LANDSLIDES – Causes, Impacts and Countermeasures

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ACTIVE ROCKSLIDES IN SWITZERLAND – UNDERSTANDING MECHANISMS AND PROCESSES

Erik Eberhardt, Engineering Geology, ETH Zurich, Switzerland
Heike Willenberg, Engineering Geology, ETH Zurich, Switzerland
Simon Loew, Engineering Geology, ETH Zurich, Switzerland
Hansruedi Maurer, Applied and Environmental Geophysics, ETH Zurich, Switzerland

ABSTRACT

To date, the study of rockslides in Switzerland has been largely descriptive and qualitative. Early warning systems are primarily based on displacement measurement systems and the analysis of the rock mass velocity evolution. This paper describes the initial stages of a project focussing on the understanding of rockslide processes and mechanisms that contribute to instability and catastrophic failure. Several examples of unstable slopes in the Swiss Alps are presented and discussed in terms of their geological controls, potential triggering mechanisms and failure evolution.

INTRODUCTION

Despite improvements in recognition, prediction and mitigative measures, landslides still extract a heavy social, economical and environmental toll in Switzerland. Recent landslides experienced in the Swiss Alps demonstrate the need for a deeper understanding of the geological and physical processes leading to catastrophic slope failure. Large-scale rockslides (e.g. Randa, Sandalp, Goldau, Elm, etc.) illustrate the destructive potential of these mass movements and the need for further study to improve our comprehension of the mechanisms involved. Advances in rockslide hazard assessment and forecasting will only be made possible when the mechanisms responsible for the evolution of catastrophic failures are better understood.

A study was therefore initiated in June 2000 to investigate the evolutionary failure processes leading to larger-scale mass movements in massive rock slopes. The working hypothesis of the project contends that rock slope instability occurs through a process that involves the progressive development of a failure surface as opposed to sliding along a pre-existing one. For example, in a massive brittle rock mass, the persistence of most discontinuities is usually limited and shear failure must proceed along a path that passes through existing discontinuities and intact rock bridges. Accordingly, these developments must involve a complex process of fracture nucleation, propagation and coalescence, combined with spatio/temporal variations in pore pressures.

This paper presents the results from the first phase of this Swiss-based study, and includes:

- a review of progressive failure and the need for mechanistic-based slope stability analysis;
- a survey of potential study sites, encompassing several known active rockslides in Switzerland; and
- the detailed engineering geology investigation and passive seismic monitoring of three key sites focussing on the acting mechanisms and processes.

An overview is then presented of the detailed *in situ* monitoring program to be commenced in the summer of 2001. This second study phase will involve comprehensive drilling, borehole testing and instrumentation installation focussing on 3-D displacement fields, microseismicity, fracture patterns and the temporal and spatial evolution of fluid pressures.

PROGRESSIVE FAILURE - CONCEPTUALIZATION

Rockslide studies that do focus on some quantitative aspect of large-scale mass movements are often limited to individual mechanisms or triggering processes. Traditional treatments have pursued phenomenological based approaches where a two-dimensional slide plane is assumed or delineated from survey or air photo data, and a back analysis is performed to determine the limiting equilibrium conditions existing at failure. In other words, the analysis of unstable rock slopes has largely focused on the back analysis of stability along a fully developed failure plane, without considering how the failure plane evolved.

The need to consider failure plane evolution as opposed to focussing on phenomenological approaches is underlined by the questions, “Why did the slope fail *now*? Why did the slope change from an apparently stable condition to that of catastrophic failure”? These are important questions to contemplate if any serious attempts at landslide prediction are to be made, i.e. the question of time. Limit equilibrium analysis and other phenomenological approaches only provide a snapshot of the conditions at the instantaneous moment of failure, and as such they provide a simplified answer as to why the slope failed, but not within the context of time as to “why now?”.

To answer the time question, in the framework of a conceptual model, requires the consideration of two factors that form the basis of most rock slope failure analyses. These are the initial slope conditions, or system processes, and the acting triggering mechanisms (Fig. 1). The initial slope conditions often involve, and in the case of most slope analysis methodologies require, the predefinition of the failure surface geometry as a continuous plane and/or as a series of interconnected planes (Fig. 2). It is unlikely, however, that such a network of natural joints forming a complete three-dimensional outline of the eventual failure surface exists prior to failure. The exception being in the case of excavated slopes where a daylighting set of discontinuities may be exposed during excavation allowing kinematic feasibility. In the case of natural rock slopes, consideration must be given to the fact that the slope has remained relatively stable over the past several thousand years with few major external changes occurring with respect to its kinematic state (e.g. loss of confinement along valley walls during glacial retreat). This is not to say that a system of natural discontinuities may not be interconnected forming a significant portion of what will eventually be the failure plane, but that a component of strength degradation with time must occur within the system. For example, the system may incorporate time-based elements such as material creep, fracture propagation, stress corrosion and/or weathering, which in turn act to reduce with time the strength of asperities between locked joint surfaces and/or intact rock bridges situated between natural discontinuities (Fig. 2).

The second factor to consider involves the influence of triggering mechanisms. Slope failures typically coincide with known triggering mechanisms such as heavy precipitation and/or seismic activity. However, with the exception of extreme triggering episodes, as in the case of major earthquakes where the frequency of occurrence is on the time scale of hundreds to thousands of years, most triggering episodes do not stand out as being exceptional when compared to those that had occurred in the recent past. In the case of heavy precipitation or high pore pressures, for example, failure rarely occurs during episodes that had not been surpassed previously in the history of the slope in question.

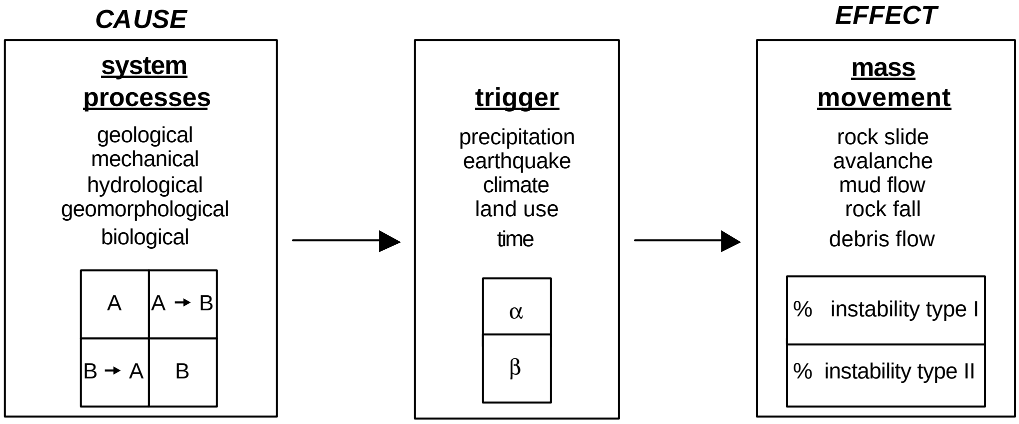


Figure 1. Illustration of cause, involving the interrelationship between system processes and triggering mechanisms, and their effect on inducing mass movements.

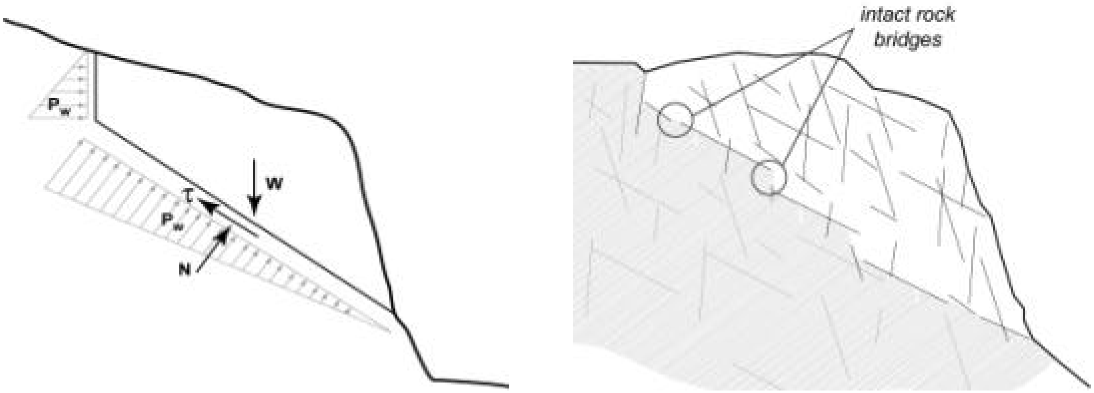


Figure 2. Continuous sliding surface assumed in simplified rock slope stability analysis (LEFT); rock slope with discrete natural discontinuities and intact rock bridges (RIGHT).

Figures 3 and 4 provide an illustration of this point using the 1991 Randa rockslide, which occurred in south central Switzerland. The failure occurred within a massive gneissic rock mass cut by extensive relief joints, parallel to the surface, cross-cut by faults (1, 2). The slide occurred in two stages with the first slide occurring on April 18, 1991 and the second failing on May 9, 1991. Although no clear triggering mechanism could be resolved from the seismic and precipitation records, it was noted that failure coincided with a period of heavy snowmelt (1). This can be seen in the snow height and temperature records for the Zermatt weather station (Fig. 4), located 10 km south of Randa. However, it can also be seen that this was not an exceptional event and that heavier snowmelts had been recorded in previous years. Again, a similar argument can then be made that if the slope did not fail during previous periods of heavy snow melt, why did it fail specifically on April 18, 1991?

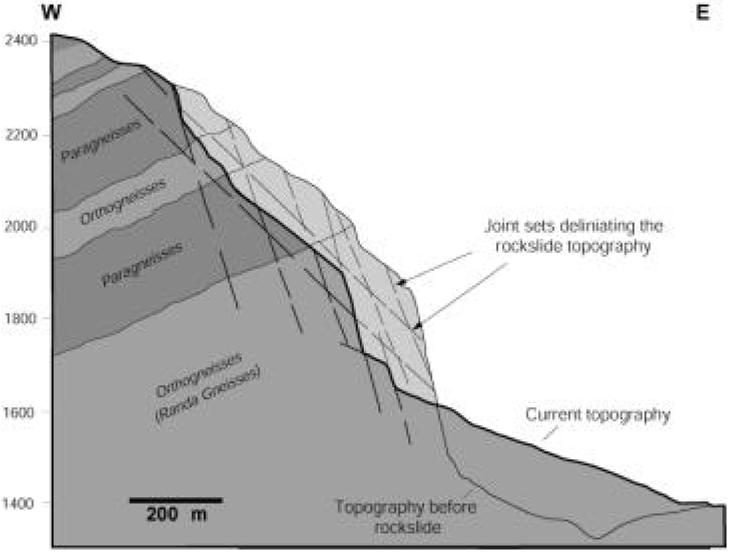


Figure 3. Schematic cross-section showing the 1991 Randa rockslide (after (3)).

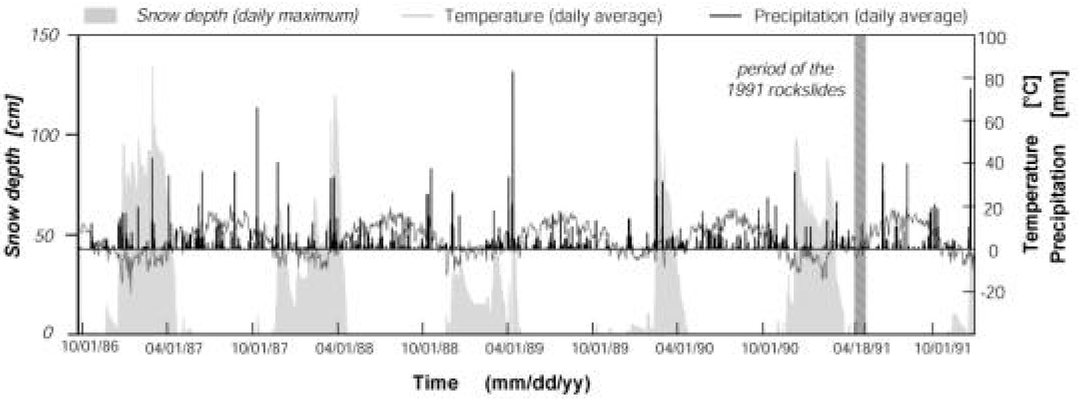


Figure 4. Snow depth, temperature and precipitation records for Zermatt climate station near the Randa rockslide (data provided by MeteoSchweiz).

Conceptually then, rock slope failure can be viewed as the progressive accumulation of events with time that act to degrade the equilibrium state of the slope, with each event bringing the slope nearer to failure (Fig. 5). In other words, each triggering type episode, such as a heavy rainfall or freeze-thaw cycle, can be viewed as progressively reducing the effective strength or cohesion of the rock mass (e.g. intact rock bridges) until the last triggering episode provides the proverbial "straw that broke the camel's back" and failure occurs. Thus it is the time factor that contributes to the development of the sliding surface in natural slopes by means of progressive failure.

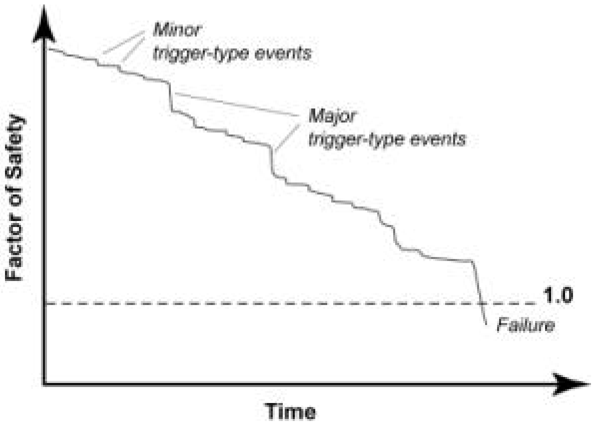


Figure 5. Conceptual illustration showing decrease in factor of safety as a function of time, i.e. progressive failure, due to repeated occurrences of triggering-type mechanisms.

GEOLOGICAL CONTROLS – STUDY SITES

A systematic search and review of all known active rockslides in Switzerland was undertaken during the preliminary stages of this investigation. Several sites of key interest were selected from this evaluation ranging in estimated sizes from 5,000 m^3 to 2.5 million m^3. These sites were primarily located in either the fractured sedimentary rock masses of the helvetic nappes or in the fractured crystalline rock masses of the penninic nappes (Fig. 6). Each of these sites had been previously instrumented with standard displacement monitoring systems, and show typical displacement rates of 10 to 30 mm/year.

Specific to each of the key sites were the geological controls promoting instability. These include:

- translational sliding parallel to sedimentary bedding (Rufi);
- flexural toppling of steeply dipping foliated metamorphic rock (Airolo);
- downslope visco-plastic material creep of massive marls (Schynige Platte);
- creep deformation of deep-seated weathered metamorphic rock mass (Campo Vallemaggia);
- joint-controlled translational instabilities (Randa, Val del Infern, Claro);
- joint-controlled wedge instability (Lago di Poschiavo, Mesocco).

Following site inspections and geological reviews, three sites were chosen to be studied in more detail. These are outlined in the following sections.

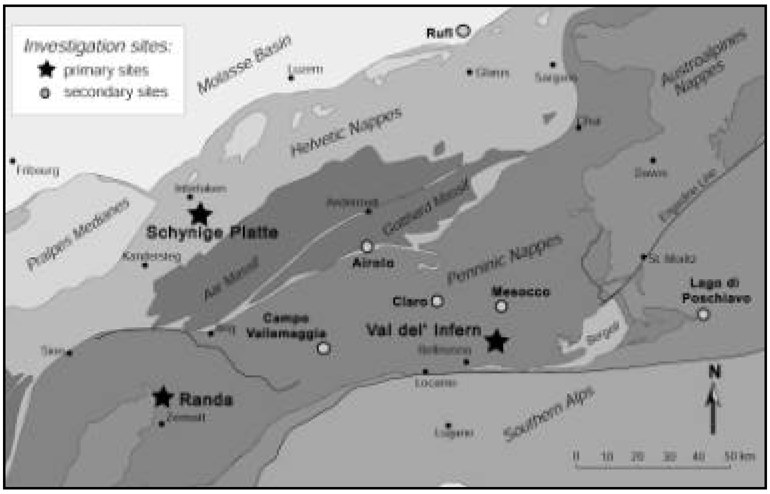


Figure 6. Location map of primary and secondary study sites.

Schynige Platte

The unstable slope at Schynige Platte involves approximately 350,000 m^3 of massive limestone overlying units of soft marls, dipping at angles of 25 to 30° (Fig. 7). Surface measurements dating back to 1929 indicate that the slope has been moving at a near steady rate of 30 to 40 mm/year (4). Extensometer measurements for the past 10 years (Fig. 8) show a similar trend with minor seasonal fluctuations due to precipitation and snow melt. Keusen (4) notes that the steady nature of the slope displacements over such a long period of time, demonstrates that the underlying instability mechanism involves plastic viscous deformation of the marls.

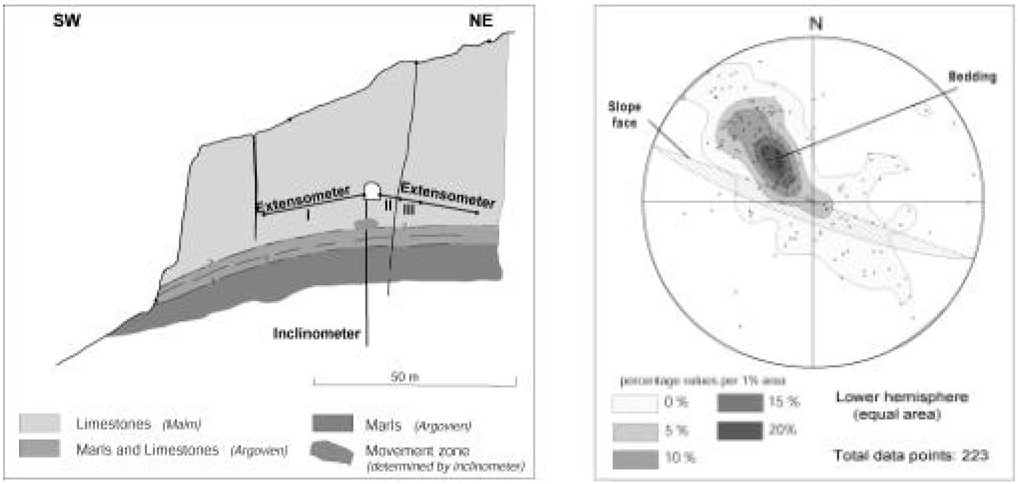


Figure 7. Profile through the unstable rock mass at Schynige Platte (LEFT – after (4)) and contoured pole plot of bedding and discontinuities (RIGHT).

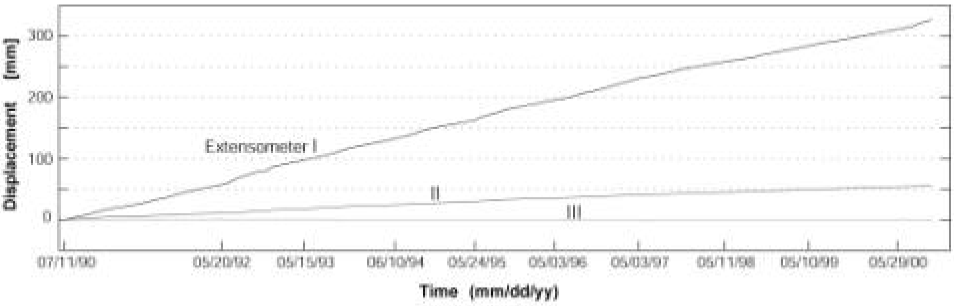


Figure 8. Extensometer measurements corresponding to locations in Fig. 7 (after (4)).

The creeping displacements of the slope, however, occur at depth whereas surface indicators are predominately brittle in nature (i.e. newly formed/open fractures). This would suggest that the massive limestone, constituting most of the unstable mass, does not share the same rheological behaviour as the underlying marls. Surface observations reveal signs of progressive failure whereby the limestone rock mass slowly creeps on top of a yield zone located within the marls, and in the process, breaks apart through internal brittle fracturing. Over time, a graben several meters in width has formed at the back of the slide and continues to widen each year. At the front of the slope, vertical columns and blocks of limestone shaped by the brittle fracturing are slowly pushed forwards where they eventually topple, slide and/or fall on a periodic basis (e.g. following seasonal snow melts or high precipitation events).

Val del Infern

Val del Infern is an unstable rock slope situated within the Penninic gneisses along the Calanca valley in south-eastern Switzerland. The potential rockslide volume of 100,000 m^3 endangers a span that includes one of two road tunnels and a connecting bridge (Fig. 9). Surface mapping reveals that the unstable mass is partly delimited by tectonic features. This includes a large fault zone, a near vertical joint set striking perpendicular to the slope face and a minor joint set dipping into the valley (Fig. 9).

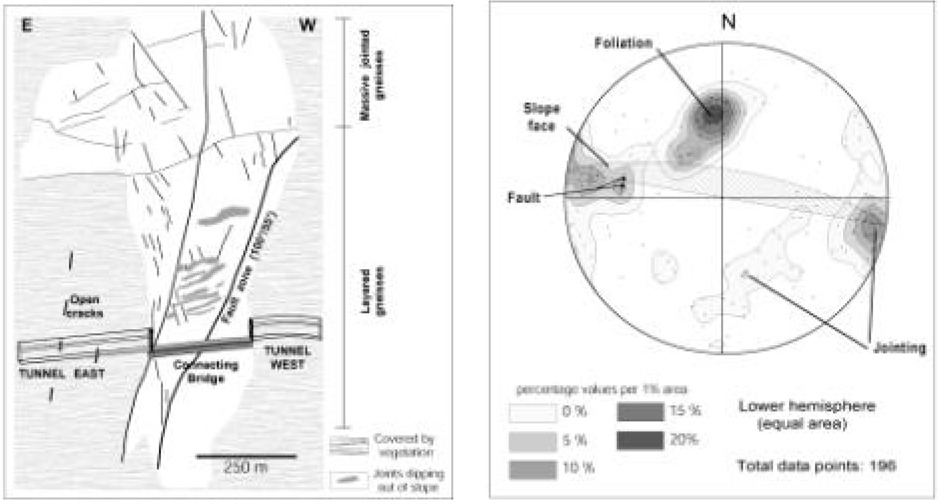


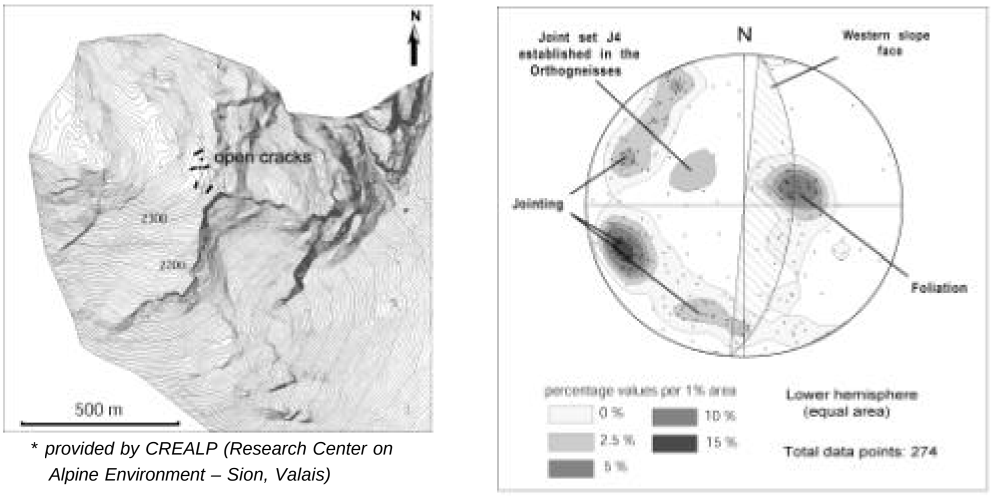
Figure 9. Schematic plan view of unstable slope region with surface observations of brittle fractures (LEFT) and contoured pole plot of foliation and discontinuities (RIGHT).

Measurements of surface displacements at Val del Infern, ongoing since 1995, indicate a slope movement rate of 5 to 10 mm/year. The relatively slow displacement rate coincides with the visible and seasonal initiation and growth of new brittle fractures in the gneissic rock mass and tunnel walls. This may suggest, given the kinematically stable orientation of the foliation (i.e. dipping into the slope), that the slope is in an early stage of progressive failure whereby new fractures are slowly propagating and forming a potential shear plane.

Randa

The initial Randa rockslides, previously described, involved the failure of 30 million m^3 of rock in two separate events three weeks apart. However, the slope mass is still active and a block approximately 2.5 million m^3 is currently being monitored (Fig. 10). Displacements rates of 1-2 cm/year have been measured since 1991. The actively moving rockmass involves massive gneisses alternating with mica-rich paragneisses (Fig. 3) belonging to the Penninic St.-Bernhard nappe. The sliding rock mass is presumably limited by shallow dipping joints (visible at the face) and sets of steep near-vertical joints (Fig. 10). Discontinuities and their role in promoting rockslide instabilities at Randa has been the subject of several extensive studies (e.g. (5)).

Shallow dipping joints, characterized by Wagner (3) as contributing to the 1991 failure, have been denoted as set J4 (Fig. 10). However, these joints appear to be somewhat limited to observations at the slope face and are rarely found during surface outcrop mapping. Tension cracks on surface behind the slope face tend to preferentially open parallel to steeply dipping natural joints. Thus, natural discontinuities are considered to be a major contributing factor to both the 1991 rock slides and the currently monitored slope displacements. Additional outcrop mapping and discontinuity line surveys are planned and will be statistically analyzed to provide a clearer picture of the natural discontinuity distribution and its influence in promoting the instability.



** provided by CREALP (Research Center on Alpine Environment – Sion, Valais)*

Figure 10. Digital elevation map of Randa showing open tension cracks (LEFT) and contoured pole plot of foliation and discontinuities (RIGHT).

FAILURE PLANE EVOLUTION – *IN SITU* INVESTIGATION

Three of the aforementioned sites (Schynige Platte, Val del Infern and Randa) were investigated in more detail in order to select a principal research site. This site will be studied throughout the remainder of the project and will include a comprehensive drilling, testing and monitoring program (to commence in July 2001). This will include the use of high precision borehole displacement, pore pressure and passive microseismic measurements. It is intended that the monitoring of spatially clustered microseismic events will be used to provide critical information with respect to the evolution, location and mechanisms of shear plane development.

The initial investigations performed at Schynige Platte, Val del Infern and Randa all involved the deployment of surface seismic monitoring systems. A small network of Mars-88 seismographs, provided by the Swiss Seismological Service, was installed and used to monitor signal frequencies between <1 Hz and 200 Hz. Experience gained through this initial survey proved valuable in characterizing the sites with respect to background noise, temperature effects and logistics. For example, heavy vehicle traffic at Val del Infern made monitoring ineffectual and the remote nature of Randa required the installation of solar and wind power supplies (Fig. 11). Of equal importance was the experience gained with respect to seismic activity, data quality and subsurface structure. The remote nature of the Randa site proved beneficial in this respect, given the lack of artificial noise caused by vehicle traffic, allowing for seismic events to be correlated to potential slope activity. During the first months of operation, the seismic network recorded several signals which could be attributed to fracturing in the underlying rock mass (e.g. Fig. 11).

Preliminary monitoring using the surface seismic system will be continued to allow for further system calibrations and for source events to be located. This information will then be used to optimize borehole drilling, testing and instrumentation plans for the next study phase. Final borehole installations will involve an array of 15 microseismic sensors and a seismograph system capable of sampling high frequency signals (up to 50 kHz) and providing a sufficient dynamic range.

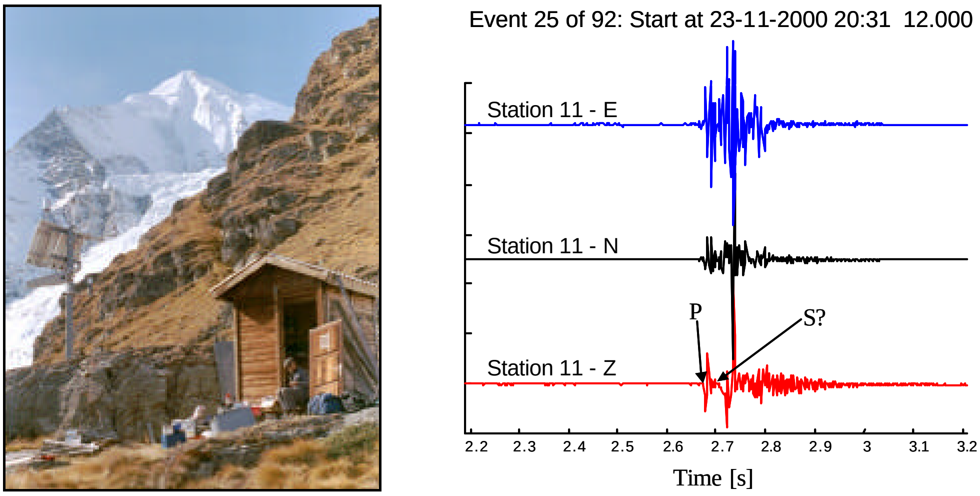


Figure 11: Instrumentation center at Randa (LEFT) and recorded seismic event (RIGHT).

Active geophysical experiments involving 2-D and 3-D seismic reflection and georadar surveys will also be used to supplement mapping data of subsurface structures (e.g. jointing). Active testing will also include borehole characterization (full-wave sonic log, acoustic televiewer) and cross-hole tomography and hydraulic testing to identify connectivity and transmissivity of the fracture network.

SUMMARY AND FUTURE DIRECTIONS

The initial findings of a Swiss National Science Foundation study "*Rockslide processes and mechanisms: Progressive development of shear/slide surfaces in rock slopes*", have been outlined. The project aims to transcend the current phenomenological level of understanding of mass movements and to move closer towards failure prediction, by utilizing newly developed technologies to focus on the processes and mechanisms contributing to the progressive development of rock slope failure. Results from the initial site investigation, mapping and passive seismic monitoring campaign are presented, in part, for three sites located in the Swiss alps: Schynige Platte, Val del Infern and Randa.

Based on the examination of different geological controls and a review of the preliminary findings, the final site selected will likely involve one for which failure is progressively developing through existing discontinuities and intact rock bridges. Passive seismic monitoring results collected at the study sites showed promising results in these cases, especially with respect to detecting new fractures. Further analysis will be directed towards source location. This knowledge will facilitate the borehole installation of microseismic triaxial transducers above and below the developing shear plane. This system will be integrated into a network including highly sensitive displacement and pore pressure monitoring devices, thus enabling the focus to be directed towards brittle fracture development and coupled hydromechanical reactions, as they pertain to rock slope failures.

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