NEW DEVELOPMENTS IN THE SIMULATION OF ROCK SLOPE FAILURE

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Abstract

Massive rock slope failure involves three main components; initiation (or trigger mechanisms), transportation and deposition. In this paper, the authors present a “total slope failure analysis” which incorporates all three stages from initiation through to deposition. This analysis is undertaken using a combined finite element-discrete element code, ELFEN that incorporates both fracture propagation and adaptive remeshing. This code provides the ability not only to simulate failure initiation but to also to investigate the complex fracturing, comminution and transportation processes inherent in most rockslides. The potential of this approach is demonstrated using both selected case histories and varied failure mechanisms.

Résumé

L'échec massif de pente de roche implique trois composants principaux; déclenchement (ou mécanismes de déclenchement), transport et dépôt. En cet article, les auteurs présentent une “analyse total d'échec de pente” ce qui incorpore chacune des trois étapes de déclenchement à travers au dépôt. Cette analyse est entreprise en utilisant un élément fini combiné et code discret d'élément , ELFEN qui incorpore la propagation de rupture et remeshing adaptatif. Ce code fournit la capacité de simuler non seulement le déclenchement d'échec mais à aussi pour étudier les processus complexes de rupture, de morcellement et de transport inhérents à la plupart des rockslides. Le potentiel de cette approche est démontré en utilisant des histoires choisies de cas et des mécanismes changés d'échec.

1. INTRODUCTION

There have been significant developments over recent years in the methods of analysis of rock slopes. Coggan et al (1998) provide a discussion of the available methods of analysis for rock slopes emphasising advantages and limitations. Limit equilibrium techniques are now routinely available in both two and three dimensions with the ability to couple with groundwater flow analysis. Several codes have developed sophisticated probabilistic capabilities including RocPlane and Swedge (Rocscience 2002); with similar codes available for circular and non-circular analysis, SlopeW (Geoslope 2002) and Slide (Rocscience 2003). Some of these codes allow not only factor of safety distributions to be derived but also probabilistic representation of varied parameters (such as wedge weight).

Numerous applications of finite difference analysis to rock slope analysis have been published using the FLAC2D and FLAC3D codes (Itasca 2002). These codes allow coupled mechanical-groundwater analyses with options for unsaturated flow and dynamic analyses. Recently a specific FLACSLOPE code has been released to allow mechanical modelling with factor of safety calculation. Finite element analyses of rock slopes has been undertaken for many decades with early finite element analyses at Hells Gate in British Columbia described by Kalkani and Piteau (1976).

A wide variety of distinct element codes have been use in the analysis of rock slopes. These codes are particularly suitable for the simulation of rock slope failure in both massive and jointed rock masses. Pritchard and Savigny (1991), Benko and Stead (1999) and more recently Nichol et al. (2002) have demonstrated their usefulness in analysing toppling failure mechanisms in Canadian slopes. Benko and Stead (1998), Stead and Eberhardt (1997) and Stead et al. (2001) have illustrated their application in complex rock slope failure analyses. In all these cases, the two-dimensional distinct element code, UDEC was utilised. More recently, the three dimensional distinct element code 3DEC has been used to investigate the stability conditions of rock slopes. Corkum and Martin (2002) describe an interesting application of the 3DEC code in the investigation of stability mechanisms in the abutment slope of the Revelstoke dam, BC. 3DEC now incorporates pore water pressure capabilities and where adequate rock mass characterisation is available has considerable potential for improving our understanding of rock slope failure mechanisms. Another distinct element code that has found significant application in rock slope analysis is the Displacement Discontinuity Analysis technique, DDA (Sitar and MacLoughlin 1997, Chen and Ohnishi 1999). The former authors provided an interesting DDA analysis of the Vaiont dam slope failure whereas the latter authors investigated a major rock slope failure in Japan. A recently introduced code, which has been used in the simulation of frictional debris flows, Calvetti et al. (2001) is the particle flow code, PFC (Itasca 2002). This code simulates rock masses using blocks comprising either round particles (PFC2D) or spheres (PFC3D). These codes offer considerable potential in investigating not only rockfall but also in simulating intact rock fracture during rock slope failures. (Intact rock fracture being simulated by the breaking of bonds between adjacent particles or spheres). Of extreme importance in rock engineering are the analysis of both rockfall trajectories and the runout characterisation of rock avalanches. Such methods are essential if the techniques of risk assessment are to be used confidently in mountainous terrain. Significant developments are being made including the routine use of two-dimensional simulators, RocFall (RocScience, 2002) and the introduction of three dimensional rockfall codes. It should be emphasised that it is essential that such analyses incorporate a rigorous characterisation of observed rockfall and improved assessments of input data including tangential and normal restitution parameters. The combined use of these rockfall codes with Geographic Information Systems is a particularly useful field of study. Hungr (1995) describes the use of the dynamic rheology based code; DAN in the characterisation of runout of the Frank slide, of Hong Kong debris flows and of mine spoil piles. Continued development of such codes is essential if runout assessments are to be incorporated into risk assessment with increased confidence.

1.1 Total Slope Failure Analysis

Of specific interest to this paper are new developments in the analysis of rock slopes using a combined finite element-discrete element code with fracture propagation capability. It is emphasised that although the analyses presented are still at an introductory stage they serve to highlight what the authors consider to be the immense potential of this technique. Using this approach, the authors feel that it will be possible to undertake what they term a “total slope failure analysis” in contrast to traditional rock engineering where the analysis of rock slopes has emphasised either the initiation mechanism or the transport/deposition stage. Figure 1, modified after Couture et al. (1999) shows the varied stages of the total slope failure analysis with the appropriate analysis codes.

1.1.1 The Initiation Stage

In this stage, dependent upon the complexity of the rock slope several options are available:

- Hazard assessment: based on a factor of safety –groundwater flow calculation. (Slide, SlopeW, CLARA).
- Rock mass characterisation using engineering geological techniques directly relevant to rock slope analysis methods.
- Risk Assessment incorporating probabilistic slope stability analysis.
- Failure mechanism investigation using continuum and discontinuum codes or hybrid codes with or without fracture propagation (FLAC, PHASE^2, UDEC, PFC, ELFEN)

1.1.2 The Transportation and Comminution Stage

- Analysis of movement using rheological flow techniques (FEM, FLAC, DAN, ELFEN)
- Analysis of the breakdown (crushing/grinding) processes during transport (ELFEN)

1.1.3 The Deposition Stage

- Prediction of runout using rheological codes and incorporation into risk assessment through spatial probability determination.

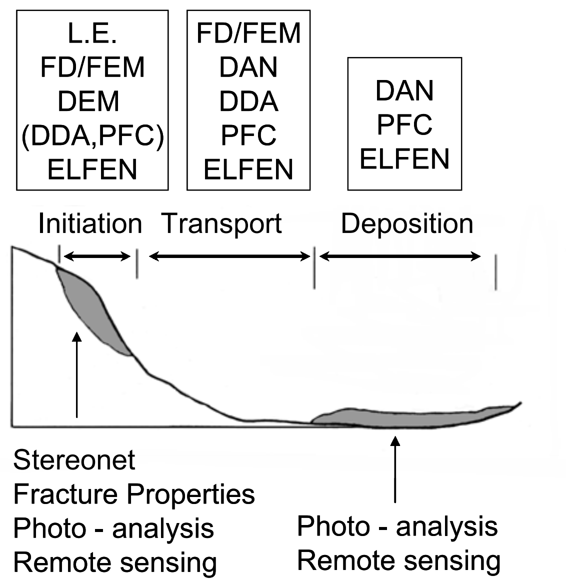

Figure 1. Stages during a total slope failure analysis (modified after Couture et al. 1999).

2. THE COMBINED FINITE ELEMENT – DISCRETE ELEMENT CODE, ELFEN.

The combined finite–discrete element method, with fracture propagation, has been used successfully in rock engineering to simulate processes of rock bursting and breakout formation in deep underground mines, mining of tabular orebodies, simulation of rock tests, and the blasting of rock slopes in open pit mining. Munjiza et al. (1995) illustrated the use of a finite element mesh to represent the rock slope to be blasted, Figure 2. The effect of the detonation of successive blast holes is simulated by the progressive growth of fractures in the rock mass resulting in the formation of discrete elements. These deformable discrete elements are re-meshed and the analysis continued. The gradual breakdown of the rock mass in response to the blast is simulated by fracture growth, re-meshing and the formation of smaller discrete elements. The ELFEN code thus allowed the efficiency of the blast to be increased and in addition a comparison between the simulated and the observed blast muck pile size distribution. The combined finite element-discrete element code with fracture has also been used to investigate comminution during the grinding of materials in rock crushers. The ELFEN code, in addition, possesses a 2D/3D particle flow code module to allow simulation of the frictional flow of circular/spherical particles. The authors saw parallels between the simulation of the processes involved in blast trajectory throw, rock pile movement, and comminution and those active in a “total rock slope failure process". It should be emphasised that as with the application of any new method, a thorough and extensive process of back-analysis against major rock slope failure with available field/laboratory data is required. The prime purpose of this paper is to demonstrate the significant potential of this technique, recognising in the need to provide more constraint through the integrated use of alternative modelling methods and site observations. The combined finite-discrete element code utilises a variety of constitutive criteria including linear elastic, non-linear (Mohr Coulomb, Druker-Prager, Von Mises, Rankine etc), time-dependent and rigid. The tensile failure and crack propagation can be modelled using a post-initial yield rotating crack or Rankine formulation. Anisotropic damage evolution is simulated by degrading the elastic modulus, E, in the direction of the major principal stress invariant. The damage parameter, ω, is dependent on the fracture energy, G_f which is related to the critical stress intensity factor, K_{IC} by $G_f = K^2_{IC}/E$. At some point in the analysis of a rock slope the adopted constitutive model predicts the formation of a failure band within a single element, Figure 3. The load carrying capacity across such localised 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 discrete elements as the rock fragments are formed. In addition to the Rankine and Rotating Crack models, a Mohr Coulomb with fracture criteria is available. (Yu 1999 and Klerk 2000). Capabilities of the ELFEN code are shown in Table 1.

Table 1. ELFEN Code capabilities

Feature	Ability	Feature	Ability
Explicit 2D/3D	✓	Multiphase	✓ (Blasting)
Implicit 2D/3D	✓	Fracturing	✓
Jointing 2D/3D	✓	Fracture+pore water pressure	✓Development (Hydrofrac)
PFC 2D/3D	✓	Virtual Reality Viewing	✓
Dynamic	✓	Thermal	✓
Creep	✓	Parallel Processing	✓ Development
Groundwater	✓		

As shown above ELFEN incorporates in one code the ability to undertake both explicit and implicit analyses. It is able to model continuum materials in both two and three dimensions. It is also able to simulate both 2D and 3D jointed media and particle flow behaviour. Options exist for dynamic, thermal, groundwater and time dependent analysis. An important feature with regard to the current paper and rock slope analysis is the ability to simulate intact rock fracture during the stages of total slope failure.

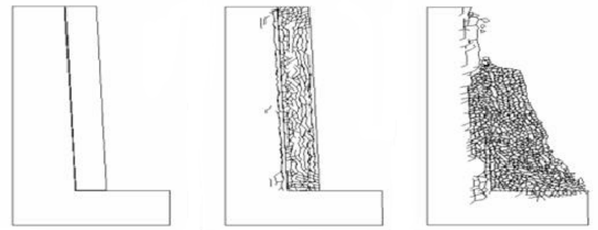

Figure 2.Use of a combined finite-discrete element code to simulate rock blasting, after Munjiza et al. (1995).

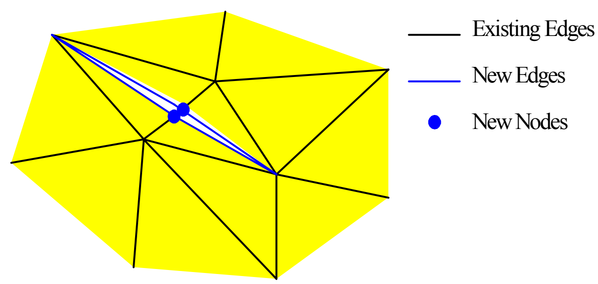

Figure 3. Crack generation within ELFEN finite element mesh.

3. THE RANDA ROCKSLIDE

The geology of the Randa rock slope, Switzerland, is illustrated in Figure 4a and comprises a predominantly gneissic rock mass with several well-developed joint sets. The authors have undertaken a program of detailed slope stability analyses on the Randa Rockslide, which involved two key slide events in April and May 1991. The analyses included initial limit equilibrium modelling using SLIDE followed by continuum modeling using the finite element code, PHASE^2 and distinct element modelling using the UDEC code (Eberhardt et al. (2002). It was found that the finite element models, even without the inclusion of jointing produced a failure surface, which closely agreed with the observed failure surface, Figure 4b.Similar results including jointing as modelled using UDEC are presented in Eberhardt at al (2002). This paper also presents preliminary combined finite element-discrete element modelling with fracture propagation using the ELFEN code. An initial analysis was undertaken incorporating the observed failure surface in order to examine the initiation, transport, comminution and deposition of the rockslide failure debris. The results of this analysis are illustrated in Figure 5, which shows a series of snapshots of the failure process that occurred in two stages. The immense potential of this modelling technique is immediately evident. This analysis was the first published use of the ELFEN code in rockslide simulation and the immense potential of this modelling technique is immediately evident. The ELFEN model complemented the continuum and discontinuum models previously undertaken by Eberhardt et al. (2002), providing significant insight into the progressive nature of the processes involved. Ongoing modeling has emphasized the importance of progressive rock mass degradation and damage within the rock slope prior to eventual slope failure. This damage appears to be rooted as far back as the initial unloading of the rock slope during glacial erosion and deglaciation, and has been shown to result in a damage zone at the slope toe through which the progressive rock slope failure may have initiated.

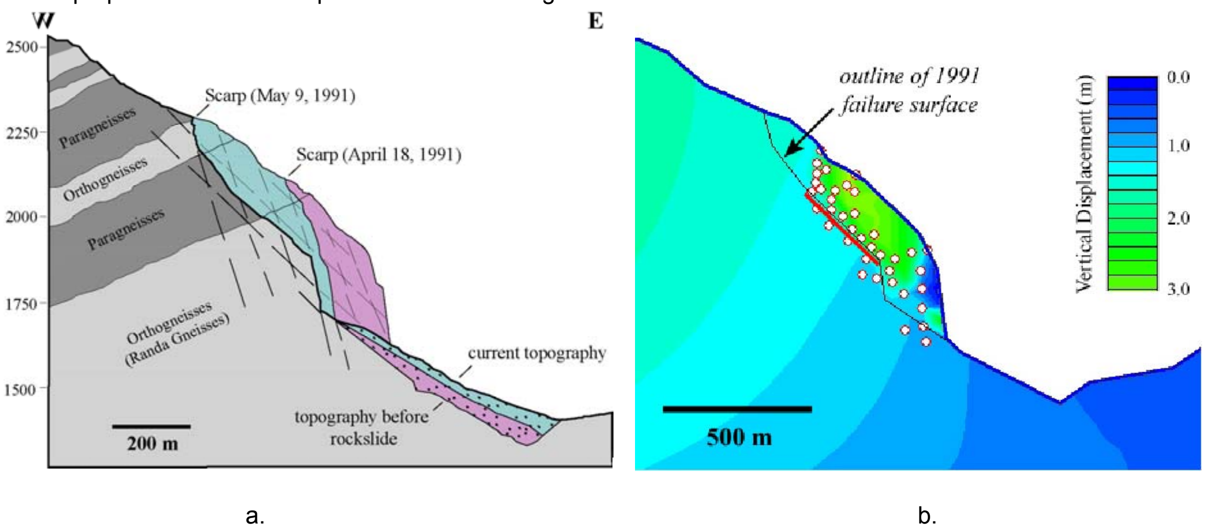

Figure 4 a. Cross-section showing the geology and geometry of the 1991 Randa rockslides and b. Finite element analysis using the Phase2 code. (note that the open circles indicate tensile damage/failure)

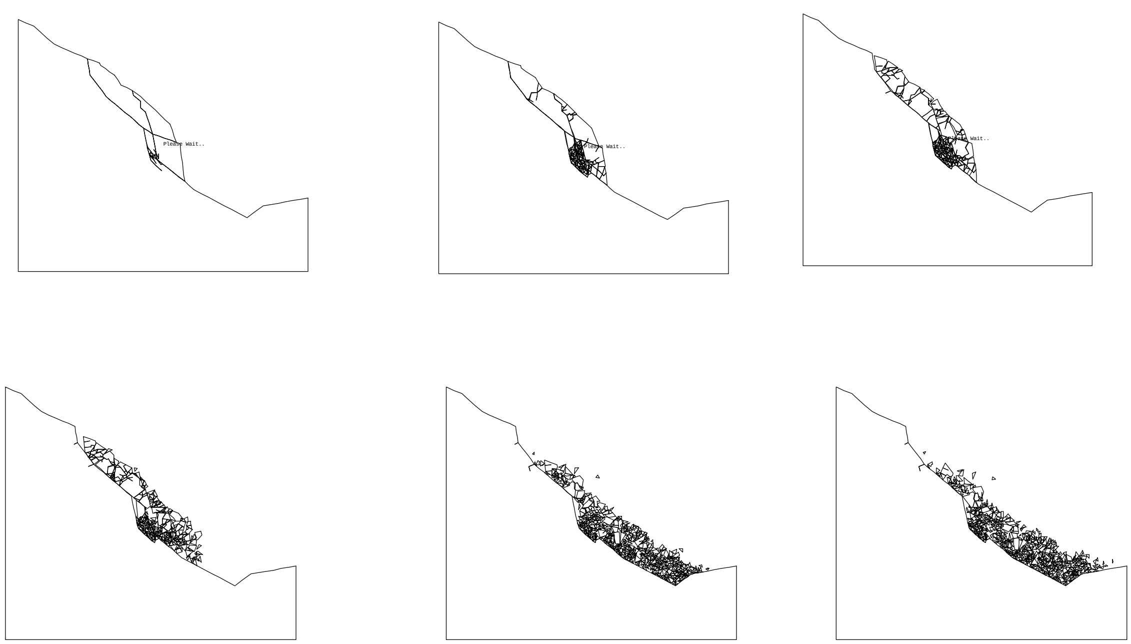

Figure 5. Use of combined the finite-discrete element, ELFEN, to simulate the Randa Rockslide, Switzerland, 1991.

In order to compare the results of the continuum finite element code Phase[2], with the combined finite element-discrete element code ELFEN preliminary analyses of the Randa rockslope were undertaken in an attempt to reproduce the observed failure surface. Results of an ELFEN analysis assuming a Mohr constitutive criterion and fracture propagation are presented in Figure 6. There is extremely close agreement between both the observed stages of failure and the simulated and observed failure surfaces. It is interesting to note that the ELFEN simulation further indicates a current area of deformation behind the 1991 failure scar, which is currently the subject of an extensive and state-of-the-art rock slope instrumentation study, Willenberg et al. (2002)

4. PROGRESSIVE – STEP PATH FAILURE IN ROCK SLOPES

There is widespread recognition that there is a need for investigation of the influence of cumulative rock mass damage on the progressive nature of major rock slope failures. It has long been hypothesised that rock slope failure may occur in response to fatigue loading due to a wide array of loading conditions:

- Dynamic seismic loading due to earthquakes
- Freeze-thaw processes
- Fluctuating pore water pressures, either naturally or due to impoundment of reservoirs.
- Strain cycling due to seasonal deformation or natural slope processes
- Influence of glacial loading
- Influence of weathering processes.

Groundbreaking work by Jennings (1970) and more a recent contribution by Baczynski (2000) have emphasised the potential importance of step-path processes in the initiation of rock slope failure surfaces. Recent research by Eberhardt et al. (2002) and Hajiabdolmajid and Kaiser (2002) has demonstrated the importance of cumulative displacement (strain-softening) in the effective mobilisation and contribution of shear strength parameters.

The authors suggest that step-path features although originally treated as the linking of joints to form through-going failure surfaces may in fact be considered on a wide range of scales. This variation may be considered at the engineering level to extend from the development of cross-over microcracks at the grain/sub grain dimension to the linking of major weakness/joint planes. It is suggested that reduction in the roughness of joints through removal of asperities is a process akin to step-path generation involving the formation of microcracks. The appeal of the ELFEN code is its ability to simulate the failure process at each of these scales. Figure 7 shows a 50m high idealised rock slope where discontinuous weakness planes dip out of the slope. A preliminary ELFEN simulation of the step-path failure process is shown by a series of plots indicating the gradual linking of weakness planes until the failure mechanism becomes kinematically possible. Ongoing parametric studies are aimed at examining the potential for step-path development with varying fracture spacing, inclination, shear and tensile strength and in particular dip and strike-persistence. The latter is arguably a relatively ignored parameter that may have a critical influence on the potential for step-path generation.

5. APPLICATION OF THE COMBINED FINITE ELEMENT-DISCRETE ELEMENT ELFEN CODE TO VARIED FAILURE MECHANISMS

The authors have simulated a variation of failure mechanisms using the ELFEN code in order to investigate the kinematic development of complex failures. Stead and Coggan (2002) describe the application of ELFEN in the analysis of translational, toppling and rockfall failures in addition to a major rockslide avalanche in Elm, Switzerland. Figure 8 shows the use of ELFEN in simulating a complex toppling/sliding failure described by Coggan and Pine (1996). The failure occurred in the Delabole slate quarry and was joint-controlled. The ELFEN analysis complemented previously undertaken UDEC simulations. Figure 9 shows an ELFEN simulation of a biplanar failure in a 50m high slope. Such failures are common where a fault forms the rear back scarp and a weakness plane forms the lower failure surface. In essence, these are active-passive block failures that have in the past have been routinely analyzed using limit equilibrium methods. It has long been recognised that such failure geometries in rock slopes require kinematic release through the development of an active-passive wedge interface. Figure 8 clearly shows the gradual development of fractures within the rock mass that allow kinematic release and translational sliding. This rock slope was assumed to have coal measures rock mass properties as this is a common environment for such failures. Of notable interest is the effect of the fracturing on the failure slope topography with the development of graben-type features as are commonly observed in practice.

6. CONCLUSIONS

The authors have attempted to show the potential of a hybrid finite element-discrete element code, ELFEN, which provides fracture propagation capabilities in the simulation of complex rock slope failures. Analyses using the ELFEN code to date have been intentionally simplified in order to build on experience gained in its application to other geotechnical engineering problems. The code has been routinely and successfully used for approximately a decade in the manufacturing industries and is now beginning to find extensive used in petroleum, mining and civil engineering.

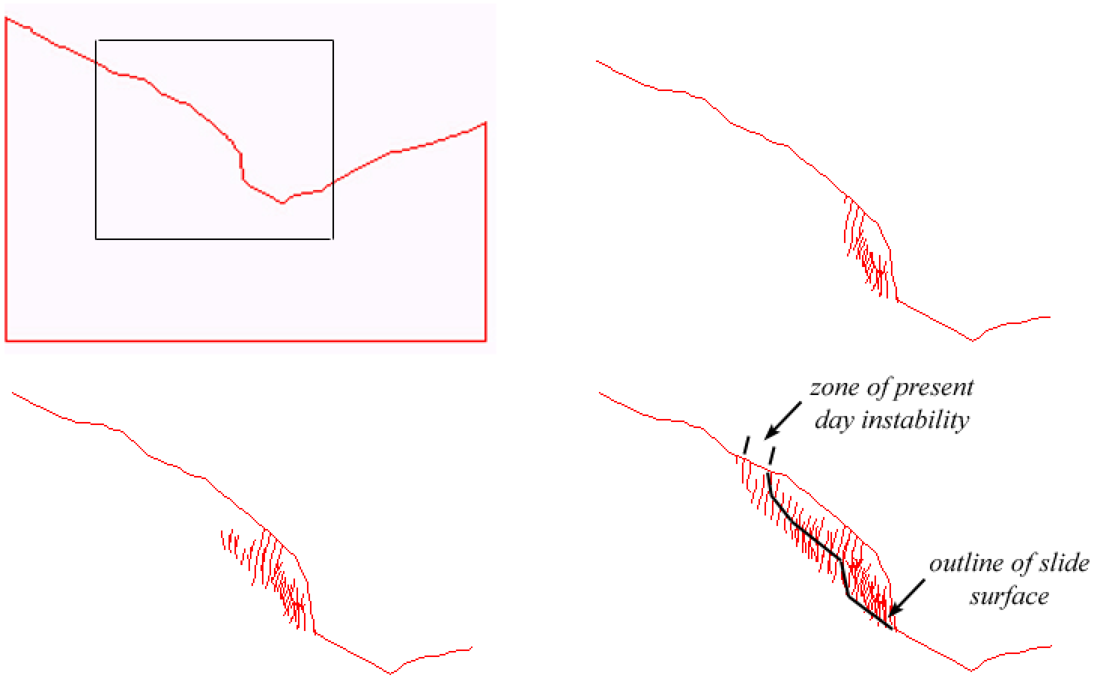

Figure 6. The Randa Rockslide. Development of failure surface simulated using Mohr model with fracture generation. Note two stages of failure and agreement between observed and failure surface simulated using ELFEN.

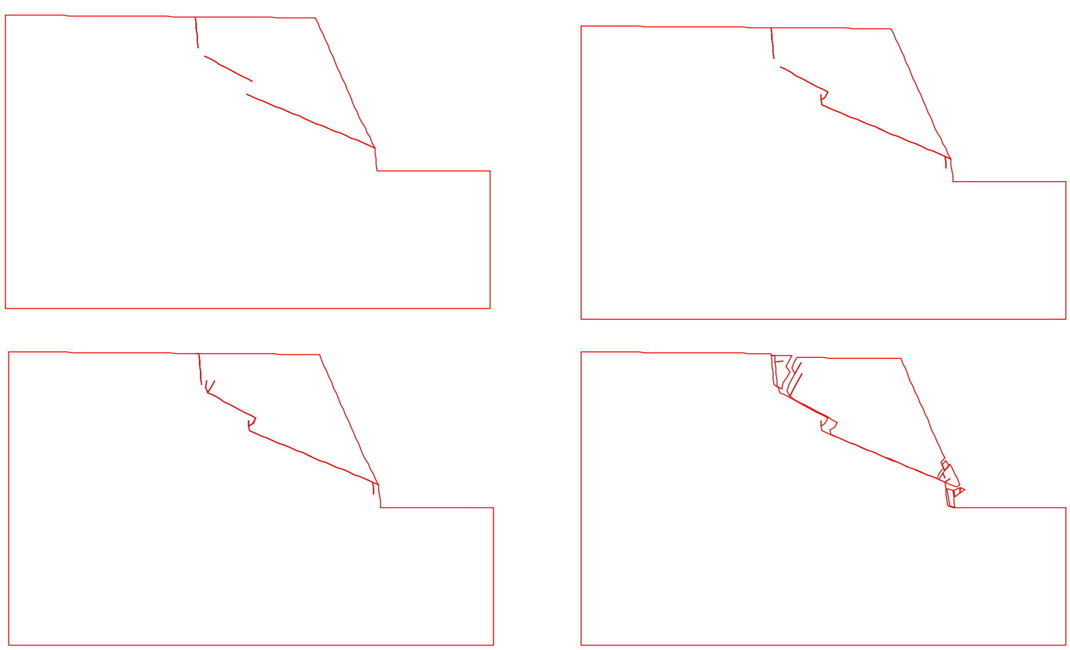

Figure 7. ELFEN simulation of step-path failure surface development in a 50m high rock slope.

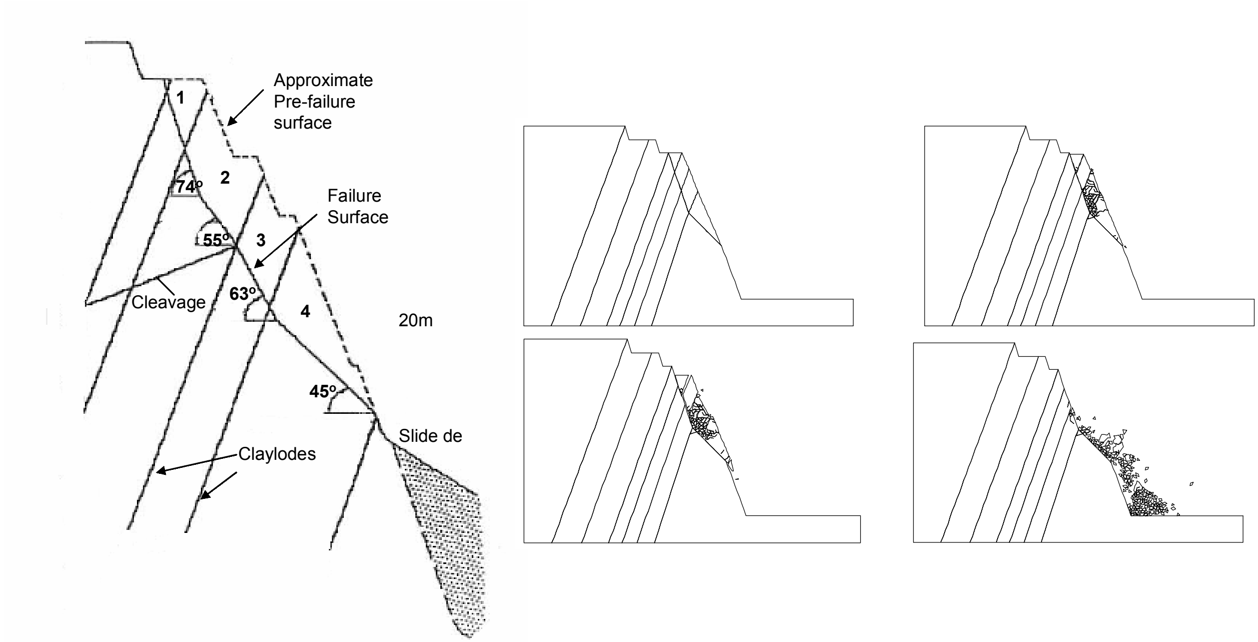

Figure 8. ELFEN simulation of the complex toppling/sliding failure at the Delabole Slate Quarry.

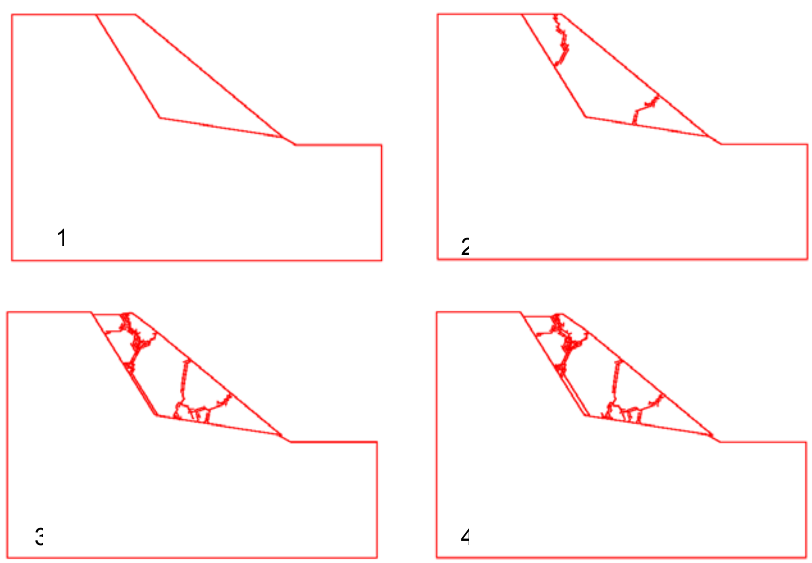

Figure 9 ELFEN simulation of a 50 m high rock slope with biplanar (active-passive) failure surface.

The analyses presented in this paper have in most cases complemented standard finite element/finite difference and distinct element analyses undertaken using continuum (FLAC/PHASE^2) and discontinuum (UDEC) codes. The ELFEN code has been shown to be extremely effective in simulating the initiation of complex rockslides with the Randa rockslide used as a case study. Furthermore, the significant potential for simulating the total slope failure process from initiation, through transportation to deposition has been demonstrated. Although the physical processes in the latter stages of the total slope failure process are inherently complex and defy a unique analysis it is suggested that the use of ELFEN in combination with other codes, such as simple rheological models can only add to our understanding of failure mechanisms and provide improved constraints in hazard and risk assessment. ELFEN has the ability to simulate comminution and has been used commercially to simulate crushing and grinding in mineral processing. This is without doubt also an important process during rock slope failure. The authors suggest that both engineering geological mapping techniques applied to rock slope stability investigation and rock testing require enhancement to include the data needed to undertake developing and increasingly sophisticated slope analysis techniques. One example the authors are pursuing is the integration of pre- and post-failure block analysis using photo-analysis and codes such as FRACMAN, in conjunction with ELFEN. It is emphasized that although codes such as ELFEN offer immense potential in improving our understanding of rock slope failure mechanisms, it is essential that they be constrained wherever possible using high quality slope instrumentation data.

7. REFERENCES

Baczynski, N.R. 2000. StepSIM4 "Step-path" method for slope risks. GeoEng 2000. Melbourne. 6pp.

Benko, B. & Stead, D. 1998. The Frank Slide: a re-examination of the failure mechanism. Can. Geot. J. 35:299-311.

Benko, B. & Stead, D. 1999. Analysis of two landslide case studies using numerical modelling. Proc. 13th Vancouver Geotech Symp, p19-29.

Calvetti, F., Crosta, G. & Tatarella, M. 2000. Numerical simulation of dry granular flows: from the reproduction of small scale experiments to the prediction of rock avalanches. *Rivista Itaianal. Di Geotecnica* , 2:21-38.

Chen, G. & Ohnishi, Y. 1999. Slope stability using discontinuous deformation analysis method. Proc 37th US Rock Mech. 1:535-541

Coggan, J. S., & Pine, R.J. 1996. Application of distinct-element modelling to assess slope stability at Delabole slate quarry, Cornwall, England, *Trans. Instn. Min. Metall., Sec. A*, 105, A22-A30.

Coggan, J.S., Stead, D. & Eyre, J.M. 1998. Evaluation of techniques for quarry slope stability assessment. *T.I.M.M. - Section B* 107: B139-B147.

Corkum, B. & Martin, D.M. 2002. Discrete element analysis of the effect of a toe berm on a large rockslide. Proc 55th Can Geotech Conf, Niagara. p633-640.

Couture, R., Evans, S.G., Locat, J., Hadjigeorgiou, J. & Antoine, P. 1999. A proposed methodology for rock avalanche analysis. *Slope Stability Engineering*. Eds. Yagi, Yamagami and Jiang. P1369-1378.

Eberhardt, E., Kaiser, P.K. & Stead, D. Numerical analysis of progressive failure in natural rock slopes. In EUROCK 2002. Proc of the ISRM International Symposium on Rock Engineering for Mountainous Regions, P145-153

Geoslope 2000. SlopeW and SeepW. User manuals. http://www.geo-slope.com.

Hajiabdolmajid, V. and Kaiser, P.K. 2002. Slope stability assessment in strain softening rocks. Proc Eurorock, Madeira, p237-244.

Hungr, O. 1995. A model for the runout analysis of rapid flow slides, debris flows, and avalanches. *Canadian Geotechnical Journal.* 32:610-23.

Itasca 2002. FLAC 4.0, UDEC and PFC User's Guides. Itasca Consulting Group, Inc. Minneapolis.

Itasca 2002. FLAC/Slope. User's Guide. A mini-version of FLAC to calculate factor of safety of slopes, 74pp, Itasca Cons. Group, (www.itascacg.com/software.html)

Jennings, J.E. 1970. A mathematical theory for the calculation of the stability of slopes in open cast mines. In "Planning & open pit mines", S. Africa, p787-102.

Kalkani, E.C. & Piteau, D.R. 1976. Finite element analysis of toppling failure at Hell's Gate Bluff, British Columbia. Bull. IAEG 13: 315-327.

Klerk, P.A. 2000. The finite element modelling of discrete fracture of quasi-brittle materials. PhD Thesis. University of Wales.

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

Nichol, S.L., Hungr, O. & Evans, S.G. 2002.Large scale brittle and ductile toppling or rock slopes. Can Geotech. Journal. 39:773-788.

Pritchard, M.A. & Savigny, K.W. 1991. Numerical modelling of toppling. Can. Geotech. J. 27:823-834.

Rockfield Software. 2001. Elfen User Manual Version 3.04. Rockfield Software Limited, Swansea, UK. http://rsazure.swan.ac.uk/default.htm.

Roscience 2002. Phases, RocFall, RocPlane, Slide, and Swedge user's manuals. (www.rocscience.com)

Sitar, N. & MacLoughlin, M.M. 1997. Kinematics and discontinuous deformation analysis of landslide movement. 2nd Panam. Symp. On Landslides, Rio de Janeiro, 9pp.

Stead, D. & Coggan, J. S. 2002. "Total Slope Failure Analysis": Abs. 4pp, NATO conf. Celano. Italy.

Stead, D. Eberhardt, E. & Coggan, J.S. 2001**.** Advanced numerical techniques in rock slope stability analysis – Applications and limitations. In UEF International Conference on Landslides - Causes, Impacts and Countermeasures, Davos, Switzerland. p615-624.

Stead, D and Eberhardt, E. 1997. Developments in the analysis of footwall slopes in surface coal mining. Engineering Geology, 46:41-61.

Stead, D, Eberhardt, E, & Coggan, J.S. 2002. Numerical analysis of rock slopes: Incorporating the effects of groundwater. Proc 55th Canadian Geotechnical Conf. Niagara Falls, p665-672.

Willenberg, H., Spillmann, T., Eberhardt, E. Evans, K., Loew, S. & Maurer H. 2002. Multi-disciplinary monitoring of progressive failure processes in brittle rock slopes-Proc 1st European Conf on Landslides, Prague, p477-483

Yu, J. 1999. A contact interaction framework for numerical simulation of multi-body problems and aspects of damage and fracture for brittle material. PhD. Thesis. University of Wales.