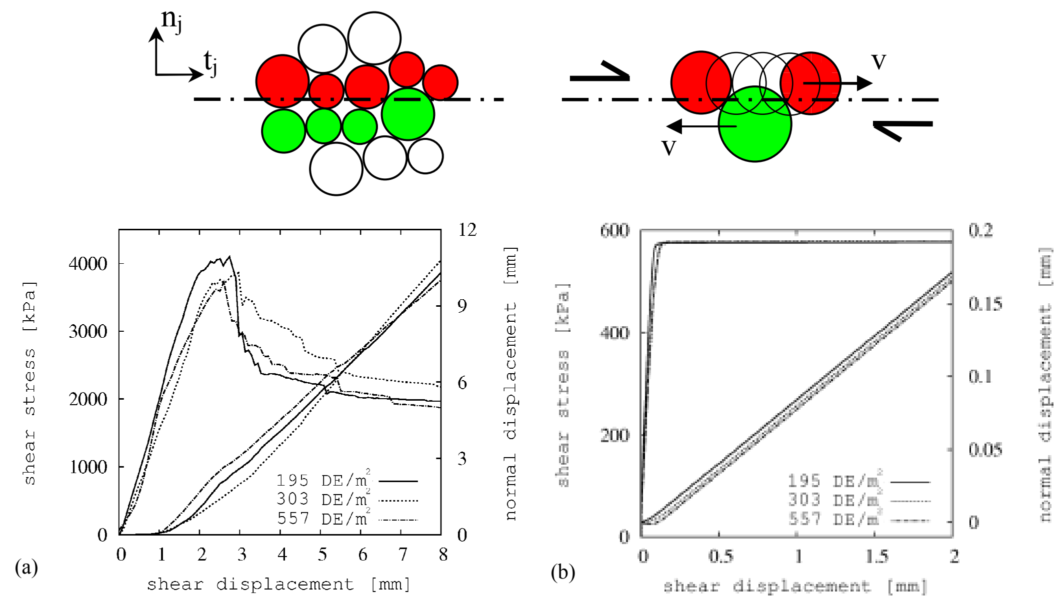

Figure 2: Joint contact logic (top) and dependence of the joint behaviour on the model resolution (bottom): Shear displacement curves from direct shear test simulations performed on a joint made up with different numbers of DEs under 1MPa confinement for (a) the classic contact logic and (b) the modified joint contact logic for an interparticle angle equal to 30 degree.

3 CRACK INITIATION AND PROPAGATION

A classical problem which has to be addressed when dealing with the progressive failure of a rock mass is to verify that the model is capable of reproducing the expected wing cracks developing at the tips of an existing fracture under compressive loading. This problem has been extensively studied in the last fifty years with numerous attempts aiming at understanding the mechanisms at the origin of crack initiation and growth into the intact medium [11].

To assess the ability of the model to tackle this problem, a uniaxial compressive test simulation has been performed on a prismatic sample containing a pre-defined frictionless disk shaped crack oriented at 45 degrees from its principal axis.

In the model, local rupture (micro-cracking) appears when the cohesive interaction between two DE reaches its tensile limit and micro-cracks are represented as disks for which the normal orientation corresponds to the actual tensile loading direction. It is the coalescence of those micro-cracks which then produces macroscopic failure surfaces inside the medium. As presented in Figure 3, the typical wing crack pattern resulting from stress concentration at the fracture circumference and the subsequent coalescence of local micro-cracks can be properly reproduced by the proposed model and is in good agreement with the experimental observations made by Dyskin and co-authors [11].

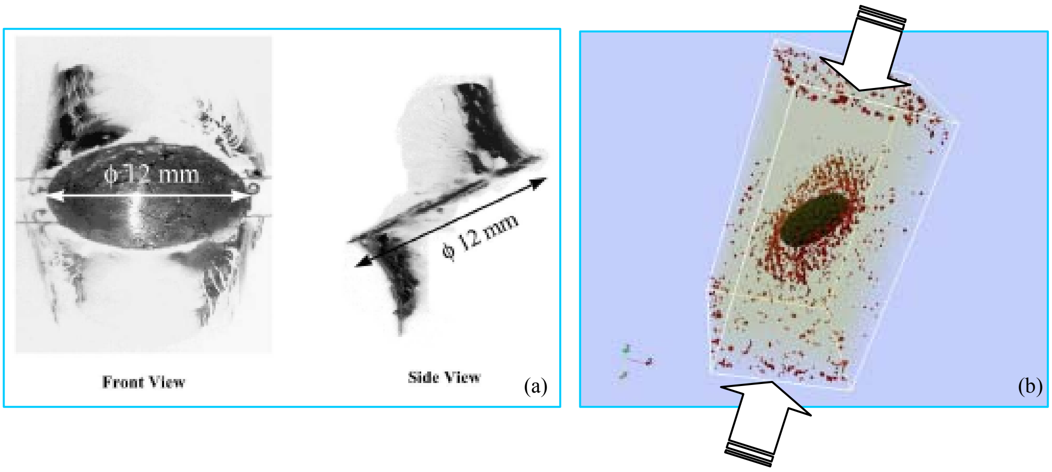

Figure 3: Crack distribution ("wing crack") induced by uniaxial compression of a pre-flawed sample: (a) experiment on Plexiglas from [12], (b) model prediction.

4 SLOPE STABILITY

In order to present the model capabilities in a clear way, 3D slices of a slope have been used in this study (see Figure 4(a)). The slope model consists of a set of 66,000 DE linked by more than 330,000 cohesive links (Figure 4). The face slope angle is equal to 80°. The DEs can move in all directions except for the ones lining the boundaries (see Figure 4(b) for details). A gravity induced stress is applied to the model before every simulation. DE density is chosen such that the gravity induced vertical stress σ_v at the bottom boundary corresponds to the one expected for a 50 m high slope consisting of a 2500 kg/m^3 rock density (in this case, $\sigma_v \approx 1.3$ MPa). In this study, the joint properties are chosen to simulate cohesionless joint planes presenting a 30° friction angle and a dilation angle of 10° and the intact medium properties calibrated according to section 2.1 to reproduce the behaviour of Fontainbleau sandstone as described by [9]. Additionally, the stiffness is 10 times smaller for the interactions located across the joint planes than for the ones inside the rock matrix.

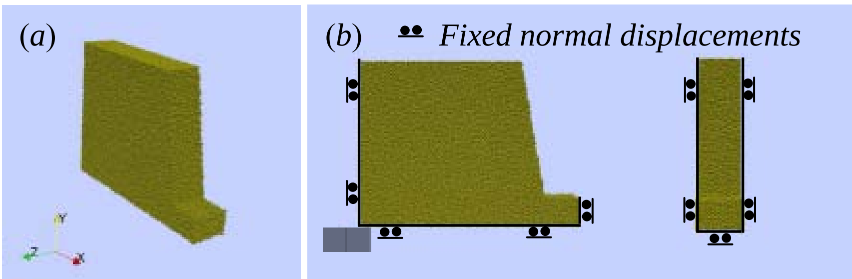

Figure 4. (a) Three dimensional slice of a slope used in this study, (b) boundary conditions (for sake of clarity, results will be mainly represented along the (x,y) plane.

In order to lead the slope model to failure, an iterative scheme has been used which consists in progressively reducing the strength of the intact part of the material, i.e. decreasing simultaneously the tensile strength and cohesion of the local interaction links. The strength reduction process is active as long as the crest of the slope stays in a stable or quasi-static condition. The quasi-static condition is ensured by checking that the velocity of one of the DE belonging to the crest corner is lower than a predefined value (0.1 mm/s here).

The simulations presented in the following were conducted on a 64-bit Intel Quad Core 2.6GHz preprocessor computer with 8 MB RAM. Each of them was run in about 3 hours.

4.1 Step-Path Failure

The following results present study-cases where pre-existing joints are not restrained to major failure surfaces, but are rather randomly distributed inside the medium. Two configurations were set up with joint sets dipping respectively at 40° and 80° inside the slope (see Figures 5 and 6). A first remarkable difference between these two configurations is that, contrarily to the sub-horizontal joint set (dip 40°), destabilization of the slope crest only occurred after a very high degradation level of the intact material for the sub-vertical one (dip 80°). Moreover, the resulting failure patterns are totally different depending on the joint set orientation. Indeed, if the sub-horizontal joint set leads to a typical en-echelon failure due to the appearance of bridging cracks caused by sliding on the pre-existing fractures, the sub-vertical discontinuities do not seem to influence the failure of the slope, with a circular failure surface appearing near the slope face, as typically observed in homogeneous slopes.

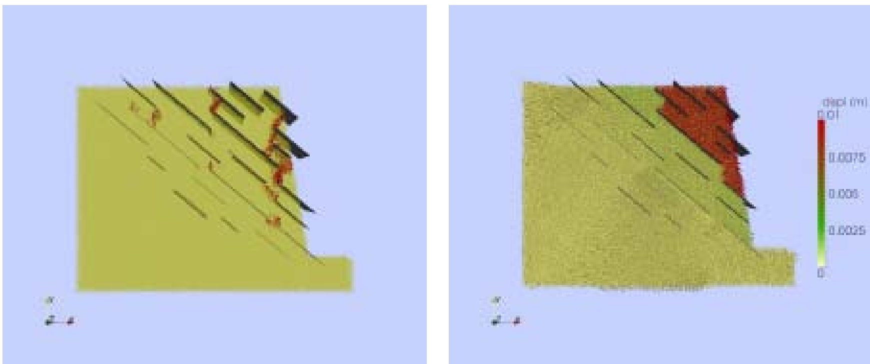

Figure 5. Cracks (left) and displacement field (right) induced by strength degradation in the case of a random joint set with a 40° dip angle.

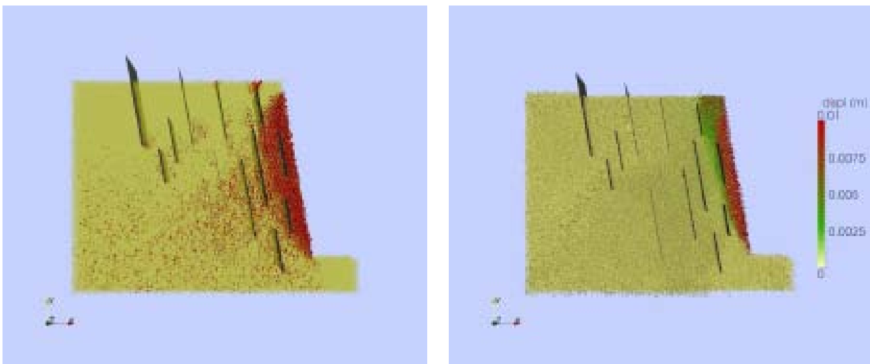

Figure 6. Cracks (left) and displacement field (right) induced by strength degradation in the case of a random joint set with a 80° dip angle.

Despite their relative simplicity, both examples nevertheless clearly show the model capabilities in terms of failure surface prediction with respective descriptions of critical path failure through breakage of intact rock bridges, and circular failure surface characteristic of homogeneous slopes.

In order to complete a simulation of a more realistic rock slope destabilization process, a slope model has been constructed which includes both 40° and 80° joint sets. Final crack patterns and displacement field are presented in Figure 7.

Even though it has been restricted to a particular joint set configuration, the model shown here can reproduce the complex interaction occurring between pre-existing natural discontinuities and fracture propagation in intact rock. The failure surface typically develops along a critical path involving both fracture propagation inside intact rock and sliding along discontinuity planes, resulting in the destabilization of the upper part of the slope. In addition, a secondary failure surface can be observed that has developed at a deeper level inside the slope. It has to be noted that, at the final stage of the simulation, the corresponding secondary block did not collapse since the degradation process was stopped after the first block destabilization. However, it is clear that this secondary block consists of a potentially unstable rock mass which would certainly destabilize after any additional perturbation of the slope.

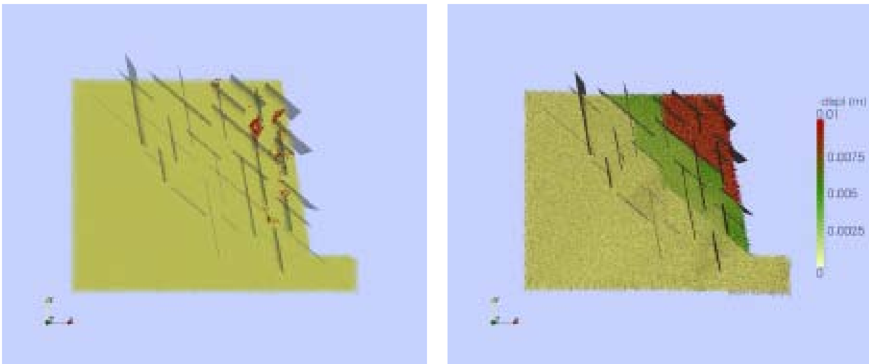

Figure 7. Cracks (left) and displacement field (right) induced by strength degradation in the case of 2 random joint sets with respective 40° and 80° dip angles.

8 CONCLUSIONS

The aim of the present paper is to present a Discrete Element Method dedicated to the simulation of fractured rock masses using a particle-based approach. YADE is a general 3D DEM open source package which has been used to study the stability of fractured media with an explicit representation of both the intact part of the material and the pre-existing structural discontinuities.

From laboratory scale simulations to slope stability case studies, the examples presented in this paper show that this method can investigate the complex behaviour of unstable fractured rock masses: the combined effect of pre-existing discontinuities on the elastic properties and strength of a rock mass as well as the possibility to follow the evolution of the fracturing mechanisms involved in the failure process promises new perspectives in slope stability analyses. Distinct configurations can be generated in order to discriminate the respective roles of the geological structures regarding the mechanical properties of both the intact rock and the discontinuities. Some new insights can also be gained concerning the effect of joint persistence and orientation on the destabilization process of jointed rock slopes.

The use of the model combined with the use of suitable field mapping techniques, would then provide relevant information for the establishment of appropriate safety plans by clarifying the potential failure mechanisms associated to the rock structure.

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