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The Randa Rockslide Laboratory: Establishing brittle and ductile instability mechanisms using numerical modelling and microseismicity

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ABSTRACT: The underlying complexity associated with unstable massive rock slopes has generally restricted the investigation of such slopes to phenomenological studies that are largely descriptive and qualitative. Continued rockslide problems experienced throughout mountainous regions of the world, however, demonstrate the need for a deeper understanding of the physical processes and mechanisms leading to catastrophic failure. This paper focuses on the role brittle fracture and plastic deformation processes play in the development of catastrophic failures in massive, crystalline rock slopes. The work presented is based on the 1991 Randa rockslide in southern Switzerland and combines several conceptual and numerical models developed with respect to tensile and shear mechanisms that drive progressive rock slope failure. The paper also presents preliminary microseismic monitoring results recorded through the Randa Rockslide Laboratory, a unique multidisciplinary alpine facility focusing on ongoing movements at Randa. Such data are expected to provide valuable constraints for specialized hybrid finite-/discrete-element modelling designed to explicitly model rock slope deformation, damage initiation and fracture propagation.

1 INTRODUCTION

Ever increasingly, experts are called upon to analyse and predict - assessing risk, rock mass response, potential modes of failure and possible preventive/remedial measures. The ability to do so, however, is limited by the descriptive and qualitative nature of most analyses, which tend to provide only minimal insights into the underlying processes and mechanisms driving instability and failure. The degree to which prediction is achievable is also contentious, with many seeing it as being limited to the assessment of a stability state (i.e. factor of safety) or the probability that a certain slope may fail. The ability to predict with respect to time, what society asks from us, seems distant as we try to contend with the large number of unknowns and complexity involved in the subsurface geology and hydrogeology.

To move in this direction and improve our ability to predict, both in terms of probability and time, more sophisticated tools are required to better assess the subsurface mechanisms contributing towards catastrophic rock slope failure. Limit equilibrium analysis and other phenomenological approaches only provide a snapshot of the force- and/or moment-balance conditions at the instant of failure, and as such provide a simplified answer as to why the slope failed, but not within the context of time or its progressive development from a stable to unstable state.

This paper focuses on the application of new advanced numerical tools aimed at better understanding the mechanistic role brittle and ductile processes play in the progressive development and evolution of catastrophic failure in massive, crystalline rock slopes. The work presented utilizes initial hypotheses based on numerical modelling of the 1991 Randa rockslide in southern Switzerland to develop conceptual models with respect to the underlying tensile and shear mechanisms that helped to promote failure. These models exploit hybrid techniques that combine finite- and discrete-element solutions, allowing for the explicit modelling of rock slope deformation and fracture initiation/propagation.

Yet it must be recognized that such modelling techniques have advanced beyond our capabilities to confidently constrain the necessary input (Stead et al. 2001). The second part of this paper touches on the collection of microseismic data from a unique field facility – the Randa Rockslide Laboratory, and its potential role in providing spatial and temporal constraints through event counting, frequency content analysis, source location and source mechanisms. Problems associated with attenuation, which negatively affect the quality of microseismic data, are also discussed.

2 BRITTLE FRACTURE PROCESSES IN MASSIVE ROCK SLOPES

A key kinematic requirement for rock slope failure is the existence of a fully interconnected discontinuity system bounding the moving mass. Three-dimensionally, this can be accommodated by intersecting bedding plane/foliation parallel fractures, faults, tectonic joint systems, unloading joints, tension cracks, erosional scarps, etc. In some cases, the failure surface can be seen to coincide with extensive geologic features such as bedding planes (e.g. 1806 Goldau rockslide, Switzerland; 1905 Frank slide, Canada), but even then such features may only explain the existence of a basal shear surface but not the lateral release scarps. In other cases, for example the 1991 Randa rockslide in Switzerland, the structural nature of the failure surface is even more complex with few signs of fully persistent discontinuities other than those limited to small outcrops relative to the total failure surface area. In either case, the likelihood of a completely developed failure surface existing for any substantial period of geologic time is unlikely, since prior to failure, many of these rock slopes have remained relatively stable for thousands of years with few major external changes occurring with respect to their kinematic state. The last major external change most rock slopes in an alpine environment would have experienced would have been the over-steepening of their slopes during glaciation and loss of confinement during ice-free periods.

Strength degradation over time and progressive failure (i.e. the progressive development of the failure surface) can be used to explain the temporal nature of massive rock slope failures (Eberhardt et al. 2004). Several authors have pointed to the presence of intact rock bridges as providing cohesive strength components along a potential failure surface (e.g. Jennings 1970, Einstein et al. 1983), while others have also examined the role of internal rock mass shearing and yield (Mencl 1966; Martin & Kaiser 1984). Figure 1 illustrates these rock slope failure controls viewed in terms of shear plane development, and strength degradation manifested through internal deformation, dilation and damage mechanisms. Underlying many of these controls are time-dependent processes such as material creep, brittle fracture propagation, stress corrosion, fatigue and weathering.

In terms of brittle fracture propagation, several authors have examined the application of fracture mechanics' principles to model the destruction of intact rock bridges leading to catastrophic rock slope failure (e.g. Scavia 1995, Kemeny 2003). Kemeny (2003) notes that these unbroken segments along the sliding surface provide a cohesive element both in shear and in tension that may deteriorate in time depending on the applied stresses.

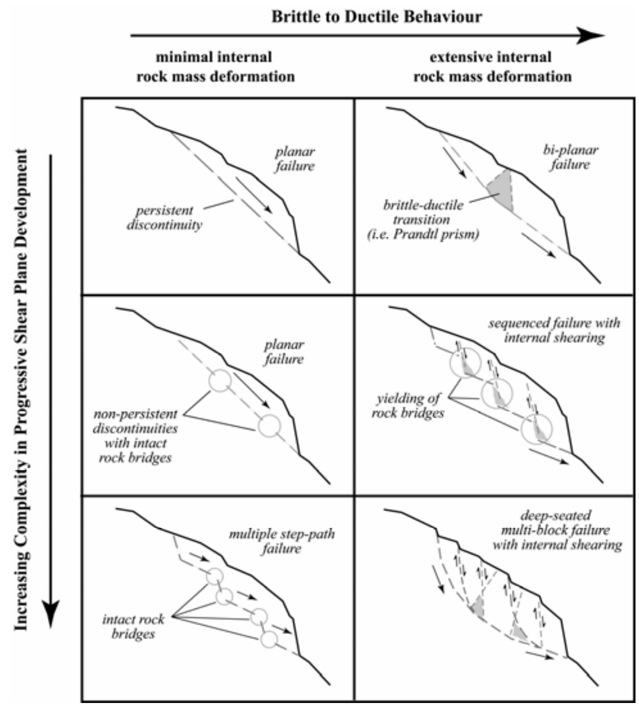

Figure 1. Massive rock slope failure mechanisms as controlled by progressive shear plane development and/or internal rock mass deformation and shear (after Eberhardt et al. 2002).

In the field, Fleming & Johnson (1989) observed the evolution of large-scale fractures over successive field campaigns with respect to the progressive development of lateral release scarps bounding an unstable slope. Thus, the importance of incorporating brittle fracture processes (both the initiation of fractures and the propagation of pre-existing fractures), can be stressed as being paramount to better assessing the stability state for a given rock slope and more realistically simulating its failure mechanism.

3 NUMERICAL MODELLING OF BRITTLE AND DUCTILE MECHANISMS

3.1 The Randa Rockslide Laboratory

The "Randa Rockslide Laboratory" in the southern Swiss Alps was conceived and constructed as a high alpine *in situ* laboratory utilising state of the art instrumentation systems to study mechanisms controlling progressive failure and pre-failure rock mass deformations in massive crystalline rock slopes (Eberhardt et al. 2001). The resulting facility represents a first of its kind installation integrating instrumentation systems designed to measure temporal and 3-D spatial relationships between fracture systems, displacements, pore pressures and microseismicity (Willenberg et al. 2002). The test site itself is located on a moving mass (with an approximate volume of 10 million m^3), but which is presumably in an uncritical state characterized by low deformation rates (max. 1-2 cm per year).

Advanced numerical models are also used in conjunction with the instrumentation data to provide key insights into the interplay between brittle and ductile mechanisms driving the development of the failure surface (i.e. progressive failure) and accommodating internal displacements within the slide mass through rock deformation, strength degradation and internal shearing (Eberhardt et al. 2004). To help further constrain these models, the site benefits from its close proximity to the scarp the 1991 Randa rockslide, for which back-analyses can be performed. The back scarp of the 1991 failure forms the face of the present day instability.

The 1991 Randa rockslide involved the failure of 30 million m^3 of massive crystalline rock in two separate episodes (Fig. 2). Structurally, the foliation dips favourably into the slope. As such, Schindler et al. (1993) suggested that failure occurred along extensive shallow dipping joints parallel to the surface. These joints can be observed along parts of the sliding surface but are limited in persistence when encountered in surface outcrops (Willenberg et al. 2002). Schindler et al. (1993) also proposed a series of steep sub-vertical faults as dividing the slide mass into smaller units. A comprehensive description of the unstable rock mass above the 1991 scarp is given in Willenberg et al. (2004; see these proceedings).

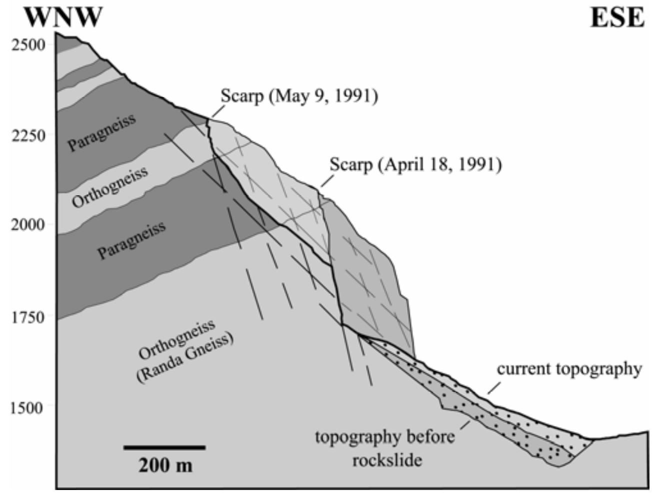

Figure 2. Cross-section of 1991 Randa rockslide (modified after Schindler et al. 1993).

3.2 Numerical formulation and model setup

The application of numerical modelling to slope stability investigations is generally approached either from the perspective of a continuum (e.g. finite-element) or a discontinuum (e.g. discrete-element). However, as discussed in the previous section, the actual complexity involved in most massive rock slope failures involves both the behaviour of the continuum (e.g. intact rock yield) and the discontinuum (e.g. shearing along pre-existing discontinuities), and most importantly, the transformation of the rock mass from a continuum to a discontinuum (e.g. the generation of new fractures). To treat these problems, new developments in hybrid finite-/discrete-element codes have been forwarded which allow for the explicit modelling of brittle fracture initiation and propagation by means of adaptive remeshing routines (Munjiza et al. 1995).

For the purposes of this study, the commercial hybrid finite-/discrete-element code ELFEN (Rockfield 2001) was used. A Mohr-Coulomb based constitutive model with a Rankine Tensile cutoff was adopted, through which the extensional inelastic strain accrued during compression can be coupled to the tensile strength degradation in the dilation direction (permitting the explicit modelling of discrete fracturing under compressive stresses). Stacey et al. (2003) argue that extensional strain is an important factor in slope stability that has not been fully appreciated.

These techniques were applied to a 2-D cross section based on the pre-1991 Randa rockslide surface topography (Fig. 2). Based on this geometry, modelling was directed towards simulating the progressive development of the 1991 failure surface from that of an initial continuum. The role of pre-existing discontinuities was not included. A Mohr-Coulomb constitutive yield model with a Rankine tension cutoff was used to model deformation and fracture initiation. The basic material properties used were based on those for a fractured crystalline rock mass: Young's modulus = 30 GPa, Poisson's ratio = 0.33, unit weight = 26 kN/m3, cohesion = 1 MPa, internal friction = 30° and tensile strength = 0.1 MPa. A strain energy release rate of 200 N/m was assumed.

3.3 Extensional strain and brittle fracture

Stacey et al. (2003) note that although the advent of numerical modelling has led to more studies in which rock slope stresses are considered, little if any consideration has been given to the occurrence of strains. When considering the free boundary or unsupported face of a steep slope, down-slope strains can be expected. Such strains would be extensional in nature, with extension strain being defined as the minimum principle strain, ε_3. Figure 3 shows the extensional plastic strains for the 1991 Randa rockslide based on a finite-element continuum analysis with a Mohr-Coulomb yield model, but without the hybrid discrete-element coupling enabling fracture initiation (using the material properties previously listed). The model shows that large extensional strains develop along a path that roughly coincides with the 1991 Randa rockslide failure surface (as shown in Fig. 2). The strains reproduced in this model are well in excess of those reported by Stacey (1981) as being the critical levels for brittle fracture initiation and propagation.

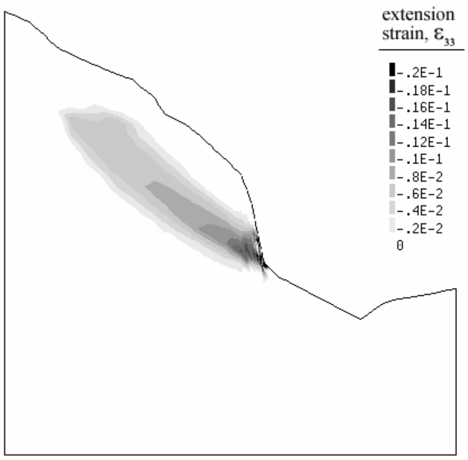

Figure 3. Extension strain, ε_3, calculated for the pre-failure geometry of the 1991 Randa rockslide.

Figure 4 shows the same model run (i.e. same geometry and material properties), but where brittle fracturing was permitted through the hybrid finite-/discrete-element solution. Again, the model reproduces the dimensions of the failed mass very well, both with respect to the outline of the first Randa slide event (Figure 4b) and the final outline of the slide surface (Figure 4d). In doing so, the influence of the shear constitutive fracture model can be fully appreciated; the extensional strains and elasto-plastic yielding induced through the down-slope movements of the continuum result in fracture initiation and propagation driving the progressive development of the failure surface (as can be seen comparing Figs. 3 and 4). This leads to the formation of numerous subvertical tension/extension cracks (i.e. normal to the direction of downslope strains). The presence of any low dipping natural discontinuities would further aid the process, aligning to form a stepped shear plane that could accommodate further movements and eventually kinematic release of the slide mass.

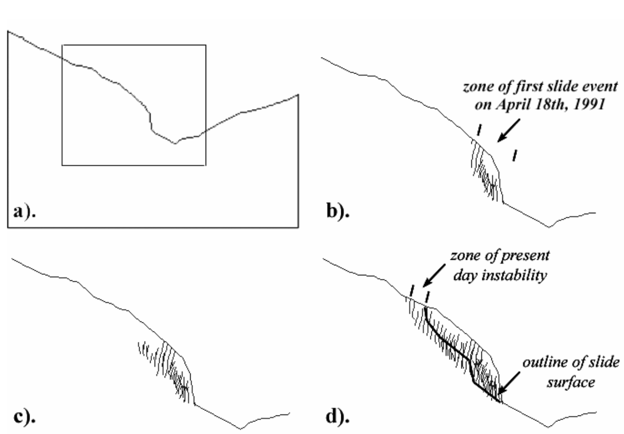

Figure 4. Hybrid finite-/discrete-element model showing the progressive development of the failure surface superimposed with that of 1991 Randa rockslide events.

Remembering that this model started from an intact continuum, it can be reasoned that shear along a potential rock slope failure surface only becomes a factor once it's almost fully developed and mobilization becomes possible. In other words, the failure surface only becomes a "shear" surface once tensile extensional fracturing has progressed to the point where significant cohesion loss has occurred along the path of coalescing fractures and larger displacements become kinematically feasible (leading to mobilization).

In addition, the progressive failure approach also clearly predicts the development of the first phase of the Randa rock slope failure (i.e. April 18th, 1991 event), prior to that of the second major event (i.e. May 9th, 1991 event). Here failure appears to first involve the progressive development and collapse of the frontal region of the slope. The modelled slide boundaries for this first failure stage closely match those 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 (Bonnard et al. 1995). Such a mode of failure would require extensive internal deformation, fracturing and dilation, as demonstrated by the models.

4 MICROSEISMIC MONITORING

Based on the modelling results presented, it can be put forward that highly persistent natural discontinuities are not solely necessary for massive rock slope failure, but that extensional strain-induced brittle fracturing can also work towards progressively driving a rock slope to failure. As such, much can be gained from field based studies that similarly focus on brittle fracture indicators. On surface or in boreholes, these may take the form of open fractures that can be measured with respect to opening rates and displacements (Willenberg et al. 2003). Another potentially useful tool is the passive monitoring of microseismic activity to detect subsurface tensile fracturing and/or shear slip along internal fracture planes. Spatially clustered microseismic events in numerous fields (e.g. mining, geothermal energy, nuclear waste disposal, etc.) have provided critical information with respect to stress-induced fault plane locations, orientations and mechanisms.

In planning the design of the Randa Rockslide Laboratory, such a system was deemed essential (Eberhardt et al. 2001, Willenberg et al. 2002). To do so, an array of twelve three-component geophones was installed in 2001 (Fig. 5). Three 28 Hz geophones (labelled A5, B2, B5 in Fig. 5) were deployed near the bottom of three deep boreholes. Nine shallow geophones with 8 Hz resonance frequency complete the microseismic array. The spatial distribution of these sensors was chosen such that

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the array's resolution was concentrated to the active sliding area (shaded in Fig. 5a). This ensured that the hypocentre parameters generated from the seismic sources could be reliably constrained within the area of interest (Willenberg et.al. 2002).

Following installation of the microseismic monitoring system in 2001, problems were encountered in the form of an unknown noise source that resulted in the frequent triggering of the system. These high frequency "noise bursts" generated exceptionally large volumes of data (>500 GBytes), requiring the testing of smaller data sets to improve event detection and develop efficient data processing routines. One such data set, for the period March to May 2002, revealed numerous microseismic events, but only one whose location fell within the projected moving volume (shown in Fig. 5b at 50 m depth). The remaining events were either related to seismic activity in the valley/region, unexplained events lying far outside the area of interest, noise, or provided such poor quality signals that accurate source location was not possible.

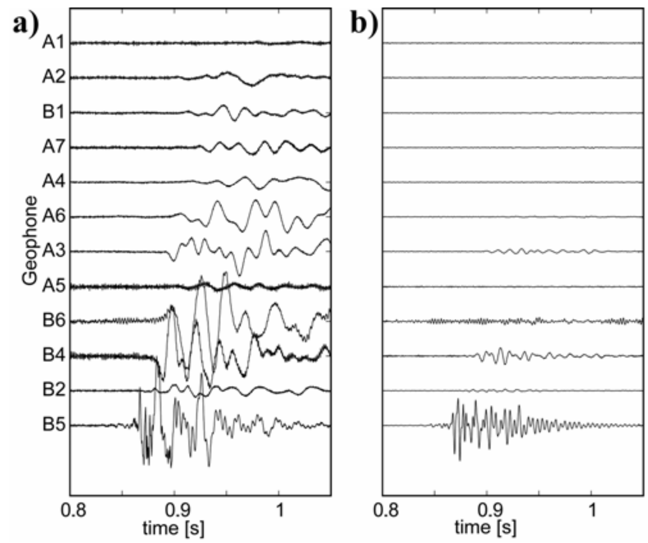

Figure 6. Vertical components of a locatable microseismic event: a) raw; b) 100-500 Hz bandpass filtered signals. Signals are sorted according to the source-receiver distance, with sensor A1 being the farthest and B5 the closest. Absolute time scale is arbitrary.

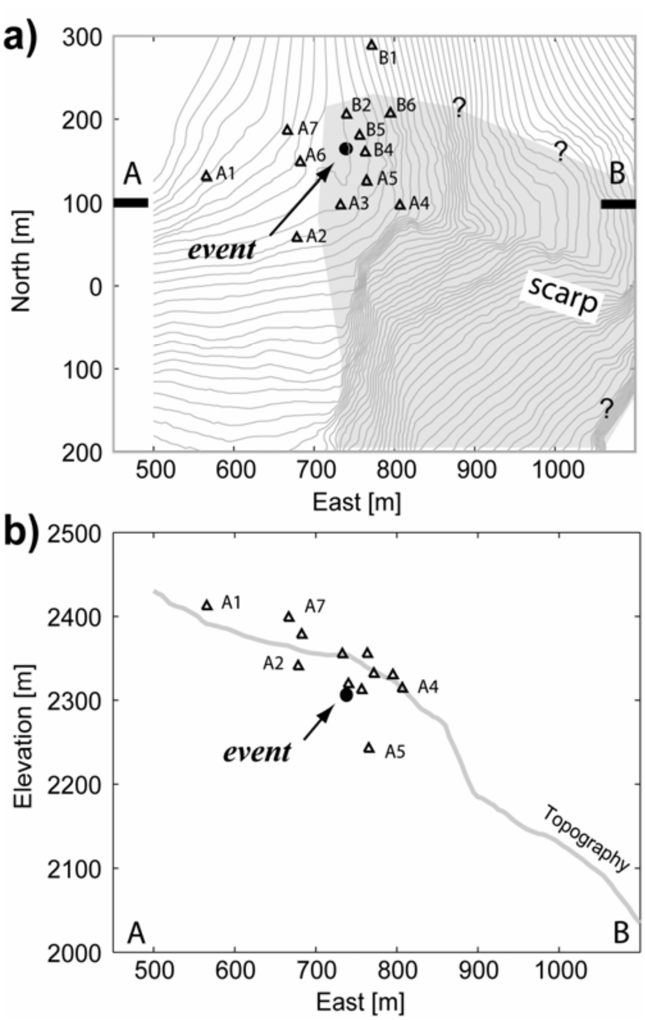

Figure 5. a) Map view and b) cross-section of the Randa microseismic geophone array showing the location of a recorded event from a limited sample data set (March to May, 2002).

The question of signal quality led to further analysis of the frequency content of the recorded events. Figure 6a shows the vertical component of the seismograms for all twelve sensors for the locatable event (as noted in Fig. 5). The seismograms are sorted according to the source-receiver distance, with receiver A1 being the farthest from the source and B5 the closest at 21 m. With the exception of B5, harmonic signals with dominant frequencies of 20 Hz and emergent first breaks characterize the seismograms. Figure 6b shows a filtered version of the same event using a 100/500 Hz bandpass filter. This frequency range covers that which would be expected for the brittle fracture-induced microseismic events (i.e. higher frequency). However, as can be clearly seen in Figure 6b, only the closest sensor B5 (21 m away from the source) was able to record significant amplitudes above 100 Hz. The high frequency information is strongly attenuated for the remaining sensors with source-receiver offsets between 40 and 200 m.

This and the poor signal quality of the other microseismic events point to the presence of large open fractures deep below surface, across which passing waves are strongly attenuated. These large open fractures are fully compatible with the geological model described in Willenberg et al. (2004). Larger low frequency events, such as those generated from natural seismic activity in the region, do not suffer as much from signal quality degradation. Based on these results, new algorithms must be devised that are capable of extracting more information on the subsurface deformation characteristics.

5 CONCLUSIONS

To explain and better predict the temporal evolution of massive rock slope instabilities and failures, subsurface processes involving rock mass strength degradation and progressive failure must be considered. Hybrid finite-/discrete-element models incorporating these processes were able, starting from a continuum, to reproduce both the shear surface outline and the staged nature of the failure of the 1991 Randa rockslide. The fractures generated through extensional strains were predominantly sub-vertical tensile fractures normal to the direction of downslope movement. As the density of these fractures increased, the shear plane progressively developed to form a failure surface typical of more ductile failures where the rock mass is heavily damaged.

These models help to reinforce conceptual models for which massive rock slope failure processes are largely driven by the initiation and propagation of brittle tensile fractures driven by extensional strain, which interact with natural pre-existing discontinuities to eventually form basal and internal shear planes. Shear failure only becomes a factor once enough tensile fracture damage was incurred to allow mobilization.

Microseismic data collected at the Randa Rockslide Laboratory, located over an unstable mass moving at rates of 1-2 cm/ year, suggest the presence of large open fractures, deep below surface. Although only a small data set sampled from the much larger data set collected has been analyzed, preliminary results show that the slope mass may be microseismically active. Difficulties arising due to poor signal quality and attenuation must be addressed though. Notwithstanding, it is believed that such mechanistically-based studies and analyses, combining state-of-the-art numerical modelling techniques, advanced instrumentation systems and multidisciplinary collaborations, will help to significantly advance current understanding of rock slope failure processes, from the early stages of development through to catastrophic failure.

REFERENCES

Bonnard, C., Noverraz, F., Lateltin, O. & Raetzo, H. 1995. Large landslides and possibilities of sudden reactivation. *Felsbau* 13(6): 401-407.

Eberhardt, E., Kaiser, P.K. & Stead, D. 2002. Numerical analysis of progressive failure in natural rock slopes. In C. Dinis da Gama & L. Ribeiro e Sousa (eds.), *EUROCK 2002 – Proc. of the ISRM Int. Sym. on Rock Engineering for Mountainous Regions, Madeira*. Lisboa: Sociedade Portuguesa de Geotecnia, pp. 145-153.

Eberhardt, E., Stead, D. & Coggan, J.S. 2004. Numerical analysis of initiation and progressive failure in natural rock slopes – the 1991 Randa rockslide. *Int. J. Rock Mech. Min. Sci.* 41(1): 69-87.

Eberhardt, E., Willenberg, H., Loew, S. & Maurer, H. 2001. Active rockslides in Switzerland – Understanding mechanisms and processes. In M. Kühne et al. (eds.), *UEF Int. Conf. on Landslides – Causes, Impacts and Countermeasures, Davos*. Essen: Verlag Glückauf GmbH, pp. 25-34.

Einstein, H.H., Veneziano, D., Baecher, G.B. & O'Reilly, K.J. 1983. The effect of discontinuity persistence on rock slope stability. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 20(5): 227-236.

Fleming, R.W. & Johnson, A.M. 1989. Structures associated with strike-slip faults that bound landslide elements. *Eng. Geol.* 27(1-4): 39-114.

Kemeny, J. 2003. The time-dependent reduction of sliding cohesion due to rock bridges along discontinuities: A fracture mechanics approach. *Rock Mech. Rock Eng.* 36(1): 27-38.

Jennings, J.E. 1970. A mathematical theory for the calculation of the stability of slopes in open cast mines. In: *Planning Open Pit Mines, Proc., Johannesburg*. Cape Town: A.A. Balkema, pp. 87-102.

Martin, C.D. & Kaiser, P.K. 1984. Analysis of rock slopes with internal dilation. *Can. Geotech. J.* 21(4): 605-620.

Mencl, V. 1966. Mechanics of landslides with non-circular slip surfaces with special reference to the Vaiont slide. *Géotechnique* 16(4): 329-337.

Munjiza, A., Owen, D.R.J. & Bicanic, N. 1995. A combined finite-discrete element method in transient dynamics of fracturing solids. *Engineering Computations* 12: 145-174.

Rockfield 2001. ELFEN 2D/3D Numerical Modelling Package, v.3.0. Swansea: Rockfield Software Ltd.

Scavia, C. 1995. A method for the study of crack propagation in rock structures. *Géotechnique* 45(3): 447-463.

Stacey, T.R. 1981. A simple extension strain criterion for fracture of brittle rock. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 18(6): 469-474.

Stacey, T.R., Xianbin, Y., Armstrong, R. & Keyter, G.J. 2003. New slope stability considerations for deep open pit mines. *The Journal of the South African Institute of Mining and Metallurgy* 103(6): 373-389.

Schindler, C., Cuénod, Y., Eisenlohr, T. & Joris, C-L. 1993. Die Ereignisse vom 18. April und 9. Mai 1991 bei Randa (VS) - ein atypischer Bergsturz in Raten. *Eclogae Geologicae Helvetiae* 86(3): 643-665.

Stead, D., Eberhardt, E., Coggan, J. & Benko, B. 2001. Advanced numerical techniques in rock slope stability analysis – Applications and limitations. In M. Kühne et al. (eds.), *UEF Int. Conf. on Landslides – Causes, Impacts and Countermeasures, Davos*. Essen: Verlag Glückauf GmbH, pp. 615-624.

Willenberg, H., Evans, K.F., Eberhardt, E. & Loew, S. 2003. Monitoring of complex rock slope instabilities – correction and analysis of inclinometer/extensometer surveys and integration with surface displacement data. In F. Myrvoll (ed.), *Proc. of the 6th Int. Symp. on Field Measurements in Geomechanics, Oslo*. Lisse: A.A. Balkema, pp. 393-400.

Willenberg, H., Evans, K.F., Eberhardt, E.. Loew, S., Spillmann, T. & Maurer, H. 2004. Geological, geophysical and geotechnical investigations into the internal structure and kinematics of an unstable, complex sliding mass in crystalline rock. In *Proc. of the 9th Int. Symp. on Landslides, Rio de Janeiro*. In Press (this volume).

Willenberg, H., Spillmann, T., Eberhardt, E., Evans, K., Loew, S. & Maurer, H.R. 2002. Multidisciplinary monitoring of progressive failure processes in brittle rock slopes - Concepts and system design. In J. Rybář et al. (eds.), *Proc. of the 1st European Conf. on Landslides, Prague*. Lisse: A.A. Balkema, pp. 477-483.