Modelling progressive failure in rock slopes

Maria Güell i Pons et Michel Jaboyedoff
Institut de Geomatique et d'Analyse du Risque, Université de Lausanne, Lausanne, Suisse.

ABSTRACT
Rock slope failure involves an interplay between existing discontinuities and development of new fractures in intact material. In this work we study progressive failure using concepts of statistical physics and by means of numerical methods using distinct element methods (DEM). A cellular automata model is used to explain qualitativelly the fracture process phenomena and the results provide a link to time-to-failure predictions. The code PFC-2d is used to test three cases of slope failures; flexural buckling, column and block toppling triggered by glacial retreat. This study aims to provide a basis for the development of a model which permits to understand why some rock masses accelerate until global failure while other are capable to stabilize under similar conditions.

RÉSUMÉ
Les éboulements rocheux sont influencés par la combinaison entre les discontinuités existantes et l'endommagement progressif du matériel intact. Ce papier étudie la fracturation progressive en utilisant des concepts de la physique statistique et au moyen des méthodes des éléments distincts (DEM). Un modèle d'automate cellulaire est employé pour expliquer qualitativement le phénomène de rupture progressive et les résultats fournissent une relation temps-rupture progressive. Le code PFC-2d est employé pour examiner trois cas d'instabilité de versant; rupture par flexure, basculement de colonne et le basculement de bloc déclenché par la retraite glaciaire. Cette étude vise à être une base pour le développement d'un modèle qui permet de décrire pour quelles raisons des instabilités accélère ou se stabilisent.

1 INTRODUCTION

In most cases it is impossible to know in advance when and where a rock instability will occur and how much volume will be involved. The volume and the potential failure mechanism can be estimated by structural analysis using digital elevation models (DEM) combined with a number of techniques, for example Sloping Local Base Level (SLBL) or COLTOP (Jaboyedoff et al., 2004, 2005) combined with field work. Monitoring techniques such as LIDAR, extensometers and total stations allow characterisation of the ground deformation of a potential landslide. The factor of safety is usually computed with Limit equilibrium analysis techniques that assume a failure plane. At the slope scale, failure is simulated with numerical models such as the Finite Element Method or Discontinuum Methods.

This paper aims to study the stages of failure processes, understand why some slopes manage to equilibrate while other fail catastrophically and identify precursory patterns leading to catastrophic landslides. We present as an example progressive failure in three cases simulated with PFC-2D subjected to glacial retreat and we compare the accelerating patterns of broken bonds in the case of a simple cellular automata model.

2 PROGRESSIVE FAILURE

Rock slope failure is a temporal process which can take from seconds to thousands of years to develop. Catastrophic failure occurs as a culmination of progressing damage, involving complex interaction between pre-existing discontinuities and brittle fracture propagation through intact rock bridges until kinematic release is possible (Eberhardt et al., 2004).

Acceleration trends of ground displacements observed in some cases such as the Vaiont landslide (Kilburn and Petley, 2003), are in general a precursory sign of final failure. However, in other cases such as La Clapière landslide (Sornette et al., 2004), the slope stabilizes after a large period of accelerating displacement.

Progressive failure does not necessarily lead to rapid rock falls, sometimes failure is completed after the triggering factor disappears and results in multiple-stage events such as the Randa rockfall (Jaboyedoff et al., 2009). The global rock-slope failure is a result of internal redistribution of stresses inside the rock mass.

Fracture is a collective phenomenon in which disorder and heterogeneity play a fundamental role; there exist complex interaction between multiple defects and growing micro-cracks. It has been demonstrated in laboratory testing and simulations that, the larger the disorder, the stronger the precursors to rupture (Sornette, 2005); systems with less disorder show a brittle fracture, whereas disordered systems exhibit ductile damage.

Fracture modelling is a difficult task as most of numerical models such as the Finite Element Model (FEM) use techniques of equivalent continuum with mean value properties and neglect the micro-structure of the medium. There is a need to incorporate distinct element methods such as UDEC and PFC (Itasca) or combined finite/discrete codes such as ELFEN (Stead et al., 2004) to capture realistically fracture propagation in rock-slopes. Progressive failure has been extensively studied in statistical physics with applications in the naval, aeronautical and space industries for several composite materials such as fibre composites, ceramics, concrete, ice etc (Herrmann and Roux, 1990; Anifrani et al. 1995; Sornette, 2005). Rock is a composite material with heterogeneous microscopic structures at the micro scale whereas at the slope scale discontinuity geometry, persistence, connectivity and the statistical distribution of the material properties control failure.

2.1 Time-to-failure predictions

In some rock collapses, superficial accelerating displacements (Saito, 1965; Voigt, 1988; Fukozono, 1990; Sornette et al., 2004; Kilburn and Petley, 2003), seismic events (Amitrano et al., 2005) have been found to follow a time-to-failure power law. The time distributions of rock micro-fracturing under a variety of conditions display fractal properties and the decrease of fractal dimension over time has a potential use as rock failure predictor (Feng and Seto, 1999; Shiotani and Ohtsu, 1999; Amitrano et al., 2005).

In general, the rate of micro-fracture events before failure for a large number of materials and conditions is well fitted using power laws. Prediction methods for rupture based on the monitoring of the stressed system, for measuring the event rate of acoustic emissions are already in use in practical cases (Shiotani et Ohtsu, 1999, Ohtsu et al., 2002; Nesvijki et al. 2000; Sornette, 2002).

In order to understand this phenomenon, we use a lattice model (Cellular Automata) in which each site represents a bond with strength thresholds chosen from a statistical distribution (Normal, Weibull...) and linear elastic behaviour. The lattice is composed of 10^{12} cells and is subjected to a step-by-step loading procedure. Each time the cell load surpasses the strength, the bond breaks and the load is redistributed to the 4-closest neighbours. This process may cause the strength in the surrounding cells to be reached and the zone of failure will grow (cascade of events) until complete collapse of the system.

Initially, the system response is elastic, while all cells (or bonds) remain fully intact. Then, as the particle bonds begin to break, the localized cracking reduces the stiffness and the response becomes elasto-plastic with a residual shear resistance (Figure 1).

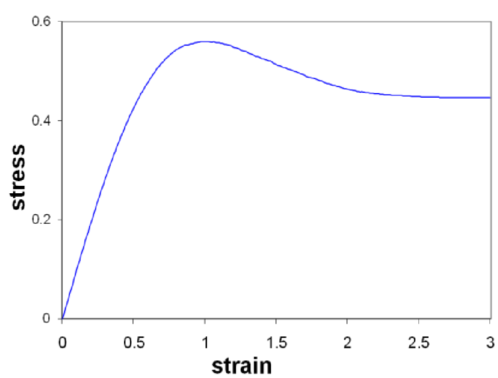

Figure 1. Macroscopic response of a cellular automata model. Each cell has a linear elastic behaviour up to a strength threshold (Weibull distribution).

Results of the Cellular Automata (CA) model plotted at a log-log scale show a change of the fractal exponent in the power law if we consider the number of accumulated bond failing before and after 40% of the final load (Figure 2). This simple model captures the interplay of heterogeneity and the stress transfer mechanism and confirms the acceleration patterns and the decrease of fractal exponent observed in nature.

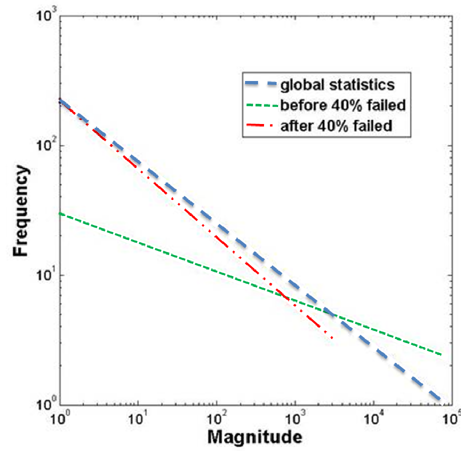

Figure 2. Cellular Automata model. Frequency-Magnitude of broken bonds during a simulation process leading to catastrophic failure. Global Statistics of failure have a linear trend. Considering the amount of failure before and after 40% of cells damaged it can be observed that the power law exponent varies and might be a hint for failure forecasting.

3 SIMULATION OF PROGRESSIVE FAILURE WITH PFC-2D

The CA model shows some limitations regarding the geometry (square cell grid), property distribution (statistical distribution over the grid cells) and stress distribution rules (stress is transmitted to the first nearest neighbours). In order to account for more realistic conditions we propose to use the code PFC-2D (Itasca, 2004) for modelling progressive rock slope failure. We present three different case studies: slab failure, column and block toppling.

A rock-slide is a mass-movement process characterized by the down-slope overturning, either through rotation or flexure of interacting blocks of rock. Slopes with well-developed discontinuities or a pervasive foliation dipping steeply into the slope and trending parallel or subparallel to the slope crest are considered susceptible (Prichard and Savigny, 1990).

3.1 PFC 2D modelling results

PFC-2D (Itasca Consulting Group 2004) models the rock-slope as an assembly of circular shaped bonded particles resistant to normal and shear stresses (Potyondy and Cundall, 2004). As with the cellular automaton presented before, crack initiation occurs where the bond strength is locally overcome. When a bond is broken, the stresses are redistributed and may cause further bond failures. In this case, the redistribution of load does not happen to the neighbouring cells, but is controlled by the force chains between particles generated by gravity compaction. The damage is accumulated progressively until global failure or stabilisation of the slope occurs (Figure 3).

This approach has been successfully applied for the calibration and stability analysis of a heavily jointed rock slope (Wang et al., 2003) and the case of a slope subjected to weathering (Utili and Nova, 2008).

PFC has been also used to model both the failure mechanism and the run out process (Tentschert et al., 2005; Poisel, 2005 and Poisel et al., 2009).

The PFC-2D models consist of >25.000 circular particles. The slope is at equilibrium under gravity loading The presence of a glacier is also simulated with bonded particles The particles are joined by parallel and contact bonds which carry the load. The Distribution of tension and compression inside the rock mass can be viewed over time.

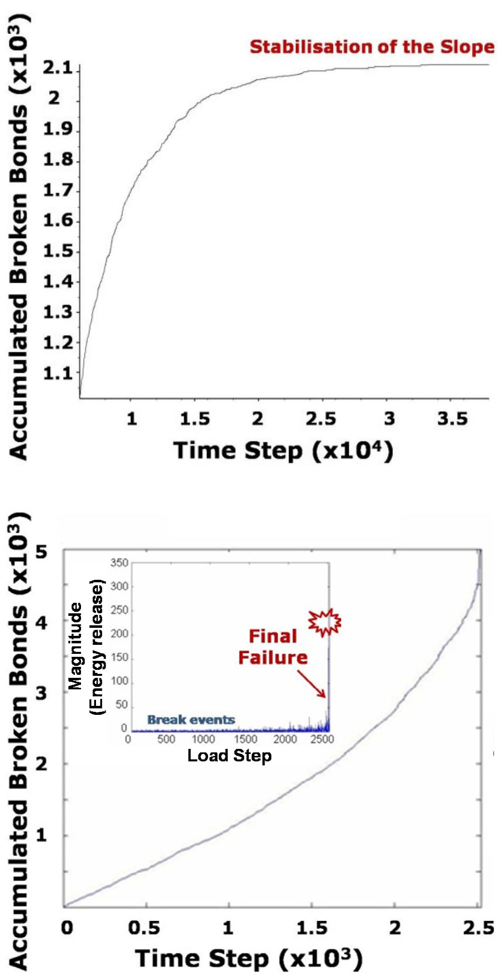

Figure 3. Number of accumulated broken bonds in the case of a) a stabilisation of the slope (block toppling model) and b) complete failure of the slope (cellular automata model). Magnitude corresponds to the number of broken bonds corresponding to one redistribution.

For the calibration of the micro-parameters a number of numerical biaxial tests (isotropic compression and biaxial loading) have been performed with moving boundary walls under stress controlled conditions.

Glacial relief undergoes slow destabilization after glacial retreat owing to reshaping of topography (Eberhardt et al., 2004) Progressive collapse of the slope is modelled by progressively deleting the glacier by phases of 3-5 m. simulating loss of confinement on valley walls. During the computation, bonds are broken automatically at locations where the normal stress carried by the bonds exceeds the bond normal strength. As cohesion bonds are destroyed, the frictional component of the strength begins to mobilize. The load redistribution triggers the breakage of additional shear bonds, leading either to the complete collapse of the slope or the stabilisation after some time (Figure 2).

3.2 Flexural Buckling

In this model we define a non-persistent discontinuity parallel to the topographic surface. This can be found in crystalline rock masses and is accepted to be the result of rock dilation due to unloading effects (Eberhardt et al., 2004). The mechanism can occur in steeply deeping bedding planes that bend forward and can break in flexure mode. Typical geological conditions of this failure are thinly bedded shale and slate with low angle shears.

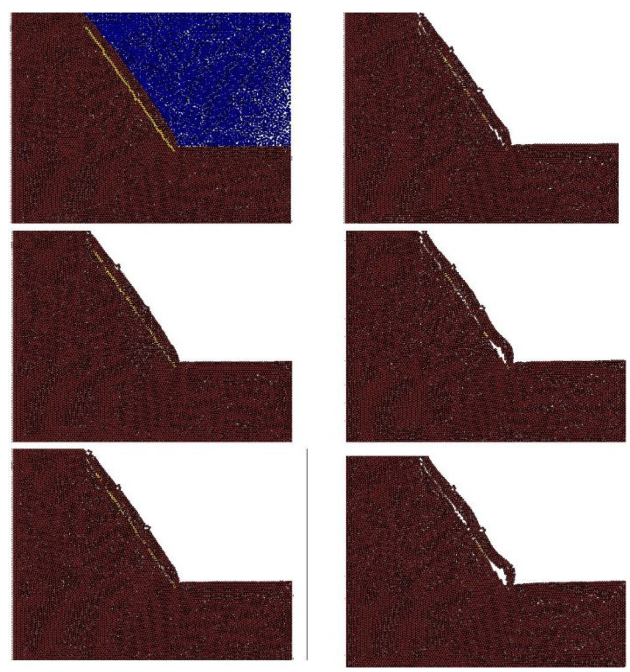

Figure 4. Slab Failure simulated with PFC-2D. Slope angle 54º, height 150 m. Slab thickness is 2 m.

Damage progresses with time until the discontinuity is fully continuous. The rock slab starts to slide progressively downwards and the bonds are broken by shearing along the surface. The slab forms a buckle at the end of the slope. With ongoing simulation time the buckled rock fractures in pieces and the slab slides down (Figure 4).

3.3 Column Topple

Slopes subjected to toppling often comprise a system of hard rock lying on an incompetent material, for example in the case of horizontally bedded sandstone and shale formation. The shale is usually weaker and, while the sandstone often contains vertical stress relief joints (Hoek and Bray, 1981). In general, the competent rocks are subjected to tensile stresses and intensive fractures are created.

The PFC2D model consists of a pre-existing bonded vertical joint with smaller threshold resistances compared to the rock mass. The fracture starts at the crown of the column (tension crack) and progressively moves downward as the block detaches. The block of competent rock plunges into the incompetent material. Damage is also developed inside the rock column in form of bands of broken bonds.

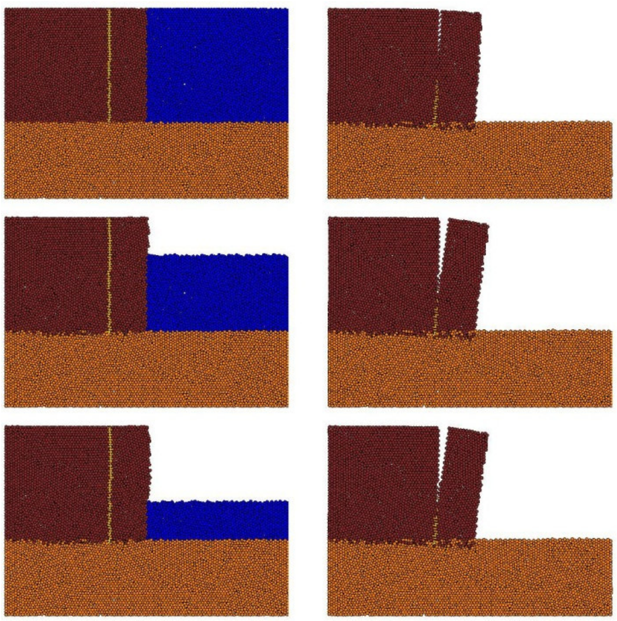

Figure 5. Column Topple simulated with PFC-2D. The block of rock is 40 m. high and 15 m. thick. The block is resting over a softer rock material of 30 m. thickness.

3.4 Block Toppling

Block toppling occurs in hard rock, bedded sandstone and columnar basalt, when individual columns are formed by a set of discontinuities dipping steeply into the face, and a second set of widely spaced orthogonal joints which defines the column height (Hoek and Bray, 1981). The PFC2D rock slope model has two discontinuity sets; one representing the bedding plane, dipping 5º and another dipping 70º into the slope.

Initially the damage is distributed over the slope up to a critical density threshold, where blocks start to slide over each other. Blocks form inverse crests similar to the ones observed in the field. Slabs are progressively deformed internally. A tension crack is formed in the upper part of the slope. At the end of the simulation the slope reaches equilibrium. The block at the toe (partially detached) stabilizes the movement. Removal of the “key block” or seismic acceleration will reactivate the slide (Fig. 6).

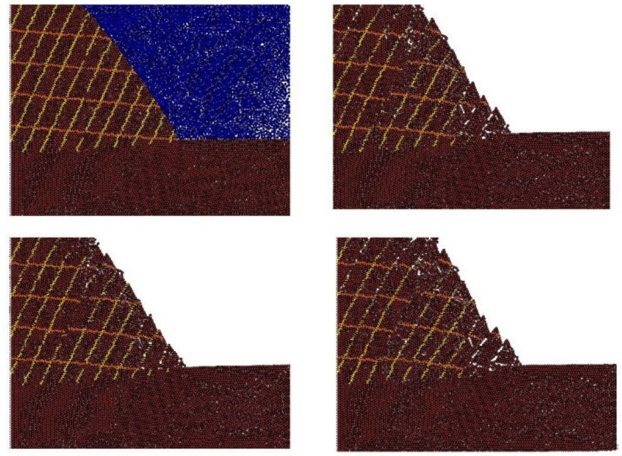

Figure 6. Block Toppling simulated with PFC-2D. Slope angle 54º, height 150 m. Joint set 1 is dipping 5º. Joint set 2 is dipping 60º inside slope.

4. CONCLUSIONS

Progressive failure is a complex interaction between existing discontinuities and the creation of new ones through brittle fracture.

A simple lattice model has been used to understand the physics of fracture. Even with a simple model, accumulated failure events show power-law acceleration and a decrease in the fractal exponent close to the failure point similar to observations (acoustic emissions, AE) in a variety of materials. Slope surface displacement or seismic activities measured in the case of rockfall collapse also display such behaviour.

In order to account for realistic scenarios, PFC-2D has been used for simulating three slope failures modes. Results show that glacial retreat causes unloading that triggers toppling in susceptible areas due to internal stress redistribution under the effects of gravity.

PFC-2D allows realistic simulation of the transition from local failure to global failure without pre-defining a temporal degradation of rock strength properties. It is possible to apply different initiation conditions due to seismic loading, deglaciation, and removal of the toe of the slope etc. PFC-2D also allows the visualisation of large material deformations in contrast with other computer codes such as the finite element method. Moreover, it permits the simulation of internal deformation and rigid block movement without the need of specifying a constitutive relationship. The use of micro-parameters instead of constitutive laws allows accounting for the influence of heterogeneities present in the rock mass and the testing of different statistical distributions.

A drawback of using PFC-2D is the demanding computation time for large number of particles. Moreover, the calibration procedure is tedious as it needs several numerical tests in order to calibrate the micro-parameters (stiffness, particle radii...) that correspond to the macro-parameters (cohesion, friction angle...) which can be measured in conventional laboratory tests. Another drawback of the model is the unability to account for water pressures inside the rock mass, one of the most common triggering factors for rock-slides.

Bond breakage in PFC-2D allows the tracking of progressive failure that could be correlated with surface displacements, seismic registers or AE on rock slopes, which show a potential to prediction.

5. REFERENCES

Amitrano, D.,Grasso,J.R. and Senfaute,G. 2005. Seismic precursory patterns before a -cliff collapse and critical point phenomena. *Geophys. Res. Lett.* 32.

Anifrani, J.C., Le Floch'h,C., Sornette, D. and Souillard, B. 1995. Universal log-periodic correction of renormalization group scaling for rupture stress prediction from acoustic emissions. J*. Phys. I France, 5*. 631-638.

Eberhardt, E., Willenberg, H., Stead, D., Coggan, J. 2002. An integrated numerical analysis approach applied to the Randa rockslide. *Proc. 1st European Conf. Landslides.* Prague. Balkema, Lisse. 355-362.

Eberhardt, E., Stead, D. and Coggan, J.S. 2004. Numerical Analysis of initiation and progressive failure in rock slopes- the 1991 Randa rockslide*. Int. Journal of Mechanics and Mining Sciences* 41, 69-87.

Fukozono, T. 1990 Recent studies on time prediction of slope failure. *Landslide News No. 4* ed. Kyoto University of Japan.

Herrmann, H.J. and Roux, S. 1990. Statistical Models for the Fracture of disordered media. Elsevier Science Publishers . North Holland.

Hoek, E. And Bray J. 1981. Rock Slope Engineering, Civil and Mining 4^{th} Edition. Duncan C Wyllie and Christopher W Mah Ed.

Itasca Consulting Group 2004 "Particle Flow Code in 2-D (PFC-2D): User's Manual, Version 3.0"

Feng Xia-Ting and Seto M. 1999. Fractal structure of the time distribution of micro fracturing in rocks. *Geophysical Journal International.*Vol.136, 275-285.

Jaboyedoff, M., Baillifard, F., Couture, R., Locat, J., Locat, P. 2004. Toward preliminary hazard assessment using DEM topographic analysis and simple mechanic modelling. In: Lacerda, W.A., Ehrlich, M., Fontoura, A.B., Sayo, A. (Eds.) Landslides Evaluation and Stabilization. Balkema, Rotterdam. 191-197.

Jaboyedoff, M., Baillifard, F., Couture, R., Derron, M.H., Locat, J., Locat, P. 2005. Coupling kinematic analysis and sloping local base level criterion for large slope instabilities hazard assessment- a GIS approach. In: Hungr, o,. Fell, R., Couture, R., Eberhardt, E. (Eds.) *Landslide Risk Management*. Balkema, Rotterdam. 615-622.

Jaboyedoff, M., Couture, R., Locat, P. 2009. Structural analysis of Turtle Mountain (Alberta) using digital elevation model: Toward a progressive failure. *Geomorphology* , 103. Issue 1, 5-16.

Kilburn, C.R.J. and Petley, D.N. 2003 Forecasting giant, catastrophic slope collapse: lessons from Vajont, , Northern Italy. *Geomorphology*, 54 (1-2). 21-32.

Nesvijki, Edouard G. and Sarkis P. 2000. Acoustic Emission and Failure Prediction of Composites. *International Symposium on NDT Contribution to the Infrastructure Safety Systems,* 1999 NOV 22-26

Ohtsu, M., Uchida, M., Okamoto, T., and Yuyama, S. 2002 Damage Assessment of Reinforced Concrete Beams qualified by Acoustic Emission, *ACI Structural Journal*, Vol. 99, No. 4, July-August 2002, 411-417.

Poisel, R. 2005 Geomechanics of Hazardous Landslides. Journal of Mountain *Science* Vol.2 No 3. 211-217

Poisel, R., Angerer, H., Pöllinger, M., Kalcher, T. and Kittl, H. 2009, Mechanics and velocity of the Lärchberg-Galgenwald landslide (Austria), *Engineering Geology*.

Potyondy, D.O. and Cundall, P.A. 2004. A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences* 41. 1329-1364

Pritchard, M.A. and Savigny, K.W. 1990 Numerical modelling of toppling. *Can Geotech. J*. 27, 823-834.

Saito, M. 1965 Forecasting the time of occurrence of a slope failure. *Proceedings of 6th ICSMFE Montreal.*

Shiotani, T and Ohtsu, H. 1999. Prediction of slope failure based on AE activity. *ASTM Acoustic Emission: Standards and Technology update.* ASTM STP 1353. 156-172.

Sornette, D. 2002. Predictability of catastrophic events: material rupture, earthquakes, turbulence, financial crashes and human birth. *Proceedings of the National Academy of Sciences*. USA 99.. 2522-2529

Sornette,D., Helmstetter,A., Andersen, J.V., Gulzman, S., Grasso, J.R. and Pisarenko, V. (2004) "Towards landslide predictions:two case studies" *Physica A.* 338, 605-632.

Sornette, D. 2005 Statistical Physics of Rupture in Heteregenous media. In: *Handbook of Material Modeling.* Springer Netherlands. 1313-1331

Stead, D., Coggan, J.S., and Eberhardt, E. 2004 Realistic simulation of rock slope failure mechanisms: the need to incorporate principles of fracture mechanics*. Paper 2B 17 SINOROCK 2004 Symposium. Int. J. Rock Mech. Min. Sci. Vol 41, No. 3 CD-ROM.*

Tentschert, E., Poisel,R., A. Preh, W.Roth 2005 „The Oselitzenbach landslide (Austria) – triggering, runout and risk evaluation. *Geophysical Research Abstract.* Vol. 7 04496, European Geosciences Union.

Utili, S. and Nova, R. 2008 "DEM analysis of bonded granular geomaterials" *Int. J. Numer. Anal. Meth. Geomech*. 33, 1997-2031.

Voight, B. 1988 "A relation to describe rate-dependent material failure" *Science*, 243, 200–203.

Wang, C., Tannant, D.D., Lilly, P.A. 2003. Numerical analysis of the stability of heavily jointed rock slopes using PFC-2d. *International Journal of Rock Mechanics and Mining Sciences* 40. 415-424.