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Hybrid finite-/discrete-element modelling of progressive failure in massive rock slopes

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ABSTRACT: Although individually both continuum and discontinuum numerical analyses provide useful means to analyze rock slope stability problems, complex failures typically involve mechanisms related to both existing discontinuities (i.e. discontinuum) and deformation and brittle fracture of intact rock (i.e. continuum). One such example is the 1991 Randa rockslide in the southwestern Swiss Alps, where failure involved several complex mechanisms, which require the consideration of progressive failure and rock mass strength degradation. This paper presents results from a series of hybrid finite-/discrete-element models directed towards the explicit modelling of brittle fracturing in natural rock slopes, enabling the modelling of progressive failure, from initiation, through to the development of catastrophic failure, transport and deposition.

RÉSUMÉ: Si les modélisations numériques de type continu ou discontinu fournissent des outils utiles pour l'analyse de problèmes de stabilité de pentes rocheuses, elles montrent de sérieuses limitations lorsque des mécanismes de rupture complexes impliquent des processus liés autant aux discontinuités préexistantes qu'au développement progressif de nouvelles fractures. Ceci se retrouve typiquement dans l'exemple de l'éboulement de 1991 à Randa dans les Alpes suisses du sud-ouest, où la rupture a impliqué plusieurs mécanismes complexes nécessitant la prise en considération de la fracturation progressive ainsi que de la dégradation de la résistance des masses rocheuses. Cet article présente des résultats provisoires d'une série de modèles hybrides orientés vers la modélisation explicite de la fracturation de pentes naturelles, permettant la modélisation de fractures progressive de leur initiation jusqu'à leur développement, leur rupture catastrophique, leur transport et leur déposition.

ZUSAMMENFASSUNG: Obwohl numerische Kontinuum- und Diskontinuum-Berechnungen einzeln nützliche Ergebnisse zur Stabilitätsanalyse von Felshängen liefern, sind komplexe Felsrutschungen typischerweise mit Mechanismen verbunden, die sowohl durch bestehende Trennflächen (s.a. Diskontinuum-Ansatz) als auch durch die Deformation und das Versagen intakter Felsbereiche (s.a. Kontinuum-Ansatz) bedingt werden. Ein Beispiel für einen solchen Sachverhalt ist der Bergsturz von Randa 1991 im südwestlichen Teil der Schweizer Alpen, bei dem die Rutschung mehrere komplexe Mechanismen umfasste, so dass "progressive failure" und Verminderung der Gebirgsfestigkeit in Betracht gezogen werden müssen. Dieser Artikel beschreibt vorläufige Ergebnisse einer Reihe von hybriden Modellrechnungen (Finite-/Diskrete-Elemente). Diese haben zum Ziel, explizit das bruchhafte Versagen natürlicher Felshänge zu modellieren, wobei das progressives Versagen im ganzen modelliert wird, von der Anfangsphase über die Entwicklung zum katastrophalen Versagen und den Transport und die Ablagerung der Rutschmassen.

Introduction

In massive natural rock slopes and deep, engineered slopes (e.g. open pit mines), potential failure surfaces are often considered as being extensive, continuous planes. The justification for this is part due to post-failure observations where fully persistent discontinuities are fitted to the failure surface to explain its origin in a geological context, and partly due to the constraints of the analysis technique employed (many of which require the input of fully persistent discontinuities, e.g. limit equilibrium wedge or planar analysis, distinct-element method, etc.). Such assumptions are often only valid in cases where the volume of the failed block is relatively small (e.g. 1000's of m^3) or where major persistent faults and/or bedding planes are present.

In contrast, Terzaghi[1], Robertson[2], Einstein *et al.*[3] and others argue that the persistence of key discontinuity sets is in reality more limited and that a complex interaction between existing natural discontinuities and brittle fracture propagation through intact rock bridges is required to bring the slope to failure. Eberhardt *et al.*[4] argue that such processes must be considered to explain the temporal nature of massive natural rock slope failures. For example, prior to failure a particular rock slope may have existed in a relatively stable state over periods of thousands of years (e.g. since deglaciation), having experienced major precipitation and snowmelt events, and/or seismic activity over time. Thus unless failure is driven by external changes to the geometry of the problem (e.g. undercutting/erosion at the toe, etc.) or addition of external loads/surcharges through human activity, a component of strength degradation with time must occur within the rock mass. In effect, such processes are similar to those proposed by Bjerrum[5] and others as progressive failure.

The key to progressive failure in rock slopes is that the process is predominantly driven by the propagation of fractures (e.g. through intact rock bridges between existing discontinuities), and strength degradation, strain softening, internal deformation and dilation through increasing brittle fracture damage and shearing [6]. Figure 1 illustrates the primary conceptual controls contributing to massive rock slope failure viewed as a function of strength degradation in the form of shear plane development and strength degradation manifested through internal deformation, dilation and damage mechanisms. For example, Martin and Kaiser[7] showed that these internal shears, and the internal distortions that occur along them, are necessary in certain modes of rock slope instability to accommodate motion along a basal slip surface. Depending on the complexity of the geology, topography and subsurface structure, these controls will vary in their influence on the overall instability state.

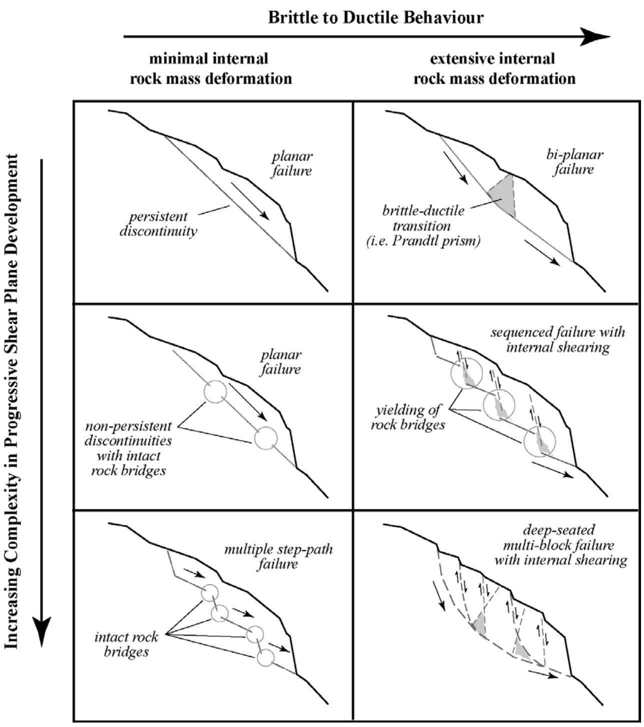

Figure 1. Massive rock slope sliding mechanisms as controlled by progressive shear plane development and internal rock mass deformation/damage (after [6]).

The analysis of these processes and their incorporation into traditional rock slope analysis techniques is limited. Limit equilibrium solutions based on Coulomb shear strength criterion have been derived to include an apparent cohesion dependent on the continuity of jointing[8]. However, such treatments only address the question of joint persistence and not the progressive development of the failure plane. Still, the analysis of rock slope stability has changed significantly during recent years with a transition from limit equilibrium analyses to the application of numerical modelling. These techniques have evolved to allow routine analysis treating the slope mass as either a continuum (e.g. finite-element method) or a discontinuum (e.g. discrete-element method). In practice, the complexity involved in most massive rock slope failures involves elements of both deformation of the continuum, interactions along existing discontinuities and the creation of new fractures. To treat these problems, new developments in hybrid finite-/discrete-element codes have been forwarded which allow for the modelling of both intact behaviour and the development of fractures [9, 10].

This paper presents the preliminary results from a study focussing on progressive failure and numerical modelling of brittle fracture processes in massive rock slopes, using the 1991 Randa rockslide in southern Switzerland as a working example.

The 1991 Randa Rockslide

The 1991 Randa rockslide involved the failure of 30 million m^3 of massive crystalline rock in two separate episodes approximately three weeks apart (Figure 2). The slide is located in the Matter Valley in the southern Swiss Alps. Damage resulting from the two events included the destruction of the main road and rail line along the valley (which provides access to the resort village of Zermatt), the damming of the Vispa River and the subsequent flooding of the town of Randa. The failed rock mass was comprised of massive gneisses alternating with mica-rich paragneisses. As foliation dips favourably into the slope, Schindler *et al.*[11] suggested that failure occurred along extensive shallow dipping joints parallel to the surface. These persistent joints can be observed along the sliding surface but are more limited in persistence when encountered in surface outcrops [12]. Schindler *et al.*[11] also proposed a series of steep sub-vertical faults as dividing the slide mass into smaller units, presumably to explain the episodic nature of the slide.

Analysis of climatic and seismic data, however, showed no clear indications of a triggering event [4,11]. Eberhardt *et al.*[4] instead suggested that time-dependent mechanisms relating to brittle strength degradation and progressive failure may more likely be the significant contributing factors that brought the slope to failure. Heavy snowmelt and precipitation prior to failure, although less than recorded in previous years, would have provided the final impetus resulting in failure, the slope having reached a state of strength degradation approaching its limit equilibrium state (i.e. cumulative deformation and fracture due to cyclic fatigue).

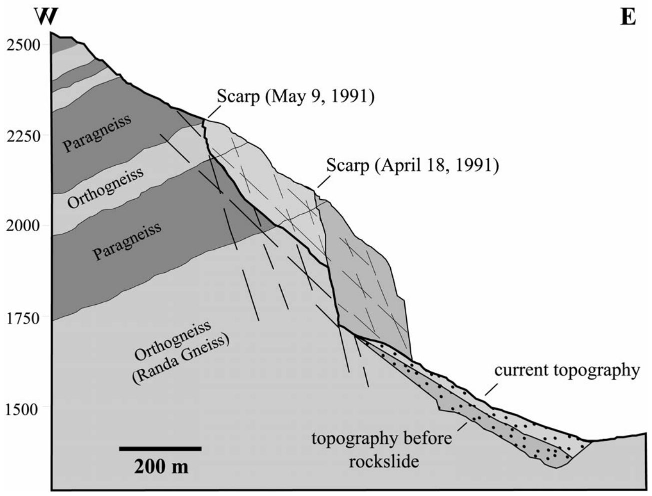

Figure 2. Cross-section of 1991 Randa rockslide (modified after [11]).

Hybrid Finite-/Discrete-Element Modelling

Methodology and Formulation

Hybrid methods combine the inherent advantages provided by both continuum and discontinuum numerical codes. In ELFEN[10], the program uses adaptive re-meshing routines to model the propagation of brittle fractures through a finite-element continuum. Pre-existing discontinuities and induced fractures are in turn represented by discrete-elements. Starting from a continuum representation of the solid material by finite elements, fracturing in ELFEN is controlled according to a fracturing criterion specified through a constitutive model (e.g. Rankine tension, rotating crack, Mohr-Coulomb, etc.). At some point in the analysis the adopted constitutive model predicts the formation of a failure band within a single element or between elements. The load carrying capacity across such localized bands decreases to zero as damage increases until eventually the energy needed to form a discrete fracture is released.

At this point the topology of the mesh is updated, initially leading to fracture propagation within a continuum and eventually resulting in the formation of a discrete element as the rock fragments (Figure 3). Subsequent motion of these discrete elements and further fracturing of both the remaining continuum and previously created discrete elements is then simulated. This evolution process is continued until either the system comes to equilibrium or up to the time of interest. By applying such techniques, it becomes possible to model both the behaviour of a continuum and a discontinuum, and the transformation of the rock mass from a continuum to a discontinuum.

Slope mass fragmentation

Through such hybrid techniques, rock slope analyses can be extended to model the complete failure process from initiation, through transport to deposition [14]. Figure 4 shows one such example from a preliminary analysis of the Randa rockslide. In this case, the model used both the topography and the observed failure plane as part of the input geometry. As such, the model only provides information with respect to fragmentation processes, but limited information with respect to initiation and failure plane development.

Initiation processes

By incorporating some constraints with respect to material properties, modelling was extended towards simulating progressive development of the failure surface assuming an initial continuum. Figure 5 shows the results adopting a combined Mohr-Coulomb/Rankine fracture model. The basic material properties used were: Young's modulus = 30 GPa, Poisson's ratio = 0.33, unit weight = 26 kN/m^3, cohesion = 1 MPa, internal friction = 20° and tensile strength = 0.1 MPa. The shear-based Mohr-Coulomb fracture constitutive model reproduces the dimensions of the failed mass very well, both with respect to the outline of the first Randa slide event (Figure 5b) and the final outline of the slide surface (Figure 5d).

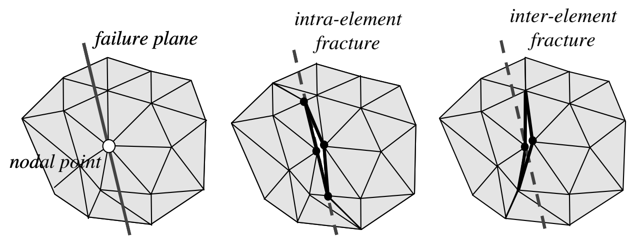

Figure 3. ELFEN crack insertion procedure showing: (a) initial state; and crack development (b) through element or (c) along element boundary (after [13]).

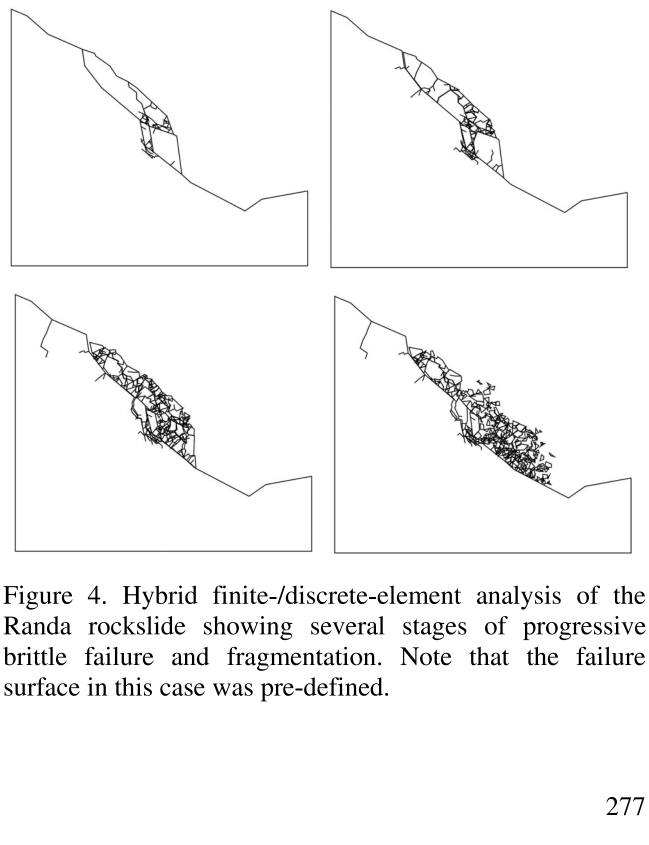

Figure 4. Hybrid finite-/discrete-element analysis of the Randa rockslide showing several stages of progressive brittle failure and fragmentation. Note that the failure surface in this case was pre-defined.

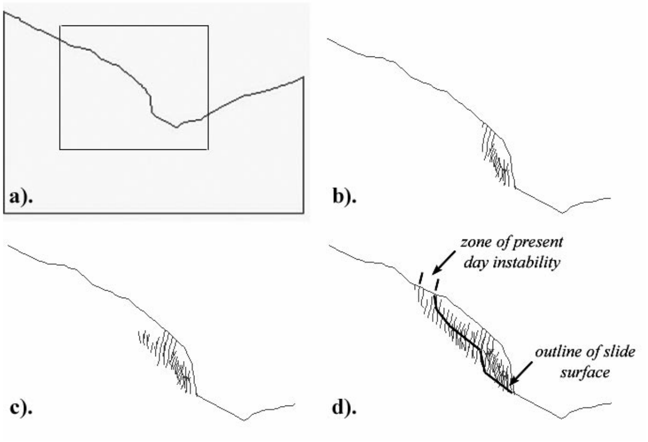

Figure 5. Hybrid finite-/discrete-element model employing a Mohr-Coulomb shear fracture constitutive model, showing: a) full model geometry; and b-d) modelled progressive development of the slide surface relative to the 1991 Randa failure surface.

Closer inspection of the model results suggest that shear stresses and strains induced through gravitational loading of the continuum drive the progressive development of the failure surface. This leads to the formation of numerous subvertical tension/extension cracks (i.e. normal to the direction of downslope strains) through the Rankine tension cutoff, that together align to form a shear plane sub-perpendicular to the tensile fractures.

Internal slope mass deformation and shearing

Further hybrid modelling was performed to more closely examine the staged nature of the failure by modelling the same problem using a Rankine tensile constitutive model. Figure 6 shows that in predicting the development of the first phase of the Randa rock slope failure (i.e. the April 18th, 1991 event), failure appears to involve the progressive internal fracturing of the rock mass leading to collapse of the frontal region of the slope (this staged development was also seen in Figure 5). The modelled slide boundaries for this first failure stage closely approximates that of the actual failure, and its progressively disintegrating nature would agree well with observations that the event lasted several hours and involved the tilting and falling of large blocks one after another [15]. Such a mode of failure would require extensive internal deformation, fracturing and dilation, as demonstrated by the models.

A second consequence of the internal fracturing during the first sliding phase was that the failed debris was deposited at the toe of the slope as opposed to a longer runout as observed in other large rockslides. In general, the runout of the Randa rockslide was relatively short compared to other slide events of comparable size [11]. The model results shown in Figure 6 concur and help to explain the shorter than normal runout experienced at Randa, by suggesting that the episodic nature of the failure as driven by brittle fracture development and the internal friction mobilized as a consequence of this internal fracturing would act to dissipate the driving energy thereby reducing the reach of the event.

Conclusions

Through the adoption of new hybrid numerical modelling techniques, combining finite- and discrete-element methodologies, results presented in this paper demonstrate the value of explicitly modelling brittle fracture processes in understanding complex rock slope failure mechanisms. Rock slope simulations incorporating concepts relating to progressive strength degradation and failure show that in the case of the 1991 Randa rockslide, pre-existing fully persistent geological structures are not necessary to explain failure. Instead, models using the hybrid code ELFEN suggest a failure process largely driven by the initial formation of brittle tensile fractures, eventually leading to shear failure and mobilization once the rock mass cohesion is significantly degraded. In other words, shear failure only becomes a factor after enough tensile fracture damage is incurred to allow mobilization.

Modelling also shows that internal deformation and damage within the slope mass due to strength degradation would result in brittle-ductile transition processes sub-dividing the slide mass into two key units through sub-vertical tensile brittle fracturing. These model results closely agree with the observed boundaries delineating the two slide phases constituting the 1991 Randa rockslide. Furthermore, the inclusion of tensile brittle fracture processes using the hybrid modelling techniques provide important insight as to the underlying mechanisms corresponding to the episodic nature of the rockslide and its relatively short runout distance when compared to other major rockslides of comparable volumes.

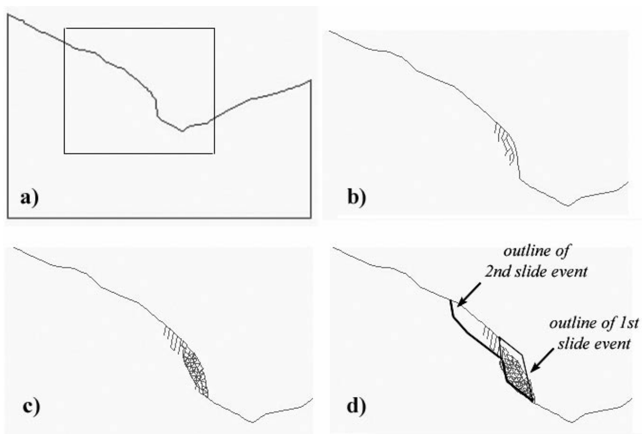

Figure 6. Hybrid finite-/discrete-element model results focussing on internal deformation to reproduce staged nature of the 1991 Randa rockslide (using a Rankine tensile fracture constitutive model).

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References

1. TERZAGHI K. (1962). Stability of steep slopes on hard unweathered rock. *Géotechnique* Vol. 12, pp. 251-270.

2. ROBERTSON A.M. (1970). The interpretation of geological factors for use in slope theory. *Planning Open Pit Mines, Proceedings, Johannesburg*, pp. 55-71.

3. EINSTEIN H.H., VENEZIANO D., BAECHER G.B. and O'REILLY K.J. (1983). The effect of discontinuity persistence on rock slope stability. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* Vol. 20, pp. 227-236.

4. EBERHARDT E., WILLENBERG H., LOEW S. and MAURER H. (2001). Active rockslides in Switzerland - Understanding mechanisms and processes. *International Conference on Landslides - Causes, Impacts and Countermeasures, Davos*, pp. 25-34.

5. BJERRUM L. (1967): Progressive failure in slopes of overconsolidated plastic clay and clay shales. *Journal of the Soil Mechanics and Foundations Division, ASCE* Vol. 93, pp. 1-49.

6. EBERHARDT E., KAISER P.K. and STEAD D. (2002). Numerical analysis of progressive failure in natural rock slopes. *EUROCK 2002, Proceedings of the ISRM International Symposium on Rock Engineering for Mountainous Regions, Funchal, Madeira*, pp. 145-153.

7. MARTIN C.D. and KAISER P.K. (1984). Analysis of rock slope with internal dilation. *Canadian Geotechnical Journal* Vol. 21, pp. 605-620.

8. JENNINGS J.E. (1970). A mathematical theory for the calculation of the stability of slopes in open cast mines. *Planning Open Pit Mines, Proceedings, Johannesburg*, pp. 87-102.

9. MUNJIZA A., OWEN D.R.J. and BICANIC N. (1995). A combined finite-discrete element method in transient dynamics of fracturing solids. *Engineering Computations* Vol. 12, pp. 145-174.

10. ROCKFIELD (2001). *ELFEN 2D/3D Numerical Modelling Package, Version 3.0.* Swansea: Rockfield Software Ltd.

11. SCHINDLER C., CUÉNOD Y., EISENLOHR T. and JORIS C-L. (1993). Die Ereignisse vom 18. April und 9. Mai 1991 bei Randa (VS) - ein atypischer Bergsturz in Raten. *Eclogae Geologicae Helvetiae* Vol. 86, pp. 643-665.

12. WILLENBERG H., SPILLMANN T., EBERHARDT E., EVANS K., LOEW S. and MAURER H. (2002). Multidisciplinary monitoring of progressive failure processes in brittle rock slopes - Concepts and system design. *Proceedings of the 1st European Conference on Landslides, Prague*, pp. 477-483.

13. YU J. (1999). A Contact Interaction Framework for Numerical Simulation of Multi-body Problems and Aspects of Damage and Fracture for Brittle Materials. Ph.D. thesis, Swansea: University of Wales.

14. STEAD D. and COGGAN J.C. (2003). Numerical modelling of rock slopes using a total slope failure approach. *Proc. of the NATO Advanced Research Workshop, Massive Rock Slope Failure: New Models for Hazard Assessment, Celano*, in press.

15. BONNARD C., NOVERRAZ F., LATELTIN O. and RAETZO H. (1995). Large landslides and possibilities of sudden reactivation. *Felsbau* Vol. 13(6), pp. 401-407.