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Multidisciplinary monitoring of progressive failure processes in brittle rock slopes – Concepts and system design

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ABSTRACT: The evolutionary failure processes leading to large-scale mass movements in massive crystalline rock slopes are the subjects of a multidisciplinary research project in the Swiss Alps. Focus is directed towards detecting and analysing rockslide processes that involve the progressive development of a failure surface as opposed to sliding along a pre-existing one. In order to monitor the underlying mechanisms of progressive failure, several new and conventional instrumentation systems were combined with an existing *in situ* monitoring program at an active rockslide site in the Valais (Switzerland). Design of the instrumentation network is based on site investigations and preliminary geomechanical models of the acting rockslide processes with respect to the rate of displacements, position and orientation of geological features that delineate the unstable rockmass. The network set-up considers additional findings from borehole logging and testing. Parameters that will be measured include microseismicity, fracture patterns and the temporal and spatial evolution of 3-D displacement fields and fluid pressures.

1 INTRODUCTION

The understanding of rock slope instabilities is becoming increasingly important as a consequence of population growth and increased land use and transportation demands in mountainous regions. In order to optimize early warning systems, knowledge about the specific geological conditions of each landslide site is necessary. However, attention must also be paid to the processes leading to rock slope failures as these are known to lead to observable signs of destabilization before the actual failure (e.g. Keusen 1997). In this sense, rock stability investigations should focus on the establishment of a valid geological model and the cause-effect relationships/mechanisms driving instability.

The progressive nature of slope failures has long been identified in the field of soil mechanics with respect to clay slopes. The initial concept of progressive failure describes failure starting at one point of a potential sliding surface and spreading outwards from it, driven largely by redistribution of shear stresses (Bishop 1967). The term "progressive" refers to the time-dependent nature of structural changes within the slope mass that act to reduce the factor of safety with time (Terzaghi 1950). Within the framework of this study, the term is used to describe the development of a failure surface in space as well as in time.

The adoption of a more mechanistic-based methodology contrasts general trends in rock slope analysis, which tend to focus on pre-defined persistent failure planes formed by bedding, foliation or faults. Yet for massive crystalline rock slopes, the assumption of pre-existing persistent failure planes formed along discontinuities is a simplification, and the link between external triggers, like meteorological events, and the actual slope failure is not clearly established (Sandersen et al. 1996).

In June 2000, a large multidisciplinary study was initiated in Switzerland with the aim to better understand the processes and mechanisms involved in brittle rock slope failure. Both field-based mapping studies and *in situ* measurements were directed towards identifying these processes. In summer 2001, this led to the construction of a unique *in situ* laboratory on an unstable rock slope – integrating instrumentation systems designed to measure temporal and 3-D spatial relationships between fracture systems, displacements, pore pressures and microseismicity. This paper presents the steps taken to conceptualise, design and implement this system.

2 CONCEPTUALIZATION

Two principal processes of progressive rock mass destabilization are considered in this study: brittle fracture of intact rock bridges between nonpersistent discontinuities and frictional sliding with asperity interlocking (i.e. stick slip). To identify and discriminate between these different processes, several forms of surface and subsurface information are required.

First, it is essential to properly investigate the 3-D geological structure of the monitored rock mass. Important geometrical parameters include discontinuity orientation, spacing, persistence and connectivity, and the location of discrete surface features (Einstein et al. 1983). This information can be attained through a combination of geological mapping, detailed discontinuity mapping, both at surface and in boreholes, and active geophysical testing. New developments in 3-D seismics, 3-D georadar, crosshole tomography and borehole to surface testing methods show promising trends with respect to improving the quality of geological models based on surface mapping data (e.g. Schepers et al. 2001).

More specific problems related to identifying and characterizing progressive failure processes can be addressed through the combined monitoring of mass movement kinematics, pore pressures and microseismic activity. Each of these physical quantities must be captured in terms of their 3-D spatial distribution and time (i.e. 4-D) to provide sufficient data quality for a mechanism-directed analysis.

The kinematics of a sliding rock mass generally manifests itself in terms of surface displacements and subsurface deformation. Surface displacements are commonly derived through geodetic measurements. Of great value are surveys providing information on displacement rates and directions. Continuous monitoring of surface displacements is less common, although new developments in GPS techniques are answering this need. In terms of monitoring subsurface deformation fields, several borehole-based methods are available to provide information that is continuous in time as well as continuous along the borehole axis (Kovari 1990). For example, the 3-D deformation field around a borehole can be measured using a combined inclinometer-extensometer system (e.g. Solexperts' TRIVEC or Interfels' INCREX systems). However, these measurements are only taken periodically and must be supplemented by multipoint in-place inclinometers to provide continuous real-time monitoring. As such, continuous monitoring is restricted to multiple zones of interest where deformations are expected or previously measured using conventional inclinometer probe surveys.

Another key to monitoring progressive rock slope destabilization is to focus in on the localized failure mechanisms underlying the development of fracture systems. Microseismic monitoring provides a key tool in this respect. Precise mapping of microearthquake swarms can resolve the geometry and extent of the developing structure (Fehler et al. 2001),

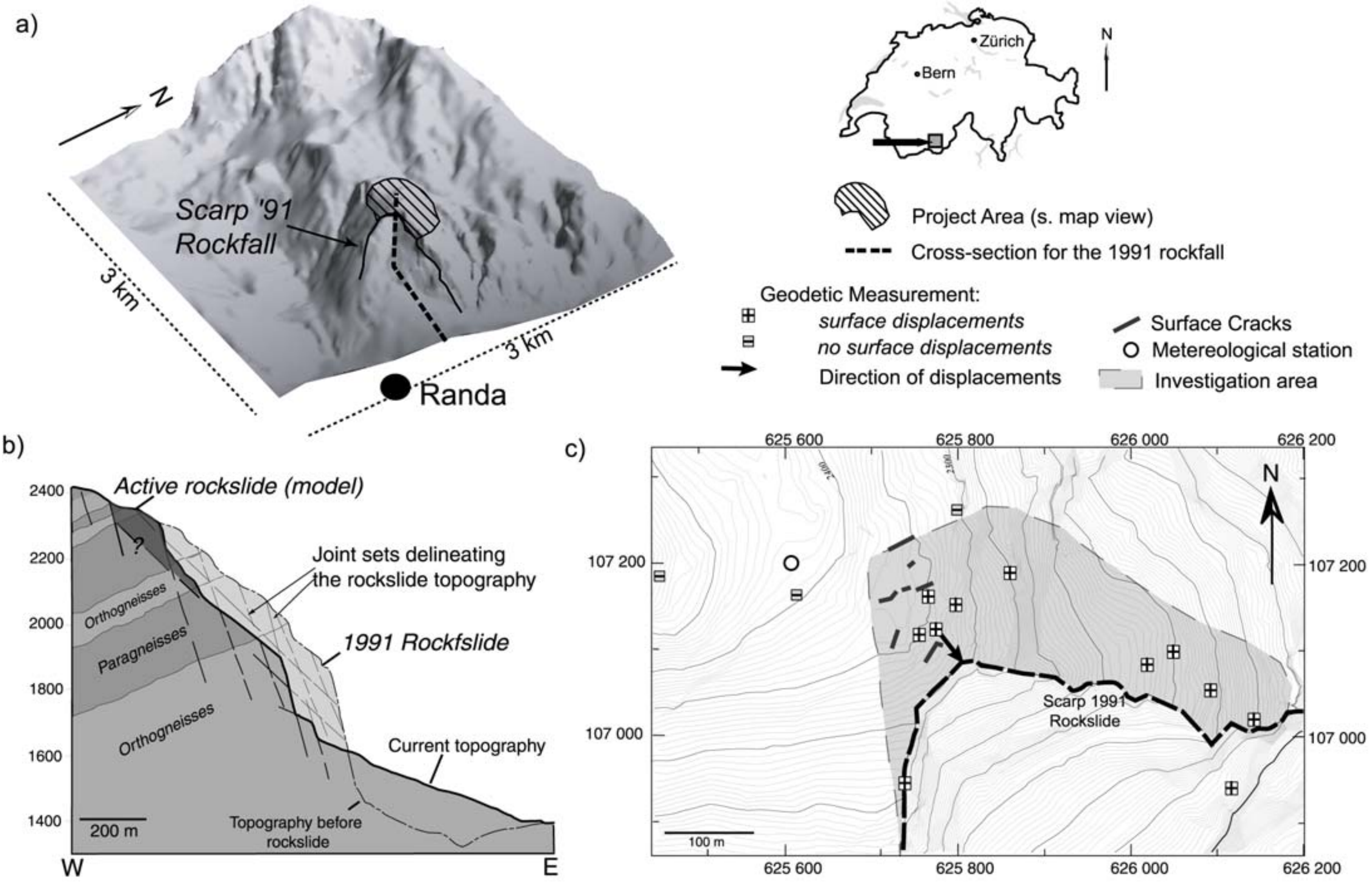

Figure 1. a) Location and digital elevation model of project area (DEM provided by CREALP); b) cross-section showing 1991 rockslide (after Wagner 1991); c) existing early warning system and distribution of surface cracks.

whilst fault plane solutions of the microseisms themselves obtained through moment tensor inversion provides insight as to its microstructure by defining the local orientation of the failure plane and the nature of slip on it (Nolen-Hoeksema & Ruff 2001). Such techniques have been successfully applied in mining (Mendecki 1997), hydraulic fracture mapping (Phillips et al. 1998), and large-scale tectonic investigations (Maurer et al. 1997). Building on these developments, it is believed that microseismic monitoring will provide a key means to image rockslide dynamics. Furthermore, it is important to recognize that these techniques must be applied at depth, i.e. through the deployment of subsurface geophones, in order to provide sufficient data quality.

The final key component to monitoring progressive rockslide processes is pore water pressures. In a fractured rock mass, water pressures act to drive fracture propagation (e.g. sub-critical fracture propagation), and during periods of significant increases, acts as an important triggering factor. To identify the influence of fracture water pressures on rock slope destabilization, piezometric conditions at depth must be recorded continuously. Temporal variations in measured water pressures can also provide additional information with respect to identifying active fracture processes, sliding mechanisms and/or dilatancy effects (e.g. Scholz 1990).

By integrating these different systems into one monitoring network design, it is believed that the key elements required to meet the objectives of this study (focussing on the progressive development of brittle rock slope sliding surfaces) can be measured and analysed.

3 SITE SELECTION AND INVESTIGATION

3.1 *Study site Randa*

Based on the preliminary investigation of several sites across the Swiss Alps (Eberhardt et al. 2001), an active rockslide site was selected near the village of Randa (Canton Valais, Switzerland) in the Matter Valley (Fig. 1a). This site was chosen based on the identification of several indicators suggesting that the destabilizing mechanisms relate to progressive brittle fracture processes. These included the massive crystalline nature of the rock mass, the absence of highly persistent discontinuities dipping out of the slope along which a pre-existing slide plane may be inferred, the presence of open fractures, relatively small displacement rates and observations relating to an earlier massive rockslide at the site (the 1991 Randa rockslide). An additional consideration with respect to the microseismic component of the planned instrumentation network was the relatively low background noise level (e.g. that arising from heavy vehicle traffic).

The research area covers a 500 x 500 m area between elevations of 1800 and 2650 m above sea level. The area belongs to the Penninic Siviez-Mischabel nappe. Its lithology comprises polymetamorphic gneisses, schists and amphibolites (paragneisses) and metamorphosed Permian granite intrusions (orthogneiss, Randa Augengneiss); the metamorphosed Permian-Triassic sedimentary cover is not included in the project area. In terms of surface topography, the lower boundary of the research area is defined by the back scarp of an earlier rockslide, which occurred as two main slide events in April and May 1991 with an estimated total volume of 30 million m^3 (Schindler et al. 1993).

By reviewing the general geological situation and initial analysis of the 1991 slide, much can be inferred with respect to the present-day instability, especially with regards to the progressive nature of the failure mechanisms. As foliation is dipping into the slope, the most important discontinuities contributing to slope instability were identified by Wagner (1991) as persistent cross-cutting joint sets along which sliding was believed to have occurred (Fig. 1b). These persistent joints can be observed in the scarp of the earlier slide but are more limited in persistence when encountered in surface outcrops. In terms of triggering factors for the 1991 rockslide, analysis of climatic and regional seismic data showed no clear indications of a triggering event (Schindler et al. 1993). Permafrost distribution models of the Matter Valley by Gruber & Hoelzle (2001) likewise show that permafrost was not a contributing factor. Instead, Eberhardt et al. (2001) suggest time-dependent mechanisms relating to strength degradation (e.g. through weathering, brittle fracturing, etc.) and progressive failure as causing the failure.

3.2 *Existing data*

Collected data used in the site selection process was supplemented by an existing early warning system established following the 1991 rockslide. This system includes periodical geodetic surveying, automatic crack-extensometer measurements, manual crack measurements and a climate station (Fig. 1c). The system is restricted to surface observations; nevertheless it supplies valuable information on the distribution of movements at surface. Three-dimensional surface displacement vectors have been established periodically since 1995 for a network of geodetic reflectors, and indicate annual displacement rates of up to 1.5 cm/year. The direction of movement is to the southeast, perpendicular to open surface tension cracks (as shown in Fig. 1c).

4 INSTRUMENTATION NETWORK DESIGN

4.1 *Geological model – Working hypothesis*

For the instrumentation network design a preliminary geological model was developed and used. The model was based on the spatial distribution of surface displacements, the location of open cracks and the analysis of discontinuity orientations and persistence. The distribution of surface displacement rates was interpreted as involving the movement of three large blocks, or zones, each separated from the other by open cracks. Maximum displacement rates were seen to occur along the block closest to the rockslide scarp and decrease with distance away from the scarp. This analysis was used to define the area for which the monitoring network would be concentrated (highlighted in Fig. 1c). To plan the borehole drilling depths, assumptions on potential shear/sliding zone depths were made. These assumptions were based on steeply dipping fractures that cut and define the unstable blocks at surface, and at depth, by several extended discontinuities outcropping in the rockslide scarp (consistent with measured surface displacement vectors). The lowest of these daylighting discontinuities can be observed in the paragneisses and was extrapolated under the study area as a persistent plane (Fig. 1b). Recognizing that a more likely stepped-path surface would run even higher, a margin of safety was thus provided in selecting the borehole drilling depths. As such, a maximum drilling depth of 120 m was determined.

4.2 *Geotechnical instrumentation*

Three deep boreholes were drilled with depths varying between 50 and 120 m. The locations of these boreholes (Fig. 2a) were constrained in part by the results of the geological model developed, as well as by drilling logistics, surface topography and geomorphology and spatial requirements for active crosshole seismic and radar experiments. Borehole SB120 (i.e. 120 m deep) was located in the area where the greatest surface displacements were recorded. Its length corresponds to the assumed maximum depth of instability. Boreholes SB50N and SB50S (i.e. 50 m deep) were located within 30 m of each other to permit active crosshole testing and to provide close spatial measurements of deformation, pore pressure and microseismic activity contrasts between two blocks separated by a steep fracture cutting down into the moving rock mass.

Instrumentation of the boreholes, as derived through the system conceptualization, included elements measuring sub-surface deformations in combination with pore pressures and microseismicity. Active testing, including geophysical borehole logging, hydrogeological testing and optical televiewer logging, provided information for locating interesting intervals along which to position continuous deformation measuring devices. Boreholes were cased with 71 mm diameter PVC inclinometer casing, lined with metal INCREX rings spaced at 1 m intervals. As such, the 3-D subsurface displacement-measuring component of the instrumentation network involves the combined use of biaxial vibrating wire in-place inclinometers for continuous monitoring, but which can be removed for periodic inclinometer-/extensometer-probe measurements (i.e. INCREX) along the entire borehole length. In addition, piezometers, triaxial geophones and co-axial cable for time domain reflectometry (TDR) measurements were installed (Fig. 2b). Specifications for these instruments are provided in Table 1.

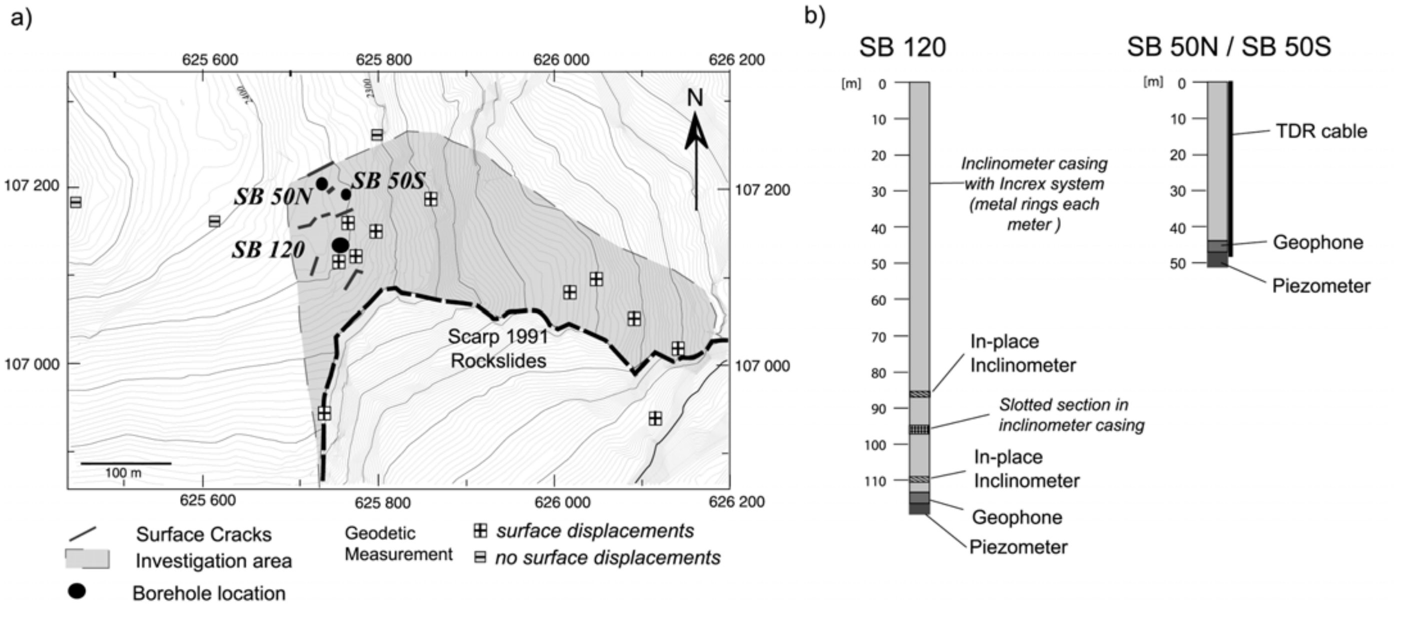

Figure 2. a) Location of boreholes (SB120 – 120 m depth; SB50S & SB50N - 50 m depth); b) installation design for geotechnical and seismological borehole instrumentation.

Table 1. Specifications of instruments installed in borehole SB120.

Instrument	*In-Place Inclinometer*	*Inclinometer Probe*	*Extensometer Probe*	*Geophone*	*Piezometer*
Type	vibrating wire	servo-accelerometers	induction coil (INCREX)	3-component (f_n = 28 Hz)	vibrating wire (690 kPa)
Accuracy	± 0.2 mm/m	± 0.07-0.1 mm/m	± 0.02 mm/m		± 3.5 kPa
Measurement Depth	2 intervals of 2 m (at 90 & 115m); biaxial	continuous along borehole axis; biaxial	continuous along borehole axis at 1m intervals	1 instrument at 114 m depth; tri-axial	1 instrument at 120 m depth
Sampling Period	continuous	periodical	periodical	event triggered	continuous

Installation was completed by modularizing the different instrumentation components (e.g. piezometers, geophones) in 3 m sections of inclinometer casing. By pre-installing these devices within the casing, it was possible to position and pack off the piezometer modules along zones showing significant fracture permeability as determined from borehole televiewer data. Furthermore, it was possible to position the geophones with a known orientation with respect to north. An additional upper piezometer module, involving a slotted section of casing, was also inserted and packed off around an upper fracture zone near 100 m depth (as shown in Fig. 2b). This was inserted as a backup to the lower automatic piezometer system and to provide the possibility of periodic measurements along a second major fracture zone intersected by the borehole.

Following installation of the instrumentation modules and inclinometer casing, boreholes and borehole packers were cemented.

4.3 *Microseismic network*

Prior to the installation of the borehole geophones described above, a small test array using 5 standard surface-mounted seismographs was installed for an observation period of approximately 8 months. Data obtained from this network were expected to provide information about: (i) the existence of microseismic activity, (ii) the characteristics of seismic waveforms and (iii) approximate event locations. Analysis of the data recorded provided evidence for seismic activity, with measured signals showing very high frequencies close to the Nyquist frequency (250 Hz) of the seismographs. Most likely, significant portions of energy were released at even higher frequencies. This prevented the detection and recording of events by 4 or more stations, which would have allowed the events to be located.

An important conclusion from the experiences gained through the preliminary test array was that a high-frequency recording system was essential. As such, two Geode seismographs from Geometrics Inc. were chosen for integration into the Randa *in situ* monitoring network. These state-of-the-art systems include 24 channel acquisition boards (i.e. for eight 3-component geophones) with 24 bit A/D converters, allowing sampling frequencies of up to 50 kHz. Since high frequency signals are most affected by near-surface heterogeneities, the geophones were deployed in boreholes – e.g. one near the bottom of each of the three boreholes, as previously described (Fig. 2b).

To complement this network of deep boreholes, a larger network of shallow boreholes (5 m deep) was drilled at suitable locations for the installation of additional geophones. The spatial distribution of these sites was chosen, such that the recordings would allow the hypocentral parameters (hypocenter coordinates and origin time) and other source characteristics (orientation of the fault plane, source-time function, etc.) to be constrained reliably. A well-known problem with standard seismic networks, which are generally planar in nature (i.e. geophone locations positioned along a flat surface), concerns trade-offs between different hypocentral parameters during the location procedure (e.g. Lee & Stewart 1981). In particular, hypocenter depth and origin time often show strong dependencies. When the seismic network is not planar, but exhibits a 3-D distribution, this effect can be reduced. This was partially achieved by placing geophones at the bottom of the 3 deep boreholes. Additional vertical aperture could be achieved by considering the pronounced topography of the investigation area. Based on these constraints, it was believed that 9 additional shallow borehole geophone sites were required.

Before the geophones were installed, a resolution analysis was performed to test the suitability of the network distribution. This involved the simulation of a dense 3-D grid of seismic events, extending over the investigation area and depths of interest. For each generated event, synthetic arrival times were calculated using a homogeneous full space velocity model. It was assumed that geophones positioned in the shallow boreholes would be limited to recording only the first arrival P-waves, whereas both P- and

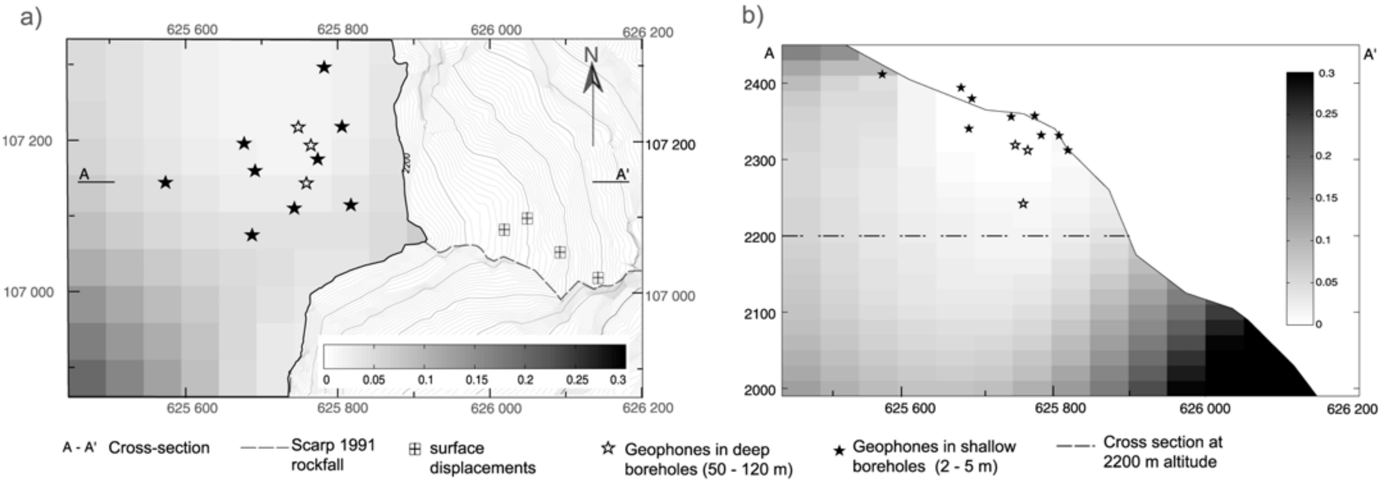

Figure 3. Seismic network geophone distribution and corresponding Dirichlet spreads for: a) horizontal plan section along 2200 m elevation; b) vertical cross-section A-A'. Values near zero (i.e. bright areas) indicate zones of optimal resolution.

S-waves could be identified at the bottom of the 3 deep boreholes.

As a measure of resolution a Dirichlet spread was chosen to approximate the sensitivity and degree of trade-off between the different hypocentral parameters (Menke 1989). Figure 3a shows the location of the shallow geophone boreholes and the corresponding Dirichlet spread along a horizontal slice through the source grid at 2200 m elevation. This is within the depth range, where the seismic activity is expected to occur. In this figure, a Dirichlet spread of 0 indicates independent resolution of all hypocentral parameters, whereas large values are diagnostic for pronounced trade-offs and thus unreliable hypocenter estimates. The absolute spread values are unimportant since their magnitudes are largely controlled by the damping parameters of the corresponding inversion problem. Only the relative changes between the centre of the array, where the location accuracy is expected to be good, and the border areas are relevant.

Accordingly, Figure 3a shows that the Dirichlet spread exhibits only minor variations, and the location accuracy should be uniformly high for the depth range targeted. Similarly, the Dirichlet spread variation along the rock slope cross-section is quite uniform (Fig. 3b). Only towards the northeastern end of the cross-section are significant increases observed. Therefore, if necessary, additional geophones could be installed to increase the performance of the network, if in future significant seismic activity is found to originate from this area.

4.4 *Communication and data management*

Seismic activity recorded by the twelve 3-component geophones (as described above, 3 in deep boreholes, 9 in shallow boreholes), will be monitored using two 24-channel seismographs. The system has been designed so that several hundred seismic events, with data files of 12 Mbytes each, can be recorded and stored every day. Retrieval of this vast amount of data has been accommodated by linking the on-site storage computer to a central recording location in the Matter valley through a wireless Ethernet connection (Fig. 4). This concept allows off-site storage and easy accessibility to the seismic data files. Furthermore, it also allows for recording parameters to be adjusted remotely, thus reducing the amounts of data transferred for analysis.

A parallel system was similarly used to automatically record borehole piezometer and in-place inclinometer measurements. These instruments are triggered every 6 minutes, with the corresponding measurement values being stored on-site on a Campbell Scientific CR-10X data logger. Through a dial-up connection, the measurement values can be directly accessed and downloaded from the data logger using a local network connection. Solar panels combined with a wind generator supply the necessary power on site.

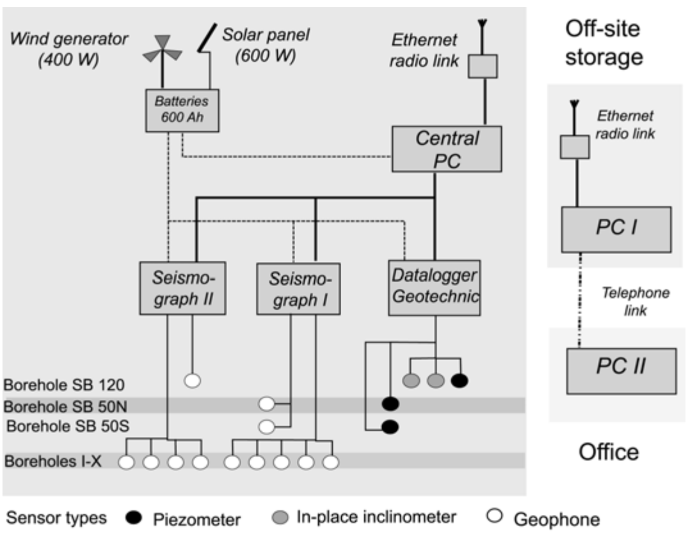

Figure 4. Schematic diagram of data acquisition system.

5 CONCLUSIONS

To measure processes relating to the progressive development of failure planes in massive rock slopes, an *in situ* multidisciplinary laboratory was constructed in the Swiss Alps. This first of its kind network integrates a variety of instrumentation systems designed to measure temporal and 3-D spatial relationships between fracture systems, displacements, pore pressures and microseismicity. The network design is based on theoretical concepts concerning progressive strength degradation and progressive brittle failure, and experiences gained through preliminary investigations.

Data recorded by this network will be analyzed and combined within the framework of a multidisciplinary study that will include geological mapping, deterministic and stochastic discontinuity analysis, 3-D surface georadar and seismics, crosshole tomography and numerical modelling.

It is believed that the unique design of the instrumentation system and the multidisciplinary nature of the study, will help to significantly advance current understanding of rock slope failure processes, from the early stages of development through to catastrophic failure.

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REFERENCES

Bishop, A.W. 1967. Progressive failure – with special reference to the mechanisms causing it. In *Proc. of the Geotechnical Conf. on Shear Strength Properties of Natural Soils and Rock, Oslo*, 142-150.

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

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

Fehler, M., Jupe, A. & Asanuma, H. 2001. More than clouds: New techniques for characterizing reservoir structure using induced seismicity. *Leading Edge*: 324-328.

Gruber, S. & Hoelzle, M. 2001. Statistical modelling of mountain permafrost distribution: Local calibration and incorporation of remotely sensed data. *Permafrost and Periglacial Processes* 12: 69-77.

Keusen, H.R. 1997. Warn – und Überwachungssysteme (Frühwarndienste). In *FAN-Forum: Frühwarndienste – Stand der Kenntnisse und Anwendungen, Zollikofen*, 1-34.

Kovari, K. 1990. General report: Methods of monitoring landslides. In Bonnard (ed.), *Proc. of the 5th Int. Symp. on Landslides, Lausanne*, 1421-1433.

Lee, W.H.K. & Stewart, S.W. 1981. *Principles and applications of microearthquake networks*. New York: Academic Press.

Maurer, H.R., Burkhard, M., Deichmann, N. & Green, A.G. 1997. Active tectonism in the Central Alps; contrastin stress regimes north and south of the Rhone Valey. *Terra Nova* 9(2): 91:94.

Mendecki, A.J. 1997. *Seismic monitoring in mines*. London: Chapman & Hall.

Menke, W. 1989. *Geophysical data analysis: discrete inverse theory*. Orlando: Academic Press.

Nolen-Hoeksema, R.C. & Ruff, L.J. 2001. Moment tensor inversion from the B-Sand propped hydrofracture, M-site, Colorado. *Tectonophsyics* 336: 163-181.

Phillips, W.S., Rutledge, J.T. & Fairbanks, T.D. 1998. Reservoir fracture mapping using microearthquakes: Two oilfield case studies. *SPE Reservoir Evaluation & Engineering* April: 114-121.

Rabinowitz, N. & Steinberg, D.M. 1990. Optimal configuration of a seismographic network: a statistical approach. *Bulletin of the Seismological Society of America* 60(1): 187-196.

Sandersen, F., Bakkehøi, S, Hestnes, E. & Lied, K. 1996. The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. In Senneset (ed.), *Proc. of the 7th Int. Symp. on Landslides, Trondheim*: 97-114.

Schepers, R., Rafat, G., Gelbke, C. & Lehman, B. (2001). Application of borehole logging, core imaging and tomography to geotechnical exploration. *Int. J. of Rock Min. Sci.*: in press.

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

Scholz, C.H. 1990. *The mechanics of earthquakes and faulting*. Cambridge: Cambridge University Press.

Terzaghi, K. 1950. Mechanism of landslides. *Geological Society of America (Berkey Volume)*: 83-123.

Wagner, A. 1991. *Bergsturz Grossgufer Randa: Etude structurale et géomécanique*. Report # 91.35. Sion: CREALP.