DEM SIMULATION OF THE EVOLUTION OF UNSTABLE ROCK FACES: AN ALTERNATIVE APPROACH TO MODELLING AND BACK-ANALYSIS

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Abstract

The evolution of unstable rock slopes is a process characterised by a succession of discrete events, each one giving rise to a new configuration of the rock face. If these events are put in a wider time frame, they can be seen as a local step contributing to the overall process. The advances in recognition systems, such as laser scanning or georadar techniques, allow to build numerical models of higher and higher precision, where the topographic and geostructural configurations may be precisely reconstructed. These improved capabilities open the possibility for defining highly representative numerical models that can be used for back analysis purposes or the design of risk mitigation works. One possible drawback of such approaches is that they superimpose structural and topographic data, whose compatibility is not independent on the mechanical behaviour of the rock mass. In fact, the initial geometry is depending on the (usually complex) rock slope history, which has a two-fold relationship with the whole set structural and mechanical features of the rock mass.

In order to investigate this point, a series of Distinct Element analyses of an unstable rock face located in Bolzano province is performed. The model is characterised by a very simple geometry, and slope evolution is studied by adopting the strength reduction technique. Structural and mechanical information is obtained from an extensive in situ survey. The aim of the simulations is to show how a model based on the available geomechanical information can be used to reproduce the main topographic features of the rock slope, and to perform a back analysis of a selected case history.

1. Introduction

The modelling of unstable rock faces requires the definition of topography, geomechanical structure and mechanical properties of rock and joints. Thanks to the advances in survey methods, the topographic and geomechanical information can be defined precisely, through the analysis of photographic images (Crosta 1997), or the use of laser scanning techniques (Slob et al. 2002; Sturzenegger and Stead 2009) and geophysical methods such as georadar (Grasmueck 1996; Boadu 1997; Jeannin et al. 2006; Ferrero et al. 2006).

However, modelling the behaviour of a rock slope remains a complex task, considering the heterogeneity of the rock mass features, the difficulty in assessing the triggering mechanisms of evolution and the effect of deformation on the mass conditions (progressive damage). In addition, the current configuration of an unstable rock slope represents just one step of the overall evolutive process, where the current geomechanical configuration is the result of history, and in turn it determines the future evolution. This establishes a strict correlation between topography and geomechanical features. Although the topography may be reproduced very closely and directly transferred into the initial geometry of the model, it is not given for granted that it is compatible with the evolutive process determined by the geomechanical features considered for the model. The aim of this paper is to show that the topography of the unstable slope can be obtained as preliminary results of a model based on the available geomechanical information and very simple assumptions regarding the initial geometry, and that such a model can be used to simulate the evolutive process.

1.1 Reference case

In this paper the analysis is focused on the evolution of a fractured rock slope, by using a discrete model based on the Distinct Element Method (DEM). The study area is located in the river Adige valley, precisely in the industrial zone of Sinigo (Merano) in the Bolzano province (Figure 1a). Two main instabilities were recorded in February 2014 on a limited portion of the slope (30 metres wide) involving 11.500 m^3 of rock and damaging the building at the foot of the face.

Fig 1. a) DTM and general view of the slope and rockslide; b) Plan of the slope with areas of investigation

The typical profile of the valley is characterised by two sub vertical rock bands with height ranging from 15 to 60 m (40 m in the site under consideration), intermixed by a less inclined (20°-30°) slope portion with soil cover approximately 1-2 m thick, and vegetation. The rock slope is composed of a highly fractured Rhyodacite, an effusive volcanic rock with porphyritic texture (Formazione di Monte Luco). Overall the slope has a S-W direction, on the average dipping at 250° from N. Information to build the model is obtained from a geomechanical survey of the whole slope with an extension along the axis of the valley of approximately 300 m, including laser scanning measurements, and a statistical evaluation of rock block size, and a more detailed survey at the detachment area (Figure 1b). The complex structure of the slope is characterised by six sets of joints and one fault (Figure 2).

	Slope scale survey			Detachment area		
Set	Dip (°)	Inclination (°)	Spacing (m)	Dip (°)	Inclination (°)	Spacing (m)
K1	310-325	70-85	3.0	260	75	3.0
K2	270-300	30-50	2.2	245	45	2.2
K3	220-235	75-85	5.4	-	-	-
K4	310-325	80-85	6.2	340	80	6.2
K5 (F)	190-210	85	6.6	202 (200)	85 (80)	6.6 (-)
K6	115-125	30	3.6	90	45	3.6

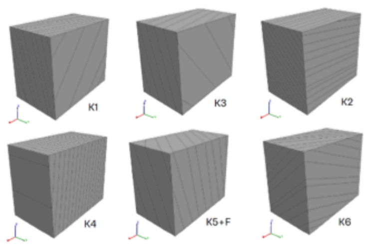


Fig 2. Joint sets: data and schematic representation

Three sets (K1, K2 and K3) are dipping almost parallel to the slope and define its main geometrical features; two sets (K4 and K5) are sub vertical, cut the slope transversely and are responsible of the presence of prominent spurs; one set (K6) has inclination opposite to the slope face and tends to form local overhanging roofs. Both dip direction and inclination are characterised by a wide variation over the whole slope. Moreover, no evidence of K3 is observed in the detachment area. Persistence of joint traces has the same order of magnitude of the spacing between joints. The observed aperture of joints ranges from 0 to 10-20 mm, with no presence of visible fill material or water. Overall, the rock mass can be rated with RMR around 60.

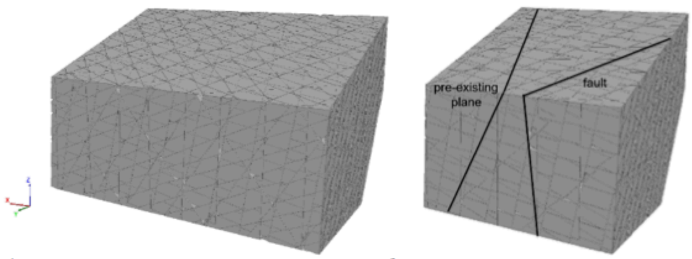
2. Numerical model

The DEM (Cundall 1971) 3DEC code (Itasca 2014) has been used for the simulations, where the rock mass is represented by an assembly of discrete blocks separated by sets of discontinuities. The state of stress is generally very low on a rock face, which suggests to use the simple rigid block approach. Note that joints must have a full geometrical persistence in order to avoid unrealistic interlocking when rigid blocks are used, and joint cohesion (c_j) and tensile strength (t_j) have to be selected accordingly (see §2.1). The evolution of the rock face is triggered by using the strength reduction procedure (Griffths and Lane 1999).

2.1 Numerical parameters, geometry and boundary conditions

Considering the back-analysis oriented scope of the paper, the initial choice of parameters is not fundamental, and as a first approximation realistic values for the density of rock and for the friction of joints were selected. An estimation of c_j and t_j can be given on the base of the continuum equivalent properties of the rock slope. Considering that *RMR*=60, a rock mass cohesion c_m = 300 kPa and a modulus E_m = 20 Gpa (Bieniawski 1978, 1989) can be estimated. As a first guess, considering the large number of discontinuities, the wide range of their orientations and the relatively close spacing, it is assumed that c_j=c_m=300 kPa and t_j =150 kPa. This latter value is justified by the fact that for the type of rock under consideration t_r is approximately half of c_r. The joint normal and shear stiffness, kn_j and ks_j were chosen on the basis of the average spacing of joints, so that the overall elastic deformability of the fractured system is of the same order of magnitude of the stiffness of the rock mass.

Rock density, ρ (kg/m^3)	2650
Joint friction angle, Φ_j (°)	35
Joint cohesion, c_j (kPa)	300
Joint tensile strength, t_j (kPa)	150
Joint stiffness, kn_j and ks_j (GPa/m)	10



a) *b)* *c)*

Fig 3. a) DEM parameters; b) *model A, rock face average data; b) model B, rockslide area*

The choice of the initial model geometry is strictly connected with the procedure of the simulations. The main focus of the research is assessing whether geomechanical data are in agreement with the main topographical features of the slope at the moment when the rockslide occurred. For this reason, the chosen initial geometry is a very simple sketch of the slope topography, characterised by a sub vertical 40 m high front parallel to the slope direction (x-axis) and a top boundary with an inclination of 20°, corresponding to the vegetation covered part of the slope. All displacements are inhibited at the base and at the back of the model. Lateral displacements are inhibited at both sides.

Two different models are built. The first one (model A) is based on the overall rockface features and is characterised by the reproduction of the system of joints recorded in the slope scale survey. The second model (model B) focuses on the rockslide area and is characterised by the system of joints detected during the corresponding detail survey. The longitudinal extension of the models is 100 m and 65 m, respectively. The depth and height of the two models are the same. Model B includes explicitly a fault (associated with the joint set K5) and a regular plane not associated to any of the fracture systems (also visible in Figure 1 at the left end of the rockslide area) which is most probably due to previous excavation processes in the area. The fault and excavation are given zero cohesion and tensile strength.

2.2 Simulation procedure

The aim of the simulation is to reproduce the slope configuration based on the mere geomechanical setting and applying a stress reduction technique. For each strength reduction step, if a failure mechanism is produced the affected blocks are removed, until a new stable configuration is obtained. The strength reduction procedure is governed by a reduction factor $\alpha < 1$ that is applied to cohesion and tensile resistance of joints. In fact, these two parameters depend on the persistence of joints, which in turn is affected by the progressive damage of rock bridges due to the evolution of the slope. Several combinations of strength reduction patterns, applied to all joints and parameters or in a selective way, have been investigated (Calvetti et al, 2018). In this paper, for the sake of brevity, only the results obtained using a global (unique) reduction factor α are shown.

3. Numerical results

3.1 Slope scale (model A)

The progressive reduction of resistance is accompanied by a progressive retrogression of the slope face and a reduction of the average slope angle (Figure 4). In particular, for large values of α the rock slope is determined by the steepest families, K1 and K3; their intersection with K4 and K5, determines unstable wedges that give rise to an irregular trend characterised by the presence of prominent spurs. For lower values of a the joints belonging to family K2 become progressively dominant and the spurs, whose profiles correspond to the steepest sections of the face, become unstable. The dominant evolutive mechanism progressively shifts from sliding along K1-K3 to sliding along K2. This latter kinematics is accompanied by the detensioning of the mass and the opening of joints belonging to K1 and K3.

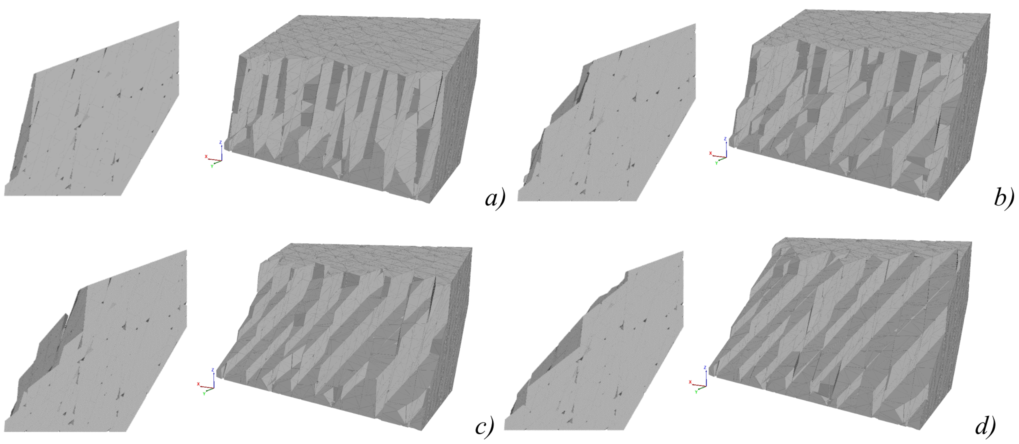


Fig 4. Model evolution. a) α = 1/3; b) α = 1/6; c) α = 1/12; d) α = 0

The best match between the configuration of the slope and the model is obtained for α = 1/6, i.e. for c_j =50 kPa (Figure 5). The model configuration for α = 1/12 suggest a possible evolution of the slope, in agreement with the change occurred in February 2014. The undulation of the top profile of the slope is very well reproduced by the model, thanks to the mutual intersection of the joint sets K1 and K3.

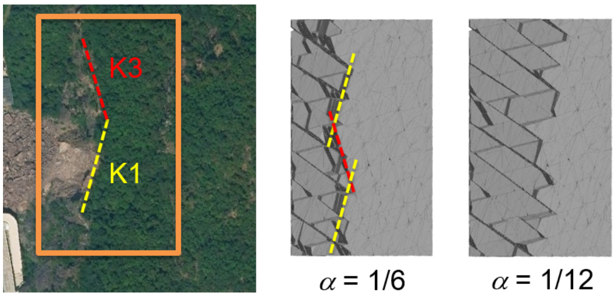


Fig 5. Comparison between topography and model results

3.2 Rockslide area (model B)

The general trend of evolution is similar to that obtained with model A, and it is confirmed that the current configuration of the slope is well matched for α in the range from 1/6 to 1/12. The effect of the pre-existing plane and of the fault is also clearly visible in top view (Figure 6).

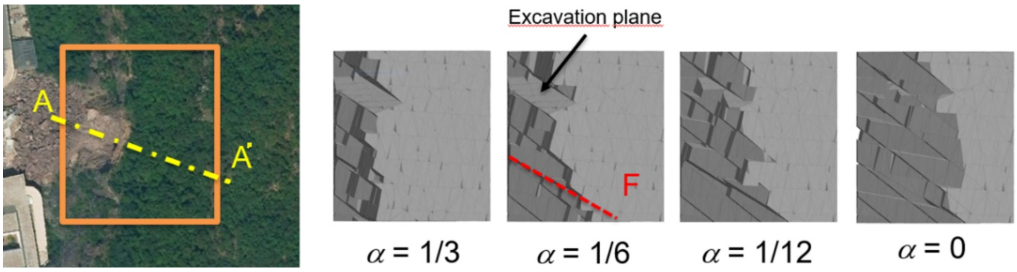


Fig 6. Model B, top view. a) $\alpha = 1/3$; b) $\alpha = 1/6$; c) $\alpha = 1/12$; d) $\alpha = 0$

Starting from these observations, in order to further assess the capability of the model to reproduce the recent rockslides, a new series of simulations are performed using c_j =50 kPa as the new reference for the strength reduction procedure, α^* being the stress reduction parameter referred to it.

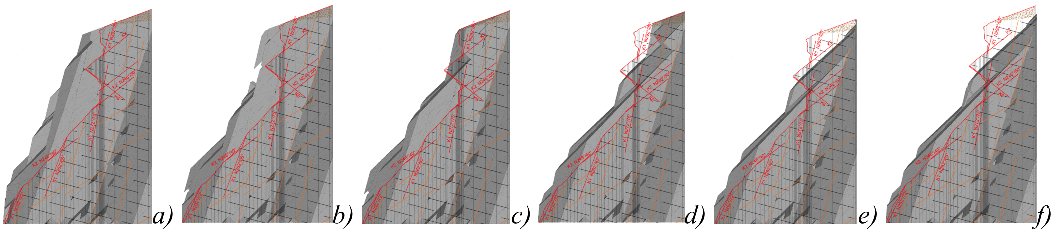


Fig 7. Model B, comparison with section A-A' of Figure 6. a) $\alpha^* = 1$; b) $\alpha^* = 0.8$; c) $\alpha^* = 0.6$; d) $\alpha^* = 0.4$; e) $\alpha^* = 0.2$; f) $\alpha^* = 0$

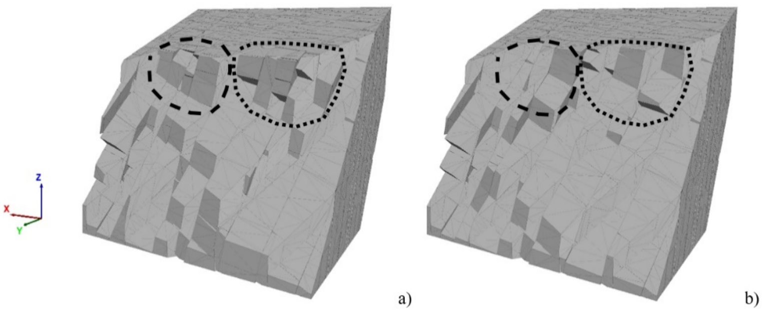


Fig 8. Model B, with highlight on unstable zones. a) $\alpha^* = 0.6$ ($c_j = 30$ kPa); b) $\alpha^* = 0.4$ ($c_j = 20$ kPa).

As a first remark, it is worth to note that in this phase small reductions of resistance can provoke significant evolutions of the slope (Figure 7), which is in good agreement with the fact that the slope is quite unstable, in its current configuration. By comparing the measured profile of section A-A' with the model results, it appears that the transition between α^* = 0.6 and 0.4 (c_j = 30 and 20 kPa, respectively) brings to a configuration very similar to the current one, which is the outcome of the events of February 2014 (Figure 7c, d). The zones affected by instabilities during this step, highlighted in Figure 8, correspond to the portion of the slope affected by the recent rockslides.

4. Concluding remarks

A series of numerical simulations have been performed with the DEM code 3DEC in order to model the evolution of an unstable rock slope. The main goal of the paper, besides merely reproducing the rockslide events that occurred on site in February 2014, is to assess the possibility of obtaining the overall geometry of the slope as part of the results of the simulation, rather than directly entering it as an initial condition of the model.
All in all, the results obtained both at the slope scale (model A) and around the rockslide area (model B) show that the proposed approach is viable, and that the model is able to reproduce the main traits of the evolution process. In particular, the current geometry of the slope can be matched by an appropriate choice of the resistance parameters, with further reductions suggesting the possible trends of future evolution and, as a consequence, giving indications about the possible stabilising and protection works and residual risks. Moreover, the results obtained with model B demonstrate the capability of the model to reproduce quite precisely not only the general trend of slope evolution, but also the relevant features of the local behaviour. This is possible thanks to the introduction of punctual geomechanical information, in particular concerning the local features of the joints.

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