ClimChAlp
Interreg III B Alpine Space

Slope Monitoring Methods

A State of the Art Report

Work Package 6

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1. INTRODUCTION

The main issues of the project ClimChAlp are climate change and the related problems to alpine regions. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007b) the impacts on mountains and sub-arctic regions due to climate change are as follows:

> "The duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps region at middle elevations. An upward shift of the glacier equilibrium line is expected from 60 to 140 m/°C. Glaciers will experience a substantial retreat during the 21st century. Small glaciers will disappear, while larger glaciers will suffer a volume reduction between 30% and 70% by 2050. During the retreat of glaciers, spring and summer discharge will decrease. **The lower elevation of permafrost is likely to rise by several hundred metres. Rising temperatures and melting permafrost will destabilise mountain walls and increase the frequency of rock falls, threatening mountain valleys.** […]"

This abstract of the latest report shows the increasing vulnerability we are facing in Alpine Space. Of course, landslides are only one possible result of climate change among many others. Furthermore monitoring slope deformations is only one element of an extensive hazard management among many others.

Since it is not possible to describe neither all problems resulting from climate change nor all possible solutions known within the frame of this report, Work Package 6 (WP6 – Monitoring, Prevention & Management of Specific Effects of Climate Change on Nature) therefore has chosen monitoring of slope deformations as one example – as a kind of "hot spot". Accordingly, the descriptions in some chapters will be going more into detail than in others.

The report compares, assesses and enhances present monitoring techniques and their application on vulnerable areas for improving prevention and risk management. A large collection of best practise examples underline the implementation of the wide possibilities of modern techniques. On the other hand technology seems to have no limits. So it was a matter of particular concern for the authors to point out realistic scenarios and to clarify the possibilities and limits of state of the art slope monitoring methods.

In large parts the extensive report is addressed to practitioners, but also the public reader may be astonished by the latest developments in this field of study. To emphasize the he main messages a list was compiled including recommendations for political decision makers and administrations.

The elaboration of the report is also based on many reports of earlier and current projects as e.g.: RiskYdrogéo[1], GALAHAD[2], ALPS-GPSQuakenet[3], RocksliDetec[4], alpEWAS[5] and many others.

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1 Risques hydro-géologiques en montagne: parades et surveillance. Interreg III A – Alcotra. 2004-2006. http://www.obs.ujf-grenoble.fr/risknat/projets/riskydrogeo/default.htm

2 Advanced Remote Monitoring Techniques for Glaciers, Avalanches and Landslides Hazard Mitigation. European Commission 6th Framework Programme – Global Change and Ecosystems. 2005-2008. http://www.galahad.it/

3 Alpine Integrated GPS Network: Real-Time Monitoring and Master Model for Continental Deformation and Earthquake Hazard. Interreg III B - Alpine Space Programme. 2004-2007. http://www.alps-gps.units.it/

4 Développement d'outils méthodologiques pour la détection et la propagation des éboulements en masse. Interreg III A-Alcotra. 2002-2006. http://www.risknat.org/projets/rockslidetec/rockslidetec.htm

5 Development and testing of an integrative 3D early warning system for alpine instabile slopes. Geotechnologien – Forschungsschwerpunkt Frühwarnsysteme im Erdmanagement. 2007-2007. http://www.geotechnologien.de/forschung/forsch2.12k.html

The collaborators of the WP6 all were practitioners with broad experience[6], coming from all alpine nations. In detail the following institutions have been official partners in WP6:

WP6 Lead Partner

	Institution	Region/State
	LfU: Bayerisches Landesamt für Umwelt (Bavarian Agency for Environment)	Bavaria/Germany

WP6 Project Partners

	Institution	Region/State
	ARPA: Agenzia Regionale per la Protezione Ambientale del Piemonte (Piemonte Regional Agency for Environmental Protection)	Piemonte/Italy
	AWNL: Amt für Wald, Natur und Landschaft (Ministry of Environmental Affaire, Land Use Planning, Agriculture and Forestry)	Vaduz/Liechtenstein
	BAFU: Bundesamt für Umwelt (Federal Office for Environment)	Bern/Switzerland
	BMLFUW: Bundesministerium für Land- und Forstwirt-schaft, Umwelt und Wasserwirtschaft (Ministry for Agriculture, Forestry, Environment and Water Economy)	Vienna/Austria
	GeoZS: Geološki zavod Slovenije (Geological Survey of Slovenia)	Ljubljana/Slovenia
	RAVA : Région Autonome Vallée d'Aoste (Aosta Valley Autonomous Region)	Valle d'Aosta/Italy
	RhôneAlpes: Region Rhône Alpes, Direction de l´Environment et de l´Energie (RhôneAlp Region, Dept. of Environment and Energy)	Rhône Alpes/France
	UCBL: Université Claude Bernard Lyon 1 (Claude Bernard University of Lyon 1**)**	RhôneAlpes/France
	WBV: Autonome Provinz Bozen, Abt. Wasserschutzbauten (Autonomous Province of Bolzano, Dept. 30)	SouthTyrol/Italy

[6] The wide number of collaborators and external experts can be found in detail in ANNEX C.

2. RECOMMENDATIONS TO POLICY-MAKERS AND ADMINISTRATION

The Alps are – from the geological point of view – a young mountain range that even is still rising up. The land-forming processes are under way and most natural slopes are only in a sub-stable equilibrium. This equilibrium is strongly controlled by climatic factors. Any change in these factors means a shift to this sensible balance. The prognoses of the recent IPCC report (IPCC, 2007a) and the results of Work Package 5 (WP5 – Climate Change and Resulting Natural Hazard) indicate several changes in the climatic factors that will put some weight on the instability side of the balance. Accordingly, an increase in landslides is to be expected, that will cause severe problems in the Alps, facing anyhow a rising vulnerability by the current growth of endangered values.

Climate change may trigger new movements, reactivate old "dormant" landslides or accelerate already moving slopes. To keep endangered areas inhabitable and to save lives, monitoring of slopes as a prevention tool has become very important. The last decade brought a wide range of new technologies to detect slope movements. The methods open new possibilities in prevention and prediction.

Conscientious of this clear need and the recent developments mentioned above, the international partners of the project give the following recommendations:

(1) Monitoring and its potential must be appreciated

Monitoring of slopes as a crucial tool for prevention and prediction must be encouraged and its potential must be appreciated also by non-technical or non-scientific stakeholders. Monitoring is an important element of hazard management that also includes hazard identification, hazard assessment and hazard information (supported by Geographic Information Systems and related databases, including historical information).

(2) New technologies open new possibilities which call for further research work

For example the detection of unstable areas within large regions that are still unknown by means of remote sensing. Besides, the irreplaceable traditional methods like terrestrial surveying should also be developed further and their practical application should be supported by the regional authorities. Special need for further research is on the fields of remote sensing, GPS, radar and laser technologies. It is recommended to the regional and national authorities to develop the methods further and to ensure the financing for test applications in co-operation with the scientist.

(3) Slope Monitoring can reduce cost

For slopes which are already in movement, monitoring is often the only chance for a prediction. They are the basis for any geo-mechanical interpretation. It must be recognised that financial means invested in the deformation analysis can reduce the cost for adequate retention works remarkably.

(4) Deformation analysis often takes years

Due to slow deformation rates a clear deformation analysis often takes time, sometimes years. In case the circumstances allow it, this time horizon should be accepted. It can only be reduced by an increase of the accuracy of measurements. In general this also leads to an increasing in efforts and means and finally costs.

(5) Special attention must be paid to the monitoring of permafrost zones

Under future climate conditions the intensities of debris flow processes in permafrost areas are probably expected to increase. This leads to the conclusion that the costs for maintenance of existing protection structures will increase. Since a relation between permafrost changes and an increase in high mountain rockwall instability is still poorly known because of the lack of observations, the change in permafrost base and its impact has to be monitored conscientiously.

(6) It is recommended to start prevention & monitoring as early as possible

Financial means invested in the prevention of disasters by slope movements are the lower the earlier they start. To avoid any building or infrastructure in a critical zone is often the cheapest mean. To monitor the slopes in the case of existing buildings is in general much cheaper than protection works. Nevertheless, monitoring cannot replace any protection. It is recommended to start prevention as early as possible.

(7) The harmonisation of the rating of the degree of danger should be aspired

Albeit the increasing landslide potential, a transnational rating of connected threats is still lacking. Therefore, steps towards a harmonisation of the rating of the danger arising from moving slopes should be taken in all countries of the Alpine Space. A common understanding in this respect has to be regarded as a crucial precondition for transnational collaboration in the field of geologic risk assessment. Such a harmonisation is also postulated by the Alpine Convention.

(8) Support of international networks of researchers & practitioners

In order to exchange experiences and to foster harmonisation a vivid international network of researchers and practitioners is necessary. It is recommended to persons in charge to support the creation and cultivation of such a network.

3. LANDSLIDE INVESTIGATION

3.1 Classification

The term "landslide" includes very different types and processes of slope movements. A slope monitoring design must be adapted to the exact process or the chain of processes. The dynamic of a landslide is also a limiting factor in the use of some methods. The commonly accepted classification after Varnes (1978) respects these needs and defines five types of landslides: falls, topples, slides, spreads and flows. The classification in Table 1 combines these five types of movement with the material involved. Large and complex landslides often show several types within one site: rocks on a cliff may e.g. spread and subsequently fall down, the resulting debris may slide or flow and include loose soil material (WP/WLI, 1993). Landslides can also evolve in time and change from one type to another. A definition of the first move (e.g. rock fall) and the second move (e.g. Rock flow or debris flow) is relevant for the process analysis. A clear definition of the different succeeding or simultaneous processes is also relevant for modelling and hazard assessment.

Table 1: Classification of slope movements (modified after Varnes, 1978)

Type of movement:	**Type of material** Bedrock	**Type of material** soil, predominantly coarse	**Type of material** soil, predominantly fine
Fall	Rock fall/avalanche[7]	Debris[8] fall	Earth[9] fall
Topple	Rock topple	Debris topple	Earth topple
Slide	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow

3.2 Landslide types and Monitoring design

3.2.1 Rock falls

Rock falls cause severe damage due to their energy and speed (v < 40 m/s). The size reaches from the fall of single stones (stone: Ø < 0.5 m, block: Ø > 0.5 m) to the collapse of large masses. The rare collapse of important masses as rock avalanches ("Bergsturz") with huge volumes (V > 1 million m^3) may result in disastrous damage. If a rock fall in preparation is detected in advance, the volume can be predicted roughly by field investigation. A detailed analysis can only be done by monitoring like scanning methods as LIDAR (→ 6.5.2) or In-

[7] The term rock avalanche is often used for large landslides: first falling, and then travelling with high velocity. The German term "Bergsturz" following Albert Heim is internationally used for such highly dynamic processes with long travel distances.

[8] Definition: debris: 20 - 80 % of the particles > 2 mm

[9] Definition: earth: 80 % of the particles < 2 mm.

SAR (→ 6.5.3) or by geophysical monitoring (→ 6.4). A deformation analysis can also predict the moment of the breakdown (Fig. 3).

Fig. 1: Reactivated landslide Falli Hölli, CH. Total destruction of the village in June 1994

3.2.2 Slides

The process of sliding is classified as rotational, translational or as complex slides. Rotational slides generally move along a curved surface of rupture (Fig. 2) so that the head of the displaced mass moves vertically downward. Further movements can cause retrogression of the scarp. The toe of the mass is sliding on surfaces with much flatter angles. Rotational slides mostly occur in homogenous materials as loose and unstratified silt, sand or gravel.

In translational slides the mass displaces along a planar surface of rupture. Very often translational slides are shallow and concern some meters only. Nevertheless, important depths can sometimes be covered. This can happen especially in rock slopes with dip slope conditions (discontinuities run more or less parallel to the slope) as e.g. at the rock slides of Elm (Switzerland) or Vajont (Italy). A concave-shape of the rupture surfaces in cross section may favour the instability, as in such sub-surface channels the sensitivity to hydrological changes is higher. Translational landslides can accelerate in short time, which means that they are more dangerous than rotational slides in general. For all kind of slides monitoring gives important hints on the mechanical behaviour. The monitoring design must consider the possibility of acceleration. If a potentially rapid slide is detected in advance, an early warning system might be appropriate. A prediction of speed evolution is difficult, but possible with precise geological data. Fig. 3 shows some typical speed curves over time.

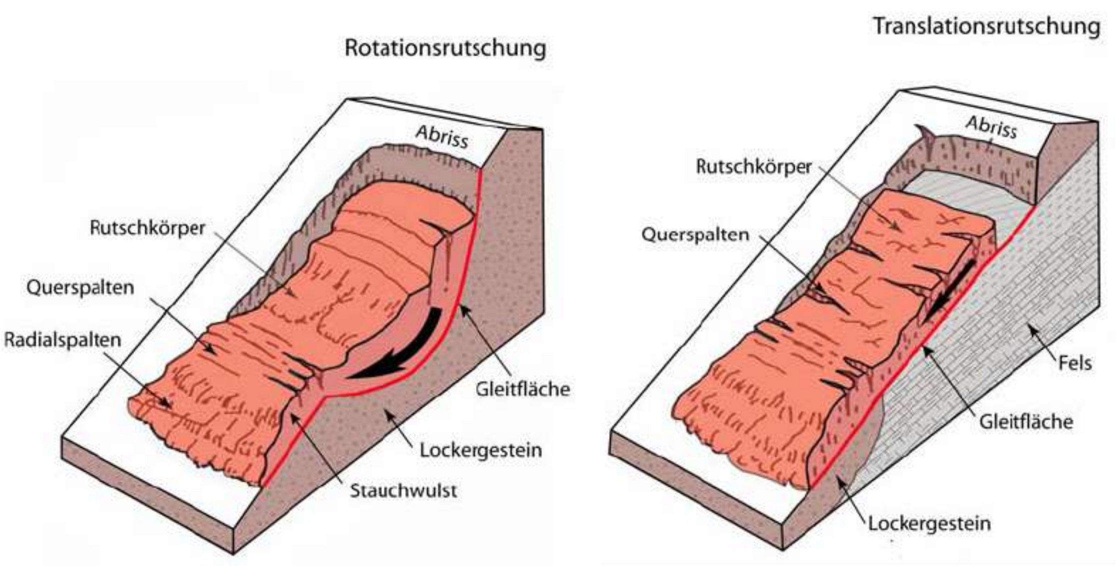


Fig. 2: Bloc diagrams with idealized types of slides: left: rotational, right: translational. The definitions of the features are following international standards: Crown, Scarp, Foot, Toe, Surface of rupture, Zone of depletion, Accumulation, Compression lobes, Landslide mass.

3.2.3 Debris flows and shallow landslides

Debris flows and shallow landslides triggered by heavy rainfall are frequent in the Alps. They are characterized by moderate volumes (some thousands m^3 only) and high speed (1 to 10 m/s). These phenomena are very dangerous and frequently cause damage, traffic disruptions and fatalities. The shallow landslides mostly occur at slope inclinations ranging from 20° up to 44° (Fig. 4; Raetzo, 1997; Raetzo et al., 2007). Preventive monitoring of these processes is sometimes difficult as they start suddenly at the occasion of extreme precipitation. The hydrogeologic conditions of a landslide mass are the main factor of high pore pressures and a sudden failure.

3.3 Assessment of landslide hazard

To evaluate the hazard given by a certain landslide in any case a model is necessary. This may be, for the simple case, only a mental model or a sketch. In more sophisticated cases, a numerical (→ 3.3.3) or even a physical model will become necessary. As basic data for each model, the deformation rates derived from slope monitoring are essential. Most common and easy to collect is gathering information about land surface deformations. Nevertheless, in order to create a valid 3D model, information from the sub-surface is necessary. First and foremost it is the depth of a sliding plane that must be integrated into the model. Inclinometers installed in boreholes are expensive but often the only possibility to access to such data. Geophysical investigation can provide additional subsurface information. As a first approach, the interpretation of the 3D vectors of the surface monitoring gives hints about the geometry of the sliding mass.

3.3.1 Temporal evolution of landslides

The evolution of a landslide in time is rarely continuous but mostly non-continuous. In many cases, the landslides show acceleration and deceleration phases. Periods of high landslide activity are often related to high ground water level and/or high pore pressure. These are in general caused by intense or long precipitation events or snow melt. That is why the occurrence of specific meteorological conditions should be integrated as a first warning signal into slope monitoring. As a general rule, small landslides react instantaneously to such external triggers, whereas large masses react slowly and retarded. The activity of large mass movements may even be correlated to long term changes, such as climatic variations.

The deformation rates of active landslides are very various: Low speeds of some deep seated landslides are in the range of several mm/year. High speeds of landslides accelerating to fall processes can attain 40 m/s and more (rock avalanches, Bergsturz). Some landslides tend to move in intervals: After an active period of some months or years, they can remain inactive for hundreds of years. The problem is that some of them can be reactivated at any time. These temporarily inactive landslides are also called “dormant” landslides. Landslides may even be cyclic if they are driven by seasonal variations (s. examples Fig. 3). The activity of a landslide is in first term determined by factors like geomorphology, water content, vegetation, erosion and drainage. To get quantitative and reliable information, verification by monitoring methods is necessary.

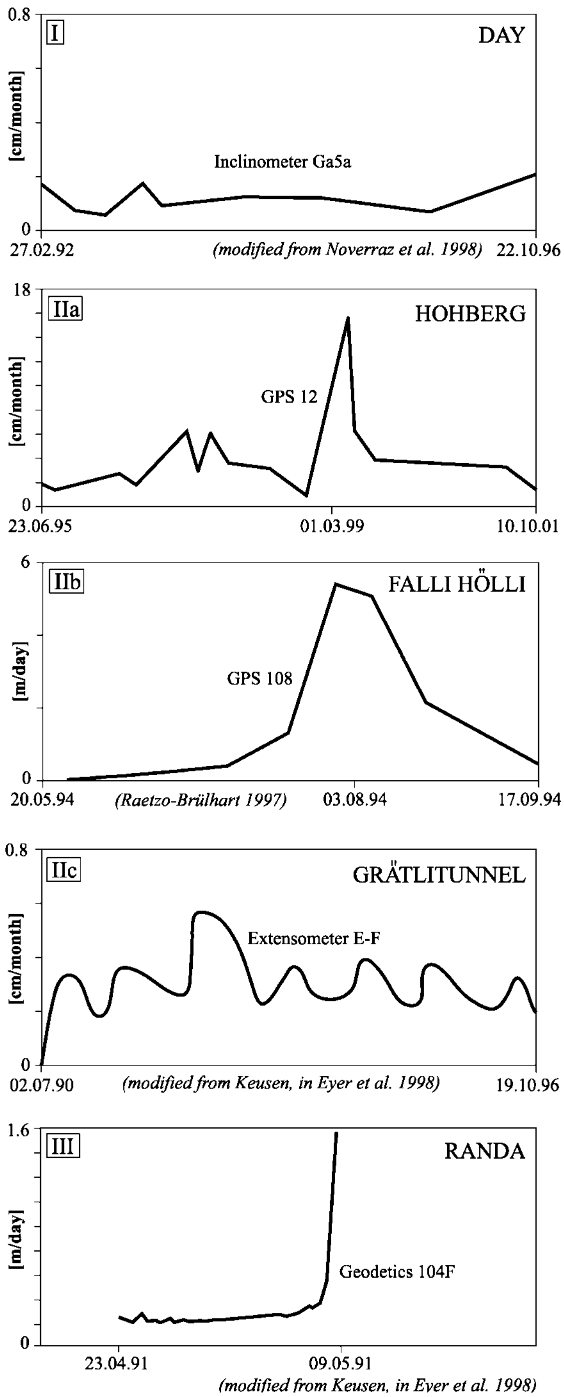


Fig. 3: Landslides and their typical acceleration through time (Raetzo et al., 2002). Type I: continuous. Type II: different accelerations triggered. Type III: sudden acceleration leading to fall process.

3.3.2 Prediction of landslide evolution

The prediction of the evolution of a landslide must be based on a detailed under-standing of its mechanism, its dynamic, its water pressure and its history.

In the case of Randa (Fig. 3, type III) an exponential increase of the deformation rate indicated the immanent collapse in advance. So, a successful prediction was made for the Randa rock fall and consequently the village was evacuated. The road and the railway were also blocked hours before. This success in risk management is due to a specific and sophisticated monitoring and to an early warning system including not only crack meters, tacheometer and geophysics, but also a detailed civil protection plan. In the case of Falli Hölli (Fig. 3, type IIb) a prediction was also made according to the exponential speed curve. Maximal velocities of 6 meters per day were measured during the predicted time. As a consequence of the high activity, the landslide blocked the river Höllbach.

This debris slide was mainly triggered by long and heavy rainfall after an already high water pressure due to a wet pre-decade. No precursory signs were observed in the village area, but a posterior remote sensing analysis showed acceleration in the scarp area already months before. In the cyclic evolution of Grätli tunnel (Fig. 3, type IIc) the snowmelt in spring is the driving force.

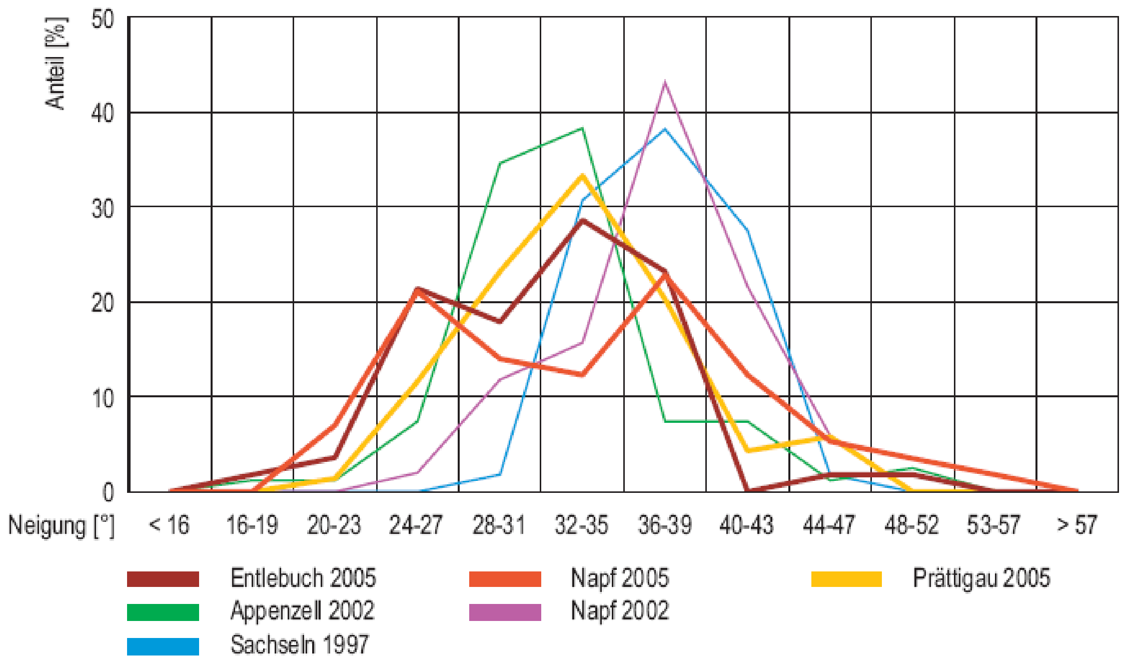


Fig. 4: Distribution of slope angles for several hundreds of shallow landslides in 3 Swiss regions (Raetzo et al. 2007). Most of the landslides are translational. The first move is slide, the second move is often an earth or debris flow (unchanneled). The minimal angle for most of these landslides is 18°.

3.3.3 Mathematical models

Modelling of landslides must be adapted to the types of mechanisms: fall, topple, slide, spread and flow. Geotechnical parameters for these models are based on the material involved (e.g. rock type, debris type, grain size distribution, soil content) and on the hydrogeological conditions, including saturation ratio. As a consequence of this variability many different models are used in practice for each type of mechanism. Due to the high number of methods, this paragraph just outlines some principles of frequently used models. For falls, slides and flows, simple quantitative approaches for the slopes are involved and eventually the run out distances are used for a first indication of the process area. In the early 20th century, Heim introduced as one of the first geologists critical slope angles and travel distances for rock avalanches according to theoretical models. Later on several methods for rock fall modelling were developed; some of them are based on the kinematical energy at each point of a travel distance. The most used rock fall models are in 2D considering trajectories of single blocks, topography, local geomorphology and specific soil parameters. Some of the rock fall models are used in a 3D GIS environment where topographic variations and lateral trajectories are considered on a very detailed level (e.g. cells of 1 m).

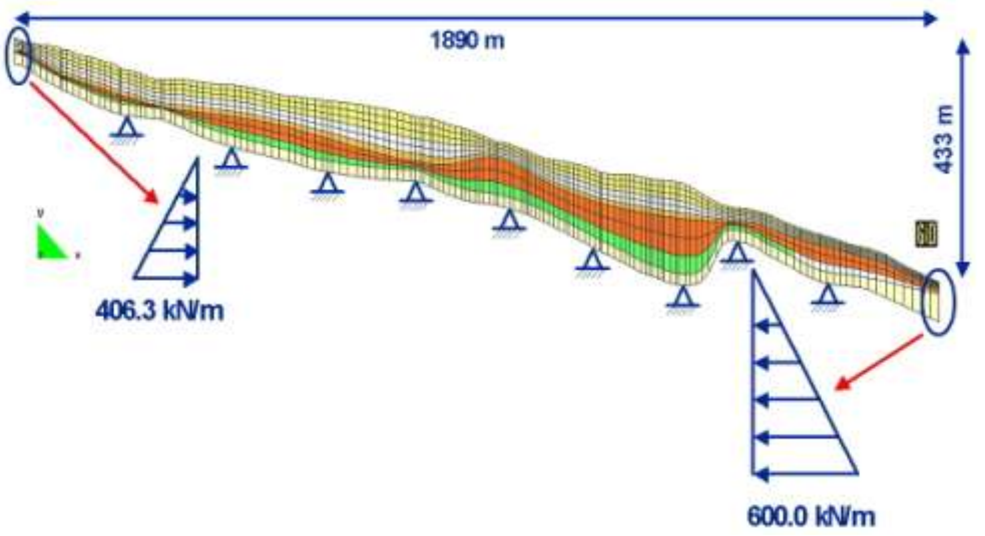


Fig. 5: Mathematical model of Frasse landslide (pers. communication C. Bonnard)

For the slide processes, classical 2D models considering the factor of safety were developed in many variations during the 20th century (e.g. Bishop, Janbu, Morgenstern & Price). The factor of safety does not represent the dynamics of landslides but only give their limit equilibrium conditions at a given state. Some of the mathematical models use the variability of the parameters to give a probability value for the factor of safety. This method takes into account heterogeneous conditions of the geology and the materials involved. Models aiming at describing the dynamics of landslides consider geomechanical deformations and the change in hydrogeological conditions. Numerical models for geomechanical analysis are used since high speed computers are available (Fig. 5). An overview of methods and software are presented by the International Association for Mathematical Geology (also on internet).

In future times, 3D modelling calculating the deformation and the hydrogeologic variations on each cell of a landslide (e.g. 1 m) will bring interesting results within the hazard assessment and for the design of counter measures. All these models are limited for the calculation of the real behaviour inside the unstable mass and especially within the failure surface. The quality of the modelled results will still stay in relation to the quality of the geological and hydrogeological information.

3.4 Historical approach for hazard assessment

In risk assessment, hazard is the probability that a particular phenomenon (danger) occurs within a given period of time (Fell et al., 2005). Then hazard assessment can be viewed as a probabilistic prediction of a phenomenon. The phenomenon to be predicted can be the occurrence of a future movement in a presently stable slope or a change of the nature of an existing movement (for example, evolving from slow to extremely rapid). The first case often occurs in the context of land use policy, where the considered period is roughly one century. It can be referred to as long term prediction. Slope monitoring can be used only in the second case (referred to as short term prediction), where it has an important part.

Different methods are used for hazard assessment (Picarelli et al., 2005), which can be roughly divided in two main approaches: the mechanical approach and the historical (or empirical) one. The mechanical approach is based on the knowledge of the internal structure and the physical processes of the landslides. As this knowledge is often insufficient to allow for a quantitative risk assessment, the mechanical approach must be combined with the historical one (Hantz et al., 2003; Nadim et al., 2005). This one is based on the principle that future landslides will be more likely to occur under the conditions which led to past ones. So the knowledge of the passed landslides and their conditions is essential in this approach. Up to now this knowledge was owned by experts or scattered in the literature. Thanks to computerized databases, a common knowledge can be available for the experts' community. A landslide database can be used in different methods involved in hazard assessment and consequence analysis:

a) Qualitative assessment based on expert judgement (Interreg IIC, 2001). The database is used to search for cases which are similar to the one under study. The outputs are in qualitative terms, e.g. low, medium or high hazard.

b) Statistical multivariate analysis. For a particular type of landslide, analyses can be performed to identify susceptibility factors and estimate the landslide susceptibility (or relative probability of occurrence) at different locations in a given area (Guzzetti et al., 1999; Zezere et al., 2004; Colombo et al., 2005; Komac, 2006). Such analyses are usually performed in a GIS-based environment.

c) Frequency analysis. If all the landslides in a given volume range, occurred in a given period of time within a given homogeneous area, are recorded in a database, the annual landslide frequency can be estimated for this volume range. This frequency alone can not give the occurrence probabilities of the individual landslides, but it brings a temporal dimension that is usually missing in the other methods. It can be used as a check on other methods or combined with relative probabilities to evaluate the absolute occurrence probabilities of individual potential landslides (Hantz et al., 2003; Nadim et al., 2005).

Computerized landslides databases including all types of landslides, exist for several countries or regions, but most of them are dedicated to informing the public and don't contain enough information to be used for hazard assessment (e.g. BDMvt[10] in France).

3.4.1 Databases for frequency analysis

To be used for a frequency analysis (method c), a database must contain:

- For each landslide, the source location, the date of occurrence, the type of landslide, the magnitude (volume or area);
- The magnitude range, the period of time and the area, for which the database is exhaustive. The period of time and the area must be respectively long and large enough for the time/space homogeneity to be insured.

The spatiotemporal frequency can be calculated (average number of events per time and surface unit, e.g. per year and square kilometre). It can be used for hazard assessment for the same landslide type and the same volume range in the observation area, but also in area with similar geological, geomorphological and climatic conditions.

The analyses of a number of databases have shown that the magnitude/frequency relation has a power law distribution over several orders of magnitude (Dussauge-Peisser et al., 2002; Malamud et al., 2004; Picarelli et al., 2005). It makes it possible to estimate the frequency of larger (or smaller) landslides, for which a record may not exist or the record period is too short. Thus monitoring of small landslides activity can be useful for larger landslides hazard assessment.

The use of databases for hazard assessment supposes that the landslides occurrence is stationary in time. Up to know the influence of climate change on the landslide frequency has been considered negligible according to the uncertainty in the frequency estimation. But today it appears that climate change will be significant in the next decades and consequently its potential influence on landslide frequency must be analysed. Such analysis should be based on landslides databases covering the Holocene period, in which climate changes are known, and on monitoring of the landslide activity at a regional scale. Landslides inventories covering the Holocene period are only possible for the largest landslides, as large rock avalanches, which remain visible after several millennia. But their age and volume have to be determined using respectively geochronological and geophysical methods. 14C dating can be used where soil covered by the landslide deposit can be reached. A new method has been developed during the last decade, based on the determination of exposure time to the cosmic radiations, using in situ produced cosmogenic nuclides like 10Be in quartz bearing rocks and 36Cl in limestone

[10] Base de Données Nationale sur les Mouvements de Terrain, http://www.bdmvt.net/

(Bigot-Cormier et al., 2005; Delunel, 2006; Cossart et al., 2007). The scarp of a landslide can thus be dated and for rock avalanches, the exposure time of the fallen blocks.

3.4.2 Databases for empirical and statistical methods

Databases which are dedicated to potential landslides identification and corresponding hazard assessment using methods a) and b), must be more detailed than for frequency analysis. They must also contain information on: the morphological, geological and hydrological characteristics of the slope; the initial and post-failure mechanisms; the triggering factors; the final state of the slope (Rockslidetec, 2006). A GIS-based environment makes it possible to determine the relationship between landslides and geology (Colombo et al., 2005; Komac, 2006).

A significant number of recent small landslides can be described in local or regional databases, allowing for frequency and statistical analyses. But for the larger landslides that are less frequent, the databases need to cover larger areas and long periods of time. It is particularly relevant in the case of rock avalanches and large rock movements (Bonnard and Glastonbury, 2005). An Alpine database for large rock falls and avalanches, covering the whole Alps and the Holocene period, has been initiated in the ClimChAlp project, starting from a first database achieved in a former Interreg project (Rockslidetec, 2006; Schoeneich et al., 2008). This database is aimed to record all the events larger than 10^6 m^3, occurred in the last centuries, and the ones larger than 10^7 m^3, occurred in the Holocene period.

4. CLIMATE CHANGE AND PERMAFROST

4.1 Introduction

Recently, large rock and rock/ice avalanches have occurred in high mountain areas worldwide (e. g. McGinnis Peak, Alaska, 2002; Kolka-Karmadon, Caucasus, 2002). In the Alps, Brenva Glacier (1997), Punta Thurwieser (2004), the Drus west face (2005) and Dents du Midi (2006) are the most recent examples, while innumerable low magnitude rock falls have detached from steep rockwalls during the hot Summer of 2003 (e.g. Mont Blanc massif or Matterhorn). Due to their frequency (rock falls) or magnitude and long runout (rock avalanches), these events posed a significant threat to outdoors activities and people safety in some mountain resorts, or even to infrastructures and people in some Alpine valleys. Because

a) ice was observed in many starting zones,
b) the mean annual air temperature in the Alps has increased by more than 1°C during the 20th century and
c) the warming trend has accelerated since 1980,

the hypothesis of a relation between permafrost changes and an increase in high mountain rockwall instability gains force. However, on the one hand, frequency and volume of instability events in high mountains are still poorly known because of the lack of observations. On the other hand, ongoing permafrost changes in rockwalls remain poorly understood because of the difficulties in carrying on in situ measurements. So far, permafrost studies are mainly based on modelling, with few existing instrumented sites.

4.2 Definition of permafrost

Permafrost or perennially frozen ground is defined as a thickness of soil or other superficial deposit or even bedrock at a variable depth beneath the surface of the earth, in which the temperature below freezing has existed continually for a long time – from two to tens of thousand of years (Muller, 1943). Permafrost is defined exclusively on the basis of temperature, irrespective of texture, water content or lithological character. The definition itself implies the sensitivity of this phenomenon against changes in temperature conditions. The mountain permafrost in the Alps is generally only a few degrees below zero Celsius. Therefore, this phenolmenon may be especially sensitive to climate changes (Harris et al., 2001).

Permafrost influences e.g. the hydrology and stability of steep scree slopes, since ice-rich permafrost acts as a barrier to groundwater percolation and can imply local saturation within nonfrozen debris (Zimmermann & Haeberli, 1992). Permafrost thawing in non-consolidated material leads to an increase of pore water pressure and a loss of cohesion (Harris et al., 2001). The disappearance of ground ice bodies in scree slopes leaves caverns and destabilizes parts of these disintegrated slope areas. With accelerated permafrost thawing, the susceptibility of these slope areas for landslide and debris flows and the triggered volumes are expected to rise (Zimmermann et al., 1997).

4.3 Impact of climate change on permafrost and slope stability

Permafrost is especially sensitive to climate change. Climatic developments during the 20th century have already caused pronounced effects in the periglacial zones of the Alps. The lower permafrost limit is estimated to have risen about 100 m and more since the 19th century.

The degradation effects of Alpine permafrost are not always visible and resulting slope instability may occur years later. The slope stability of steep high mountain flanks may be influenced by changes in permafrost as well as by resulting changes in the hydrological regime. This affects especially areas with unfavourable geological factors. Extensive parts of rock walls perennially frozen up to now will most probably warm up, shifting the actual permafrost boundary to even higher altitudes. Important rock masses, so far frozen, will reach temperatures of around 0°C, which are most critical for stability because of the simultaneous occurrence of ice and water in cracks (Fischer et al., 2006).

An increase of slope instabilities in high altitudes was in fact observed in warm years of the 20th and 21st century. During the last summers, an increase of rock fall intensities and frequencies as well as debris flow events has been observed within the higher parts of the Alps. Examples of such events are the rock falls on the Matterhorn (Fig. 7), Dent Blanche and Thurwieser, the debris flow events at Guttannen, Täsch and Val Roseg. Other landslides in Swiss mountains are related to ice and glacier melting, for example at Eiger, Monte Rosa and Aletsch Glacier.

4.4 Monitoring of permafrost

Considering climate change, monitoring of permafrost is essential. First of all, an overview of the distribution of permafrost, as well by modelling as by collecting field evidences is needed to give an idea of sites at risk. Switzerland e.g. realized a permafrost indication map based on GIS analyses (Fig. 6). The consequences of the general warming on permafrost are also monitored by temperature loggers in boreholes.

Fig. 8 indicates a general trend in such boreholes of the PERMOS sites. The sensitivity of permafrost on global warming is a general problem for almost all alpine countries. In order to evaluate the permafrost evolution in the whole Alps and to manage the hazards related to it, a transnational monitoring network is needed. Satellite Radar Interferometry is a new monitoring method for deformation analysis and recent studies in the swiss permafrost improve the use of this technique. The detection of landslides as well as the monitoring of accelerations is easier to apply over large areas like high mountain ranges. This remote sensing data should be combined with in situ monitoring network (e.g. boreholes, Fig. 7).

Because of the increasing frequency of rockfall events in high mountain areas, a better knowledge of the triggering factors and the relation between rockfalls and permafrost degradation is needed. To achieve this aim, in the frame of the Interreg IIIA - Alcotra, the PERMAdataROC project has been developed in Western Alps area[11].

[11] Partizipating institutions: Fondazione Montagna Sicura, on charge of Aosta Valley Region; Agenzia Regionale per la Protezione Ambientale (ARPA) Valle d'Aost; the Laboratory EDYTEM of the University of Savoie and the Research Institute for Geo-hydrological Protection of the Italian National Research Council (CNR-IRPI), http://www.interreg-alcotra.org

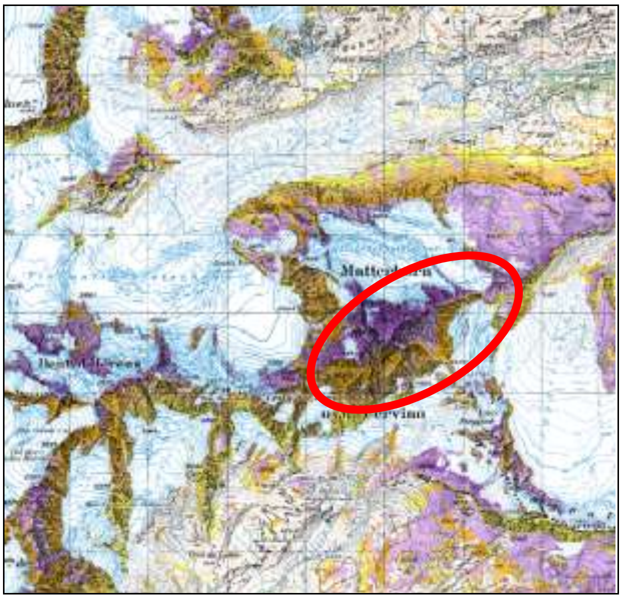


Fig. 6: Permafrost indication map of the region of Matterhorn. The colour scale ranging from yellow to violet represents permafrost areas with increasing thickness. The red circle indicates the rock fall area of summer 2003.

Fig. 7: Rock fall starting zone on the Matterhorn in summer 2003. On the left side ice is still visible on the surface of rupture.

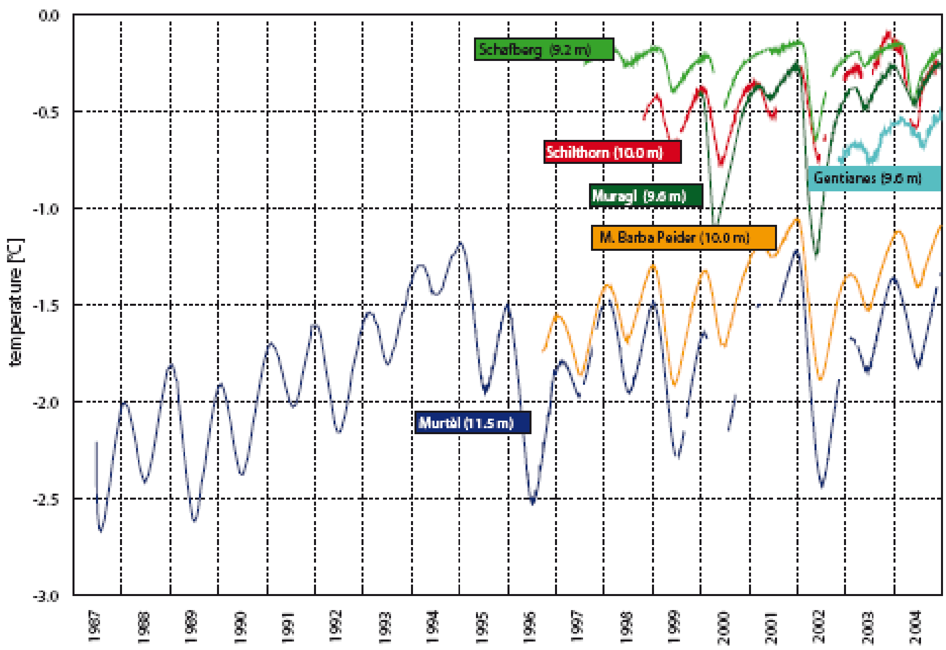


Fig. 8: Permafrost monitoring. Ice temperature in a depth of 10 m within 5 boreholes in the Swiss Alps (PERMOS, 2007). Note the general trend to warmer temperatures since 1987 due to climate change. The impact of the very warm summer of 2003 is visible over several months up to 2004.

The PERMAdataROC project focused on the relation between rockfalls and permafrost degradation by means of three research axes (Work Packages), i.e.

- collection and analysis of rockfall data in high altitude areas (CENSI_CRO),
- thermal measurement inside rockwall and correlation with external parameters (PERMA_TEMP),
- rockwalls surveys by means of application of new technologies (PERMA_CRO).

A network of local observers and a communication system in the Western Alps area was set up in order to collect data about rockfalls as complete as possible; a database of events was set-up and analysed, in order to find possible correlation between event frequency and other parameters. Survey of selected sites allowed formulating a "handbook" of the main signs of permafrost degradation. Many instruments were tested to achieve the best results in inside rockwall temperature measurement. Finally, technologies and methods (TLS, photogrammetry and seismic measurement) were applied to recognize rockfall activity, so allowing to find possible correlation with inside-rock thermal conditions.

From the experience achieved, a network of observers and databases collecting rockfall events data should be usefully set up all above the Alps. This will allow to:

- share and improve databases about rockfall events in areas prone to permafrost;
- carry out exhaustive statistical analysis and find a possible correlation between events and climate changes.

Moreover, results and experience achieved from local analyses (Mont Blanc and Matterhorn area mainly) can be applied to other Alpine areas, e.g.

- to establish the altitudinal range subjected to permafrost degradation and, potentially, increased rockfall activity,
- to collect and organise data about rockfall events,
- to set up thermal surveys and rockwall surveys (by means of different methods) in high altitude areas.

4.5 Situation in the Autonomous Province of Bolzano

In the Autonomous Province of Bolzano, about 5.8% of the total area is possibly interspersed with permafrost conditions. Within this project, the Autonomous Province of Bolzano identified and localized the permafrost areas following the simulation approach of Stötter (1994). The resulting map of potential permafrost areas has been overlaid with the hazard index map for debris flow processes calculated by geo7 (2006) following the procedures of Zimmermann (Zimmermann et al., 1997) and Gamma (1999). The intersection of these two databases leads to the identification and localisation of potential debris flow processes starting in permafrost and permafrost degradation areas. The analysis showed that about 40% of the potential debris flow process areas have parts of their starting zones in permafrost and permafrost degradation areas. 11% of these process areas are endangering settlements. The potential debris flow processes starting in permafrost and permafrost degradation areas are endangering about 4% of the settlements in the Autonomous Province of Bolzano. Thus, these areas are sensitive against the impact of climate changes. The environmental changes in the starting areas of debris flows have to be observed and monitored.

In combination with the expected increases of rainfall intensities the intensities of debris flow process starting in permafrost areas are expected to increase. This leads to the conclusion that under future climate conditions, the sediment management in alpine torrents will meet challenges. In future, the costs for maintenance of existing protection structures will increase due to higher deposition volumes and a higher frequency of removal of debris flow deposits from sediment retention basins. The case study about the analyses of the possible impact of climate changes to the Tschenglser Bach torrent described in WP5 underlined this assumption (Zischg, 2007).

Fig. 9: Erosion channels due to debris flow processes started in permafrost degradation area of the Tschenglser Bach torrent, Community of Laas, Autonomous Province of Bolzano South Tyrol)

4.6 Conclusion

The studies made within the ClimChAlp project and previous Interreg projects show the importance of monitoring the changes in the environmental systems. Although monitoring the environmental changes in permafrost areas are more time-consuming and more costly than e.g. for landslide areas because of the climatic conditions and logistic problems, the monitoring efforts provide a crucial basis for the prediction and prevention of natural hazards. The results can reduce the costs for the implementation of adequate permanent protection structures and provide a basis for decision-making in civil protection issues.

5. MONITORING AND EARLY WARNING SYSTEMS

5.1 Monitoring

5.1.1 Introduction

Monitoring in general can be regarded as the regular observation and recording of activities taking place in a certain structure. It is a process of routinely gathering information on all aspects of the object. The term may be narrowed down with respect to deformation monitoring, whereas deformation monitoring is the systematic measurement and tracking of the alteration in the shape (position and altitude) of an object as a result of external forces. However, especially in slope monitoring the inclusion of soil parameters like water content, vegetation, erosion and drainage as well as geomorphology and historical information is a major concern.

Deformation monitoring and gathering measured values is a major component for further computation of soil and rock stability, deformation analysis, prediction and alarming (Moore, 1992).

Since each monitoring project has specific requirements, the used measuring device (→ chapter 6) for a deformation monitoring depends on the application, the chosen method and the required regularity and accuracy. Therefore, monitoring of slopes or landslide areas can only be defined, designed and realized in an interdisciplinary approach (Wunderlich, 2006). A close cooperation with experts from geology, geophysics and hydrology together with experts from any measurement discipline such as geodesy and remote sensing and other academic fields is an indispensable requirement.

Development and improvement of measurement and observation systems in real time for online transmission of decisive physical hazard parameters could be the final aim, although this requirement is not imperative for every monitoring task. The following section formulates some general consideration about (integrated) monitoring systems to clarify the complexity of such an undertaking.

5.1.2 Geodetic datum transformation

Monitoring of land or rock mass movements by geodetic and remote sensing observation techniques is selected when absolute displacements shall be derived. In contrast to other (e.g. geotechnical methods which mostly give relative evidence) these results always refer to an agreed, common reference surface and coordinate system. Within such a frame, which surveyors call datum, the behaviour of each single point or mutual motions of several points can be investigated from epoch to epoch (Wunderlich, 2004).

One has to be aware that terrestrial and satellite methods refer to completely different datums. Terrestrial observations are related to gravity – practically because geodetic instruments are levelled and theoretically because a separation of horizontal and vertical displacements is desired. Heights are commonly referred to a certain physical surface (the geoid) in mean sea level and called orthometric. Spheroidal (ellipsoidal) height differences may be converted to orthometric ones by adding the respective undulation differences, i.e. the change in height differences between geoid and spheroid along the vertical profile between two points. To do so, a detailed knowledge of the geoid is required.

Baselines derived from GPS phase measurements have no relation to gravity. They refer purely geometrically to an international mean earth spheroid, agreed upon within the WGS84[12] datum frame. The relation to this datum comes implicitly with the satellite's ephemerides[13] which are computed in this system.

Obviously, the transition from WGS84 to a national datum is a demanding procedure. In practice, the conversion is managed easily by a spatial transformation with 7 parameters (3 translations, 3 rotations and 1 scale). These 7 parameters are determined by the coordinate values of in minimum 3 points known in both systems. It is of utmost importance that a sufficient number of such points is included in the (stable) control points. Otherwise point losses could make it impossible to maintain consistent transformation parameter computation, which would prevent to precede rigorous deformation analysis (Niemeier, 1992).

5.1.3 Long-term monitoring

The monitoring regularity and time interval of the measurements must be considered depending on the application and object to be monitored. Objects can undergo both: rapid, high frequency movement and slow, gradual movement. To cover the whole time spectrum of mass movements, measurement intervals often range from fractions of a second (e. g. micro-seismic waves) to hours (e.g. to detect daily periods). Seasonal periods or long-term trends may be covered by regular measurement campaigns ranging from days or weeks to years and decades.

When starting with a monitoring project, looking back in history is a precious chance. Thanks to existing archives it is (sometimes) possible to derive former movement rates and learn about the type of movement which may influence the choice for further advancement. Normally, quantitative information on movement rates is only possible with federal & national surveying archives or with means of remote sensing, whose data archives go back for up to five decades. Another historical approach uses geological, chemical and physical analysis to determine the age of a rock avalanche and estimate its volume (→ 3.4).

But designing and implementing a long-term monitoring system that should suit for many years of observation, experts face numerous problems. This is due to the fact that the monitoring constraints as well as the technological potentials will change over the years. It is not a simple attempt to switch over from one system to another. Particular surveying methods have particular claims for inter-visibility and might refer to different datums. Other monitoring methods such as radar interferometry measurements become difficult over longer period of time due to decorrelation of interferograms. Hence, prudent station selection and capable transformation solutions are a must. Equally important is to set a sufficient number of well-

[12] World Geodetic System 1984

[13] An ephemeris (plural: ephemerides; from the Greek word *ephemeros* = daily) is a table of values that gives values on a satellite's (or any astronomical object) orbit to derive the position of the objects in the sky at a given time

monumented control points and creating an adaptable evaluation concept to ensure that results of campaigns by different observation methods will stay comparable.

5.1.4 Integrated monitoring systems

The elastic term of "integrated" ideally describes a monitoring system that provides a highly flexible monitoring system that combines e.g. geodetic, geotechnical and meteorological sensors to match the needs of a monitoring challenge – whether it is a small scale or large scale system or a temporary or permanent monitoring installation. Within an integrated monitoring system (IMS) several sensors have to be combined to one homogeneous output signal. Thus it includes:

- sensor fusion: a multi-sensor system that is able to observe different kind of parameters,
- sensor control: a responsible software/online application for (automatic) data collection,
- data communication: data transfer to a central processing station via LAN, UMTS, etc.,
- data processing: sensor specific software to transform raw data into first results,
- data fusion: different data rates, types, dimensions, reference frames, mapping, accuracy,
- data and quality management: recording and handling of a large amount of information,
- data analysis: robust processing algorithms for final output.

All of these items are challenging tasks, but maybe the last item requires the most sophisticated solutions. Most "IMS" are satisfied with the visualization of results, which can be done with time series and scatter-/vector-plots. In this case, the operator is always the responsible decision maker. Human experts have the sufficient skills and expertise to make considered decisions on the appropriate response to the results, e.g. independent verification through on-site inspections, re-active controls such as repairs and stabilizing and emergency responses such as site evacuation (Moore, 1992). Therefore, a human mind is superior to artificial intelligence and this will never change; but the question is: How can information technology and mathematical models adequately support a human's decision process? Concerning the future way of processing and analysing, one has to make use of robust error detection procedures (Brunner et al., 2003). Fundamental models are listed below, for detailed description it shall be referred to literature:

- Deformation analysis: numerical deformation analysis is directly related to the science of network adjustment and is concerned with the determination of a statistically significant displacement (→ 6.2; Shanlong Kuang, 1996).
- Kalman filter: predictive Kalman filtering estimates the state of a dynamic system, even if the precise form of the system is unknown. The filter is very powerful in the sense that it supports estimations of past, present and even future states (Heunecke, 1995; Welch & Bishop, 2004).
- Fuzzy logic: rule-based decision making, e. g. that if one sensor shows an increasing movement, some other sensors must show the same tendency. This helps to overcome the limitation of strict thresholding (Wieser, 2002; Haberler, 2005; Haberler-Weber et al., 2007).

5.2 Early Warning Systems

5.2.1 Introduction

An “early-warning-system” is a tempting method to reduce risks. In several cases it has been used and showed good results. Sometimes also mere alarming signals were declared as an early warning, as e.g. the loud rumours in the mountain at Art-Goldau in Switzerland before the whole slope collapsed in 1806 or the registration of increasing deformation before the break down of Monte Toc at Vajont in 1963. In both cases the threat was evident, but not correctly realised by the responsible persons and so no protection procedures were initialised. Apparently, it is often not clear what is really meant by “early-warning”. The terms “monitoring” and “early-warning-system” are often mixed. Therefore it is necessary to mark the difference between both.

In a **monitoring system** data can be collected at intervals or continuously and are analysed at regular time intervals. It consists of a group of devices which basically allow to:

- determine depth and shape of the sliding mass
- determine the movement rate of the sliding
- monitor the activity of marginally stable slopes
- monitor groundwater levels or pore pressure.

A **warning system** (Fig. 10) is a monitoring system in which:

- data are continuously collected
- data are continuously analysed
- if a threshold is exceeded, some predefined civil protection procedures are activated.

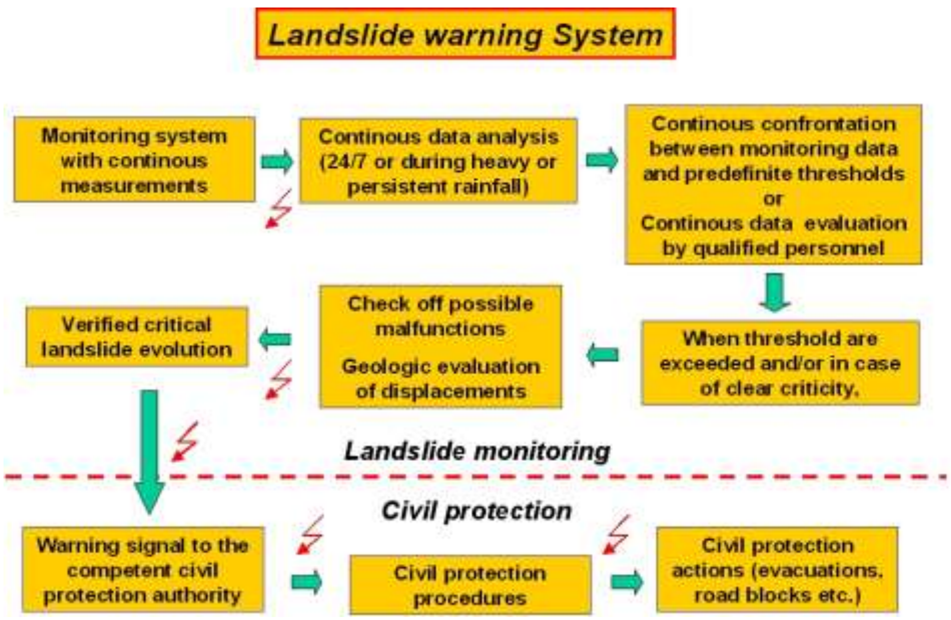


Fig. 10: General flowchart of a landslide warning system. The red arrows mark passages where communication may be a major concern.

Landslide warning systems are often proposed for several reasons:

a) warning systems have a strong technological appeal,
b) the companies which produce and/or install the monitoring instruments propose warning systems as up-to-date/state-of-the-art devices; moreover the tremendous evolution of electronics seems to indicate as natural, obvious and straightforward an application to slope movements,
c) in complex crisis situations a landslide warning system is often regarded as a cheap and temporary solution which gives evidence to the fact that something has somehow been done; thus sparing local authorities from more drastic or more unpopular decisions.

5.2.2 Elements of a warning system

According to United Nations (2006) effective early warning systems must be people-centred and must integrate four elements:

- knowledge of the risks faced,
- technical monitoring and warning service,
- dissemination of meaningful warnings to those at risk and
- creation of public awareness and preparedness to act.

Failure in anyone of these elements can mean failure of the whole early warning system. A landslide warning system usually requires the following basic elements:

- a geologic analysis in order to define evolution scenarios,
- a meteo pre-alarm,
- a monitoring system with continuous measuring and data transmission (no restriction acceptable),
- continuous data analysis,
- civil protection procedures and
- communication procedures among the involved subjects.

5.2.2.1 Geological study to define scenarios

The first necessary element of a warning system is the definition of temporal and space evolution scenarios. These consist of:

- evaluation of the different possible evolutions of the displaced volumes
- evaluation of the endangered zones
- evaluation of the order of magnitude of the time intervals in which the landslide can evolve.

Scenario definition is based upon a general modelling which takes into consideration all the landslide elements (historical records; hydraulic, hydrogeologic and climatologic records; geologic, geometric and geostructural data, etc.). Scenarios have to be adapted to varying input information. Following the precaution principle, scenarios must be related to those evolutions which may cause greater harm to people or structures, and must be based on the elements resulting from the most critical landslide sectors.

As for the warning systems, the presence of scenarios is mandatory for several elements:

- definitions of pre-alarm rainfall thresholds (if any)
- definition of displacement thresholds
- definitions of the most critical landslide sectors, in order to define which instruments, or which group of instruments, have to be used to define the thresholds
- precise definitions of the area over which the emergency procedure must apply.

5.2.2.2 Pre-alarm on rainfall thresholds

In most parts of Europe, the meteorological surveys are able to produce some kind of alarm codes based on the expected rainfall. These codes may be precious as pre-alarms for landslide warning systems, in order to concentrate the maximum attention to critical situations. This kind of pre-alarm may obviously be related only to those phenomena with a strong relation to rainfall.

5.2.2.3 Continuous measuring of displacements; data recording and processing

The system may be totally automated or totally human-operated, with several intermediate possibilities. In a totally automated system, an alarm signal is automatically emitted (by phone line, GSM/GPRS/UMTS, horn etc.) when one or more instruments exceed prefixed thresholds. In other cases part of the interpretation and signal transmission is made by operators. All systems, moreover, may be operated remotely. Nevertheless, in this note we do not deal with the delicate problem of threshold definitions.

5.2.2.4 Instruments, data recording and processing

Data recording from the measuring instruments has to be continuous. The instruments to be used for warning purposes are normally those recording some kind of displacement: in-situ inclinometers, extensometer and/or joint-meters. Use of geophysical devices, such as geophones, is less common.

Continuously recorded data must be analysed continuously. This analysis may be really continuous (24/7) or be limited to the periods of alert as defined by the foreseen meteo-conditions. Ordinary processing consists of data validation and comparison with predefined threshold values. Processing can be made by some kind of intelligent system or by competent personnel. In case of automated analysis, the warning signal is emitted when one or more instruments contemporaneously exceed the fixed thresholds or indicate sudden accelerations. In the latter case, the warning signal is manually emitted by the personnel. Note that, in this case, it is not strictly necessary to predetermine the threshold values.

When thresholds are exceeded or in any case of results indicating a critical evolution of the landslide, there should be two (desirable but not indispensable) checks:

- check of possible system malfunctions

- "geological" check, consisting in a survey of a geologist who knows the landslide, evaluating whether a proximal evolution is actually undergoing or the foreseen scenarios are valid.

The more complex the "civil protection machine" activated by the warning system is, the more necessary these checks become. They are also essential to prevent false alarms, but require for a fast intervention personnel near the site.

5.2.2.5 Civil protection

The automatic system or the personnel must alert the civil protection staff in charge for activating the security measures (evacuations, road blocks etc.). All these measures must already be carefully predefined on a purpose-made civil protection plan. The plan must be kept updated with any variation of the scenarios.

5.2.2.6 Communication procedures and protocols

Without entering in details, for each system is a case of its own, it is necessary to stress how the number of involved subjects and their different levels of responsibility may easily create major problems concerning communication procedures and protocols. The actors are many for each warning system and, moreover, they can often change.

Here is an example list of subjects (given the warning system is already installed):

- the client (commune, local authority, ...) who acts on the base of regional financing
- professionals (geologists and/or engineers) who are in charge of managing the system
- the company (or the companies) who is in charge of system maintenance
- someone who is in charge of receiving the warning signal and forward it to whom it is concerned
- civil protection authorities, who are in charge of civil protection measures.

5.2.3 Problems related to warning systems

5.2.3.1 General problems

- *Costs and sustainability of the systems:* Warning systems are usually installed after landslide activation, which often implies the opening of preferential financing channels and a generalized request for intervention by the local communities. Thereafter, when landslides remain quiescent for long time spans, after some years the enthusiasm which led to the installation of the warning system generally vanishes. The funding which is necessary to operate the systems is thus more and more difficult to obtain. Moreover, as time goes by and local politics change, the warning system may be perceived as nothing but a constraint. The simple existence of a warning system may induce, directly or indirectly, a reduction of the economic values of some facilities. Furthermore, a change in the local administration or in the local technical survey transfers the system to persons that did not live the former emergencies. The result is that the management of the system is perceived as a strongly demanding and useless task. Therefore, after a certain time, many warning systems cease to be operated, most in order to shift the financial means to solve problems apparently more immanent.

- *False alarms:* Repeated false alarms are normally not tolerated by both local administrations and the population. They usually end in the abandonment of the warning system. But false alarms are very difficult to avoid. On the base of an elementary precaution principle, also in order to avoid possible legal troubles, the responsible generally tends to adopt conservative thresholds. A way to reduce false alarms is to provide *human* manual checks between the alarm by the system and the emission of the warning signal to the civil protection. These manual checks are not always applicable and increase, anyway, the cost and the complexity of the system.
- *Theft and vandalism:* Cases of theft or vandalism concerning monitoring devices are not frequent. Especially if the devices are located in remote mountainous areas they are rarely subject to this kind of trouble. Otherwise, the problem is grave and real, for it is almost impossible to provide a total protection of the devices. Moreover, the presence of a warning system may be unwelcome to a part of the population which perceives it as useless, unmotivated and reductive of the economic values of some facilities. Risk communication with the inhabitants may help to reduce this threat. The indications of the purpose of the device together with an address of the responsible including a phone number may further reduce any aggression.
- *Management and legal implication:* Warning procedures require involvement, communications and, in particular, coordination of a multiplicity of subjects. These procedures are often difficult to put into practice, to update, and to keep operating over long periods. The existence of a procedure concerning a landslide warning system may imply a cascade arrangement of duties, some of which may fall over subjects that do not understand or that ignore their importance. Moreover, when some elements of the chain change, it may be very hard to maintain the entire procedure package. Professionals, technical officers of the public administrations, mayors etc. are often afraid of the possible legal implications of a warning system. This is mostly due to the fact that the limits related to landslide monitoring and warning systems are not clear to both the general public and those technicians without a deep knowledge and a personal experience of these systems.

5.2.3.2 Technical problems

- *Failures and vulnerability of the systems:* Even with optimal protection, on mountain slopes the devices are subject to a hostile environment for electronics. Thermal shocks and humidity may create problems but the electrical surges related to lightning are the actual system-busters. Several orders of electrical protection may reduce, but not eliminate, the problem.
- *Data transmission:* Data transmission among the various components of the systems can take place by wire, by GSM or by radio. Wire data transmission is often adopted for small systems or to connect sensors to data recorders or transmission units. Wires

are strongly vulnerable: rodents may cut any wire which is not strongly and properly protected and the presence of wires acts as an antenna which greatly increases the lightning-related vulnerability. GSM is widely used wherever the GSM signal is available. But, in alpine valleys GSM signals are transmitted by a limited number of repeaters. Hence, there is often no redundancy and the failure of a single repeater can shadow entire valleys. Such failures are common during storms or heavy rains so that GSM may be unavailable at the time it is most needed. As a general principle a warning system should not rely on *external*, non controllable elements. Data transmission by dedicated radio frequencies is possibly the best solution. The development of wireless systems (e.g. WLAN) or the use of satellites may improve the situation in the future.

- *Longevity and maintenance of the devices:* Warning systems should work over long time spans. One of the obstacles is the rapid evolution of electronic systems and their related software, causing a rapid obsolescence of the system components which thus need continuous modifications and updating. Even more than for other electronic systems the frequent need to replace damaged parts in the fieldcause problems. Maintenance of a warning system is difficult, complex, costly and demanding. Moreover, the laws and the rules governing the acquisition of goods and services in many public agencies may hamper a rapid solution to the many problems posed by the maintenance of a warning system.

5.2.4 Conclusions

Landslide warning systems can help to reduce the risk remarkably. In the case of an imminent event they can help to determine the date of a collapse. So they are an important part of the civil protection procedures. The clear definition of a protection plan as mentioned above is a prerequisite. For a long-term installation on a landslide instead, the problems related to such systems often preponderate the advantages. The systems are strongly promoted and are often very appealing to manufacturers of geotechnical instruments, professionals and sometimes also to local authorities. Good and useful as they may be, however, these systems may result difficult, complex, and troublesome to operate and maintain over long time spans, so that their use should be carefully evaluated and limited to some few critical cases only.

6. SLOPE MONITORING METHODS

6.1 Overview

Slope monitoring methods respectively measuring devices or sensors can be subdivided in four main categories: geodetic (→ 6.2), geotechnical (→ 6.3) and geophysical sensors (→ 6.4) as well as remote sensing (→ 6.5). Although sometimes the membership may be matter of opinion, all methods can be used for or even seamlessly combined in modern deformation monitoring.

- Geodetic measuring devices measure geo-referenced displacements or movements in one, two or three dimensions. It includes the use of instruments such as total stations and terrestrial laserscanners, levels and global navigation satellite system receivers.
- Geotechnical measuring devices measure non-georeferenced displacements or movements and related environmental effects or conditions. It includes the use of instruments such as extensometers, piezometers, tilt meters and accelerometers.
- Geophysical measuring devices measure soil parameters and conditions. It includes seismic surveys and electrical resistivity of soil.
- Remote Sensing devices measure geo-referenced displacements or movements without being in contact with the object. Remote Sensing often operates from aircraft or spacecraft platforms and uses electromagnetic waves emitted, reflected or diffracted by the sensed objects. It includes the use of instruments like radar, lidar and optical cameras.

6.2 Geodetic Surveying

Geodesy is the science of the measurement and the mapping of the earth's surface which includes the earth's external gravity field, as well as the surface of the ocean floor. Therefore geodesy may be included in the geosciences and also in the engineering sciences, since it involves geometry, mathematics, physics and general methodology.

Surveying – as a segment of geodesy – focuses on practical measurements and their evaluation as well as on the instruments used. In the case of slope monitoring the main target of geodetic surveying is the description of geometrical changes (e.g. point coordinates) of the site's surface topography by measuring a plurality of geometric elements (e. g. angles, distances or height differences). The following chapters describe the most typical geodetic solutions that are practicable for monitoring surface deformations. All introduced sensors can be combined and integrated into one overall solution.

Basically geodetic monitoring solutions can be described as a network (Fig. 11) for almost all methods. Geodetic networks consisting of (Welsch et al., 2000):

- A reference network with stable control points (e.g. pillars) and several witness points. The reference frame must be outside of the expected deformation area. To ensure the stability of this reference frame it is necessary to check, by a preliminary investigation, that the sites are really stable.

- Observation points where geodetic instruments are set up to take measurements to several stable or unstable points. Such a station does not need to be stable; observation points can be placed directly on the moving slope as well. Their coordinates must be determined each epoch prior to the survey of object points. Measurements done from one standing point to another point are absolute measurements.
- Object points that discretize the slope. Special targets can be set up over this kind of point and only measurements to (but not from) these points are made. Object points are linked by relative measurements. Current research aims monitoring objects also by prismless tacheometry or terrestrial laserscanning.

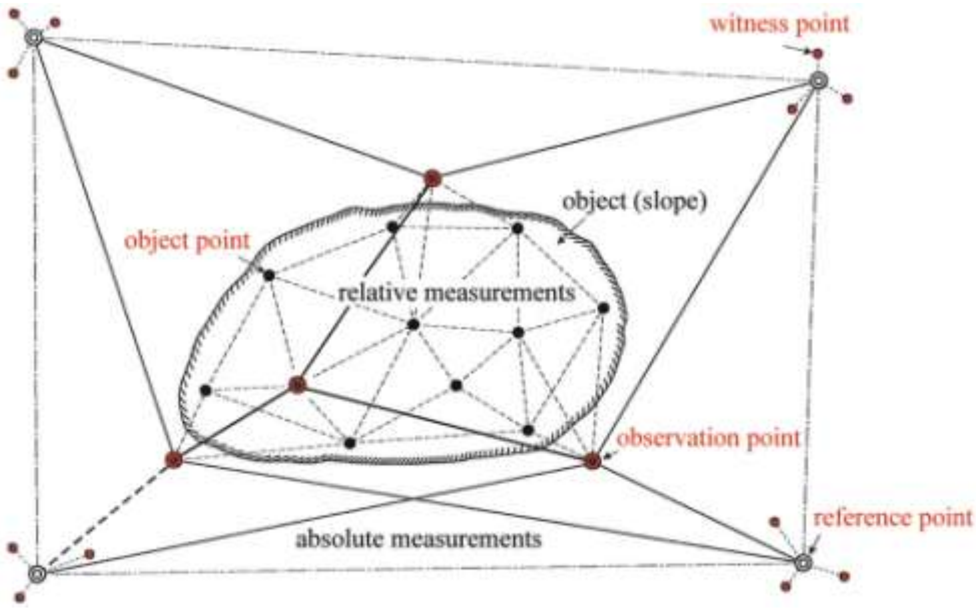


Fig. 11: Design of a geodetic monitoring network (on the basis of Welsch et al., 2000)

Such a network design allows measuring more elements than for a mathematical solution stringently necessary. The entire observations form an over-determined network. This redundancy can be used to verify the data by adjustment calculation. Besides the measurement technique adjustment theory plays a prominent role in geodesy. This part of mathematical statistics goes further than simply calculating results out of observations: by formulating a functional and a stochastic model, geodesists are able to regard their redundant measurements e. g. as a normal (Gaussian) distribution with a certain standard deviation. Thus results (e. g. point coordinates) can be estimated by minimizing errors occurred due to measuring noise or remaining small systematic errors. The major spin-off is information that is both correct and precise: adjusted coordinates are delivered with additional information (e. g. $h = 153.137$ m $\pm$ 2 mm; 1σ) where 1σ stands for a confidence interval of 68% ($2\sigma \cong 95\%$, $3\sigma \cong 95\%$). As a consequence this information is also essential for deformation analysis.

6.2.1 Tacheometry

Tacheometry is the combination of (horizontal and zenith) angle and (slope) distance measurements from a standing point to observation/target points (retro-reflectors). It allows the determination of a point's coordinate in three dimensions by transferring polar measurements into a cartesian coordinate system (Fig. 12). This technique can be used for monitoring surface deformations precisely on a slope.

For angular measurements, one can use theodolites with a sensitivity of up to 0.1" (= 0.03 mgon[14]) and a precision of nominal reading of up to 0.5" (= 0.15 mgon). For distance measurements, electro-optical distancemeters (EDM) based on infra-red light can be used. Distances (D) can be measured with an accuracy of nominal reading of up to $\sigma_D = \pm (1\text{ mm} + 1 \times 10^{-6} \cdot D)$.

This terrestrial technique has considerable advantages, especially related to the precision of measurements, their low cost and to a high potential of automation: 3D-point accuracies of about 5 mm to 2 cm are realistic. Under special conditions and with high effort, accuracy can be increased to 1 mm. There are however some limits:

- the distance between the fixed points and the reference points has a limit which varies according to the used instruments (1 to 10 km) and meteorological modelling (< 2 km).
- the problem of distance can become critical if, as it is often the case, an observation place does not exist at proximity of the slope. Generally, for large instabilities, the observation place is installed on the opposite slope of the landslide.
- required intervisibility (optical line-of-sight) between standing points and the reflectors
- the weather conditions finally can prevent the measurements and, for certain categories of instruments, can influence the precision.

Nowadays instruments typically integrate both sensors and lead to so called tacheometers. Modern tacheometers also provide automatic data recording and include features like servo-motorization and automatic target recognition. These instruments belong to the category of total stations (Fig. 13). Total stations are equipped with servodrives for circular motions around both the vertical and the horizontal axis and with an automatic aiming system.

Total stations were originally created to carry out surveys with only one operator. As they are able (if they are equipped with the necessary devices like prism reflectors, radio operator or different transmitters) to follow a moving target, these instruments can be used in the continuous assessment of unstable slopes.

By means of programming it is possible to use total stations as autonomously working monitoring stations: it is possible to teach the system to aim at a certain number of references and object points. The system is generally connected to a computer, which controls the engine (e.g. according to a preset sequence with arbitrary measurement intervals) and stores data or sends data to the office by internet or other communication structures. Either the apparatus or

[14] A milligon (mgon) is 1/1000 gon (resp. grad). The gon (resp. grad) is a unit of plane angle, equivalent to 1⁄400 of a full circle.

a processing engine in the office calculates the planimetric-altimetric coordinates of each point to follow its evolution in time. Since such a process can be realized in real time, it can not only be used as a monitoring system (→ 5.1) but also as a tool for early warning systems (→ 5.2). For this kind of monitoring various commercial software solutions are available, e.g. GeoMoS (Leica Geosystems) which combines geodetic and geotechnical sensors for temporary or permanent monitoring installations. MoSTUM as an alternative product by the Technische Universität München was mainly developed for monitoring historical ecclesiastical architecture (Foppe, 2006; Foppe et. al. 2006) but is also suitable for landslide monitoring applications.

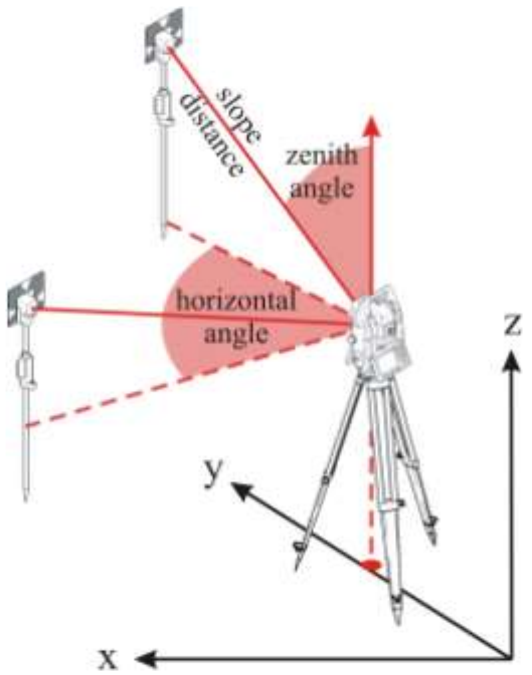


Fig. 12: Polar measuring elements to target points, cartesian coordinate system

Fig. 13: Tacheometric surveying (Foto: Landesamt für Umwelt)

6.2.2 Terrestrial Laserscanning

Terrestrial Laserscanning (TLS) or laser profiling is primarily a ranging method designed to measure the earth's surface topography. The basic idea of the operating method is simple: The laser source emits a short pulse of light, usually near-infrared radiation; at the same time, an electronic clock is started. The pulse propagates trough the atmosphere, bounces off the target's surface, propagates back and is detected by a photodiode. Detection of the pulse stops the clock so the two-way travel time to the surface can be determined. If the absolute position of the instrument is known the absolute position of the reflecting point on the target's surface can therefore also be determined by knowing the spatial direction of the laser beam. The object is scanned in both horizontal and vertical directions by deflecting the laser with rotational mirrors. Scan rates of several thousands points per second can be realized.

The output of this process is a highly detailed 3D image of the object, typically consisting of millions of densely spaced points, called "point cloud". For each point, 3D coordinates in the coordinate system fixed to the scanner and the amplitude of the reflected laser signal (intensity) are recorded. This method of operation is called Time-of-Flight (TOF) and entered the field of surveying in the late 1990's – early 2000's and provides several advantages in comparison with traditional geodetic surveying methods. For example, a total station surveys (→ 6.2.1) or Real-Time Kinematic (RTK) GPS measurements (→ 0) are not quite suitable for the collection of an enormous amount of 3D data within tight schedules since they only allow measuring discrete points, whereas in some cases one might only be interested in getting information about the whole object (a 3D model) immediately. Therefore, these methods are rather slow compared to TLS.

Fig. 14: Riegl LMS Z390

Fig. 15: Leica ScanStation

Most TOF scanners available on the market today can measure ranges to objects up to a few hundred metres (some models to over 2000 m), with the single-point accuracy of 0.6 to 15 mm in a distance of 50 m (Ingensand, 2006). As alpine terrain is in most cases large and of complex shape, a series of scans from different positions with different viewing angles is needed to capture the complete surface geometry. In order to provide a complete representation of the terrain surface, these scans should be accurately merged (registered to each other) and brought into the geodetic coordinate system (georeferenced). The latter is very important for the integration of the TLS data with other spatial data (e.g. GPS measurements). Afterwards, one can perform 3D modelling and visualization of the measured object to obtain a high-resolution 3D digital surface model, which can be exported into many geo information system (GIS) software packages and used for a variety of purposes. The main advantage of TLS over traditional surveying techniques is therefore its property of direct, rapid and detailed capture of object geometry in 3D. TLS provides a dramatic reduction in costs and a much faster project completion (especially compared to airborne laser scanning (→ 6.5.2). A further advantage of scanning is its completeness and comprehensiveness. Everything visible in the scene is captured at once, which allows the multipurpose use of the data, both currently and in the future (Reshetyuk, 2006).

Inaccessibility of the alpine terrain, as well as the acute danger of natural hazards explain why there is a fundamental need for investigating such locations from safe, remote places. Therefore TLS, under hazardous environmental conditions, where human intervention would be difficult or even impossible, is a helpful tool. In hazard assessment TLS is used as a helpful observation method to collect 3D data from changing landscape surfaces to obtain information about the current states of processes of natural hazards. Erosion and deposition zones of material can be determined by comparing the gained surface models with each other after registering those models together. The speed of slope parallel movements can only be measured in combination with colour information provided by additionally mounted and calibrated digital cameras. This hybrid sensor system is needed to determine prominent points on surfaces to recognize their motion speed in time.

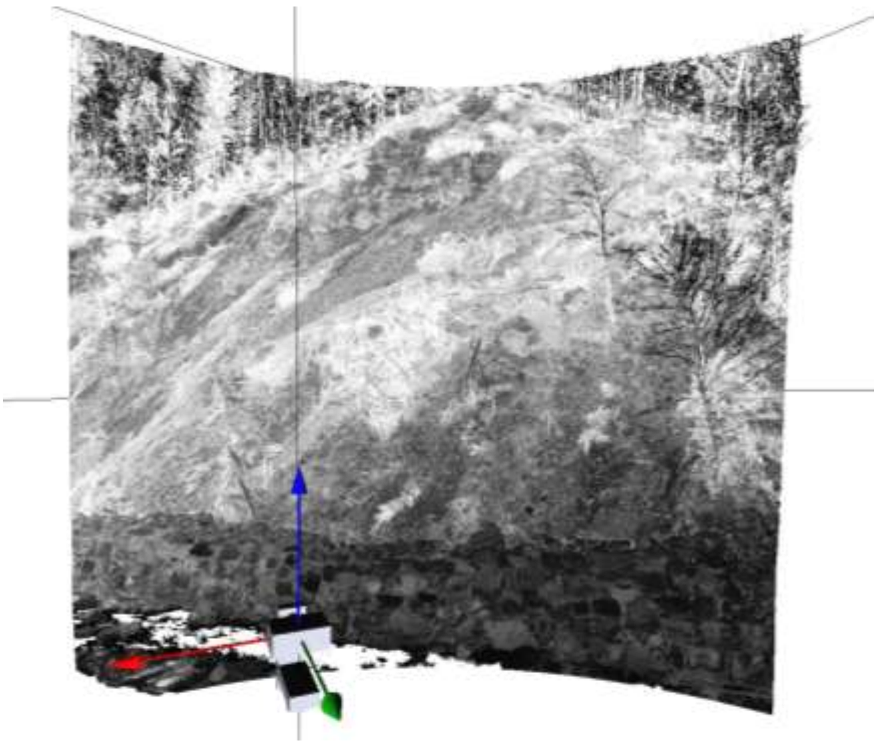


Fig. 16: 3D point cloud of a TLS measurement showing a slope (Prokop, 2007)

In recent years about several slope monitoring projects using terrestrial laser scanners have been carried out, for monitoring rock falls (Biasion, et al., 2005; Mikŏs, et al., 2005; Vojat, et al., 2006), rock glaciers (Bauer, et al., 2003), landslide bodies (Bitelli, et al., 2004; Hsiao, et al., 2003), as well as for snow pack observation (Prokop, 2007).

In fact, there are several commercial manufacturers which are producing different models of laser scanners. The actual device, which has to be chosen for a certain monitoring application, is defined by the technical features of the devices. Different range capabilities, beam diameters, scanning speed, target resolution properties and wavelengths define the achievable accuracies of results. In general, the accuracy of a TLS measurement decreases with increasing range to the target and with increasing angles of incident. The incident angle is defined as the angle between the axis of the laser beam and the normal vector of the target surface. In case of an incident angle of 0° the laser beam hits the ground perpendicular and the footprint is a circle. With increasing incident angles the illuminated area arises and turns into a prolate elliptic shape.

In future an improvement of the technical properties of the laser devices mentioned above will lead to a wider field of application of TLS and more reliable results.

6.2.3 Precise Levelling

Levelling is a very simple method to transfer height information (its basic principle was already used by the ancient Egyptians) between several measuring points or networks (e. g. referencing of tide gauges, connection to national levelling networks or to GPS reference points).

The method provides a means of accurately measuring height differences between points some tens of metres apart. Therefore a levelling instrument is set up on a tripod and levelled so that the line of sight is horizontal (Fig. 17). Modern levels will all use some form of automatic compensator, which allows the user to level the instrument with a circular bubble only – any small departures are compensated by the compensator. A graduated staff is held vertically over the first point and a backsight reading (b) is made of the intersection of the cross-hair with the image of the staff seen through a telescope. The same staff is then held vertically over the second point and a corresponding foresight reading (f) can be made. The difference between the two readings is the difference in height between the two points.

This process can be repeated - the level can be moved to beyond the second point and the height difference between the second and a third point measured by the same process. Further repetitions will allow the height difference between widely separated points (e. g. to realize a connection to geological stable areas) to be determined by accumulating the height differences between temporary, intermediate points (represented by metal ground plates or pegs/bolts).

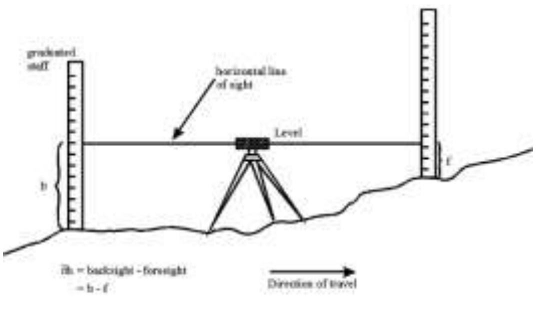


Fig. 17: Principle of levelling (Figure by G. Spencer)

Fig. 18: Staff reading (Figure by G. Spencer)

Nowadays digital levels are state of the art. This type of level uses a special bar-coded staff (Fig. 18). The image of the staff passes through the objective lens and then via a beam splitter to a photodetector array, where it is digitised. The microprocessor compares this image to a copy of the bar code and calculates the staff reading, which is displayed and/or stored. The sensitivity of the device is such that single reading accuracies of σ_h = 0.2 - 0.3 mm can be achieved.

Therefore levelling is particularly suitable for monitoring zones of subsidence or uplift areas, e. g. foundation settlements due to changes in groundwater level and any altitude changes of single points, profiles and cross sections. An accuracy of single point altitude displacements of σ_h = 0.2 - 3.0 mm/km can be achieved (first-order vertical networks typically accomplish the demand on accuracy of σ_h = 0.3 mm/km), but no information on horizontal displacements is provided. Vast settlement measurements cannot be automated and are usually done on demand (within temporarily measurement epochs). According to the swiss company Solexperts AG, automatic measuring systems, where motorized levels observe fix mounted bar-coded staffs, can however be used for local settlement measurements within a radius of up to 40 m (Meissl & Naterop, 1995).

There are a large number of potential sources of systematic and random errors in levelling (Kahmen & Faig, 1988). Many of these are only significant for over long distances (collimation error, error due to earth curvature, error due to refraction). Special measuring routines help to minimize these influences.

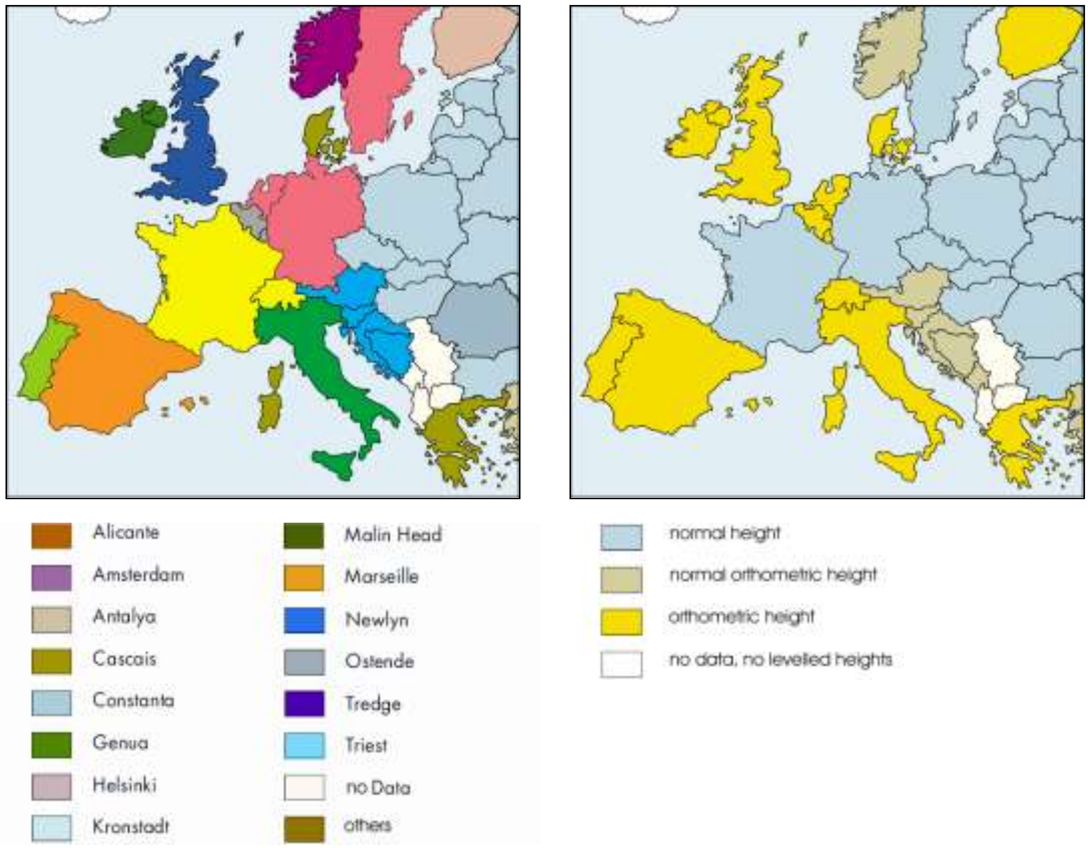


Fig. 19: Reference gauges and height types used across Europe (Source: LVA NRW)

Besides these instrumental and methodical errors, the geodetic background of height systems must not be neglected. On the one hand, several mean sea-level gauges are well-established across Europe (Fig. 19) and provide physically defined reference surfaces (vertical datums) with different zero points. On the other hand, different height types are used. Heights come in the following variants: normal heights, normal orthometric heights and orthometric heights (for detailed explanation see Torge, 2001). In all these cases, height considers the geopotential number (unit: m^2/s^2) and therefore in some way gravitational effects.

Consequently only these official (physical) heights give an exact information on "bottom and up" and are not related to ellipsoidal (geometrical) heights, which express the height of a point above a (mathematically defined) reference ellipsoid (e.g. gained by GPS (→ 0)). If neglected, both the reference gauges and height types lead to differences of several centimetres to decimetres and are possible sources of error in transferring height information across European borders (e. g. the Eurotunnel and bridges) or in combination with other monitoring methods. To unify European height systems, the European Vertical Reference Network (EUVN) was realized (Adam et al., 1999). The creation of EUVN was a milestone to an integrated reference system, in which spatial coordinates, the earth's gravity field and sea level observations are combined.

6.2.4 Global Positioning System

Besides the US American (military) GPS the Russian pendant GLONASS has been reactivated in the past and in the future the European System GALILEO will complement space-based Global Navigation Satellite System (GNSS). Nevertheless the focus in this section will be on GPS since it is the most common and functional GNSS at the moment.

Utilizing a constellation of at least 24 satellites (space segment with an orbit altitude of approx. 20.000 km) the system (control segment) enables a GPS receiver (user segment) to determine its location, speed and direction of movement. Basically the satellites transmit precise coded microwave signals that a GPS antenna is able to receive (Hofmann-Wellenhof, 2001):

- By measuring the time delay between the signal's emission and reception at the receiver, a code pseudorange[15] can be calculated by multiplying the delay time with the speed of light.
- Knowing such a pseudorange to at least four satellites (with known satellite coordinates at emission time) the position of the receiver can be estimated.
- All low cost GPS receivers use this method which enables a robust positioning with an accuracy of approximately 3 to 20 m which can be used of topographic surveys and tracing of trajectories of vehicles.

The main civil application of GPS is surely navigation, but in contrast to navigational purposes, sophisticated geodetic receivers are used if high accuracy is required[16]:

[15] The pseudorange is a first-approximation measurement for the distance between a navigation satellite and a navigation satellite receiver.
[16] Civil applications only. Precise Positioning Service enables authorised users (US Military) to decode a more precise signal effortless.

- Besides the code-based approach, geodetic receivers are able to measure the phase of the carrier wave. Phase measurements have a higher resolution than code measurements[17] and therefore offer higher accuracy as well.
- Using two different carrier waves/frequencies (L1 and L2) it is possible to produce several combinations. One is the so called "ionosphere-free phase combination" which eliminates most of the influence due to ionospheric refraction.

However, to achieve sub-centimetre accuracy one has to consider tropospheric effects as well. This only works with a long observation time, special receiver configurations and observation techniques as described in the following sections.

6.2.4.1 Static/Relative GPS (RGPS)

The troposphere causes a time delay of the GPS signal resulting in erroneous pseudoranges respectively in wrong coordinates. As tropospheric parameters change over time RGPS concentrates more on the inner accuracy of a GPS network than on its true location.

Imagine a small or medium scaled network of only two control points (< 20 km apart), one called "reference" and the other called "rover" station. On each site a GPS antenna and receiver is set up and for the whole region identical conditions (satellite availability, metrological conditions) shall prevail. In this case the (absolute) positional inaccuracy is about the same on both stations, but the distance in between will be rather constant over time (Fig. 20). In GPS terminology such a distance is called a "baseline". Observing several baselines for a long time span, the relative coordinates of the rover stations in relation to the reference station can be measured very precisely within centimetre to millimetre accuracy[18].

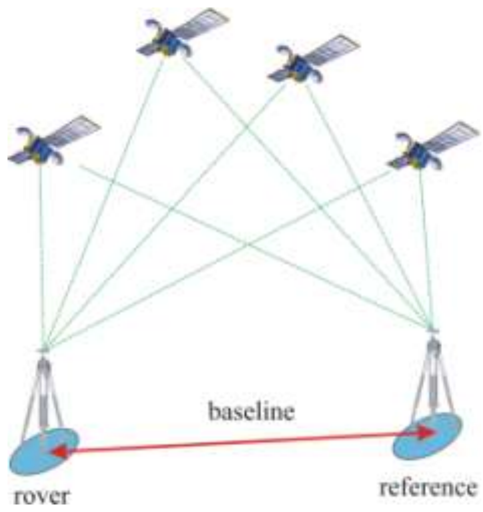


Fig. 20: Principle of RGPS

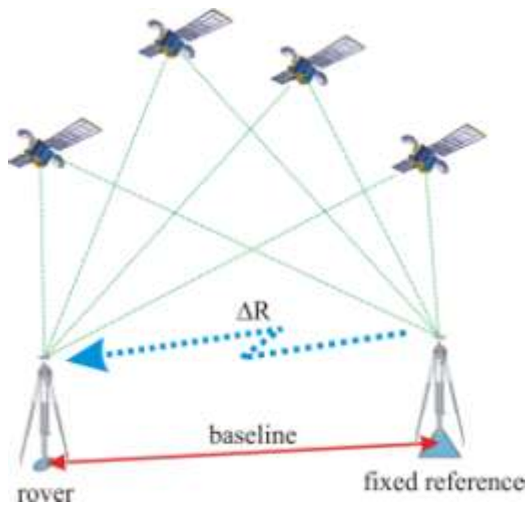


Fig. 21: Principle of DGPS

[17] GPS pseudo code has a cycle width (resp. one bit) of about one microsecond. Multiplied with the speed of light, such a bit has a length of 300 km. The cycle of the carrier waves are only ~ 20 cm (L_1: λ = 19.05 cm, L_2: λ = 24.45 cm).

[18] Depending on observation time, net configuration and data processing

This kind of measurement is evaluated in post-processing and is not suitable for real-time applications. Therefore the method is basically used for temporally separated measuring epochs followed by deformation analysis (→ 6.2).

6.2.4.2 Real Time Differential GPS (RT-DGPS)

A further enhancement to GPS is closely related to RGPS but is not only suitable for post-processing (rapid static and kinematic) but also for real-time (kinematic) applications, depending whether code or phase information can be evaluated. RT-DGPS uses one or even a network of reference stations. The reference stations are set up over known points (e.g. control points of a national reference frame) and their coordinates are fixed (Fig. 21). The reference stations calculate the differences between the measured pseudoranges and the actual (internally computed) pseudoranges. Simultaneously these stations broadcast the differences as a correction signal to the rover stations (by GSM, GPRS or UMTS) which now may correct their measured pseudoranges by the same amounts. In the case of post processing, the correction signal can be downloaded from a webserver and allows higher precision due to finalized satellite orbits that are available with a time delay of 14 days. The resulting baselines then are precise due to the relative measurement technique (→ 6.2.4.1) but also the absolute position of the measured points can be found in relation to the coordinate system in which the reference stations are given[19].

Table 2: Accuracy of DGPS according to SAPOS specifications

DGPS-Service	Accuracy (absolute)	Communication
Real-Time (HEPS)	Position: 1-2 cm Height: 2-5 cm	GSM, GPRS, UMTS
Post-Processing (GPPS)	Position: $\leq$ 1 cm Height: 1-2 cm	Internet (Webserver)

For ground-based RT-DGPS solutions one can use one's own reference station during a measuring campaign or consult a commercial service provider[20] who generally runs national GPS networks permanently. Such a service provider offers different categories of services for real-time (e.g. HEPS[21]) and post-processing (e.g. GPPS[22]) applications. Table 2 gives an overview of the achievable accuracies of SAPOS. Satellite-based augmentation systems such as WAAS[23] or EGNOS[24] transmit their corrections from orbiting satellites instead of ground-based transmitters. The transmission area covers large regions such as North Amer-

[19] A change of coordinate systems is possible with available ellipsoidal parameters and map projections.

[20] E.g. in Germany: SAPOS (Satellite Positioning Service of the German State Survey , http://www.sapos.de/) or ASCOS (DGPS-Service by E.ON Ruhrgas AG, http://ascos.eon-ruhrgas.com/)

[21] High Precision Real-Time Positioning Service by SAPOS

[22] Geodetic Post-Processing Positioning Service by SAPOS

[23] Wide Area Augmentation System. Operated by the U.S. Federal Aviation Administration

[24] European Geostationary Navigation Overlay Service. Operated by the European Space Agency (ESA), the European Union (EU) and the European Organisation for the Safety of Air Navigation (EuroControl)

ica (WAAS) or Europe (EGNOS) and was basically conceived for aviation users. The use of satellite-based augmentation systems is not yet common for geodetic surveying.

6.2.4.3 Observation Techniques

There are several observation techniques that can be used by GPS survey receivers. Both RGPS and DGPS are adequate for accurate landslide monitoring with centimetre accuracy in a static mode. But other strategies are possible if the requirements vary on each landslide, the surveyor should choose the appropriate technique for the application:

- *Static:* used for long lines, geodetic networks, tectonic plate studies etc. Offers high accuracy over long distances but is comparatively slow due to long observation time.
- *Rapid Static:* used for establishing local control networks, network densification etc. Offers high accuracy on baselines up to about 20 km and is much faster than the Static technique.
- *Kinematic:* used for detail surveys and measuring many points in quick succession.
- Real Time Kinematic (RTK): uses a radio data link to transmit satellite data from the reference to the rover. This enables coordinates to be calculated and displayed in real time, as the survey is being carried out. Used for similar applications as Kinematic.
- *Sensors fusion:* uses e.g. RTK-DGPS in combination with Inertial Navigation Systems (INS) to determine position and orientation of sensors (→ 6.5.2).

Table 3: GPS observation techniques and baseline accuracy[25] (Kahmen, 1997)

Observation Technique	**Position, Reference**	**Length of Baseline**	**Observa-tion Time**	**Accuracy (1σ) of Baseline** (height component: ×2)
Static	Relative	> 10 km 20 to 40 km	> 1 h > 6 to 24 h	2 to 5 mm + 0.01 to 1 ppm[26]
Rapid Static	Relative	< 5 km < 15 km	5 to 8 min 8 to 20 min	5 to 20 mm + 1 ppm
RT-DGPS (static/kinematic)	Absolute	< 10 km	3 to 5 sec	5 to 20 mm + 1 to 2 ppm

6.2.4.4 Data Processing

Measuring and collecting GPS data with adequate hardware is (in some circumstances) linked with high acquisition effort, but the task remains manageable. But to get good (accurate and reliable) results for baselines and coordinates, data processing demands one's attention far more. Software tools underlie slightly different processing concepts which can not be explained in detail, but there are two fundamental approaches for post-processing:

[25] Mode: phase observation of both carrier waves

[26] ppm = parts per million = 10^{-6} × length of baseline

- Standard software: Hardware producers usually develop their own processing software (e.g. Trimble Geomatics Office[27] or Leica Geo Office[28]) but also independat software development is procurable (e.g. WaSoft[29]). In order to minimize effort and sources of error, these tools must be regarded as "black box" systems. They deliver excellent results for small and medium networks but the user only has limited opportunity to interact. There are several parameters that can be changed, but finally many parameters are set as default. For example, the error due to tropospheric delay is taken into account by using several standard models of the troposphere.
- Scientific software: (like Bernese GPS Software[30]) not only allows changing more parameters but also includes different modelling possibilities (media propagation in troposphere and ionosphere, phase centre variation, polarisation, cycle ambiguity). For example, the error due to tropospheric delay can be estimated for each station. That means that the actual meteorological conditions are calculated instead of using a standard model. Such software is essential for high precision GPS networks, especially when long baselines (> 20 to 30 km) have to be processed. Unfortunately these software solutions are only operable for highly experienced personal.

Special Software is needed if data has to be processed in real-time (fully automated). They are often included in the mentioned software but are based on a more complex processing engine. Other research developments (e.g. GOCA[31]) use existing processing engines and augment their software with the possibility of sensor fusion and hybrid deformation analysis (Jäger et al., 2006).

Table 4: Advantages & Disadvantages of GPS

Why use GPS?	Limitations
• Intervisibility between points is not required (no optical line-of-sight) • Can be used at any time of the day or night and in any weather. • Produces results with high geodetic accuracy. • More work can be accomplished in less time with fewer people.	• The GPS antenna must have a clear view to at least 4 common satellites. • Satellite signals can be blocked by trees and is difficult to use in woodland. • Accuracy of height component is 2 times lower than positional accuracy • Energy supply needed on every station • Due to this limitation, it may prove more cost effective in some survey applications to use an optical total station.

[27] Trimble Navigation Ltd., http://www.trimble.com/geomaticsoffice.shtml
[28] Leica Geosystems AG, http://www.leica-geosystems.com/corporate/de/products/software/lgs_4611.htm
[29] Wanninger Software, http://www.wasoft.de
[30] Bernese GPS Software, http://www.bernese.unibe.ch/
[31] GNSS/LPS/LS-based Online Control and Alarm System (Hochschule Karlsruhe - University of Applied Sciences, http://www.goca.info/)

6.2.4.5 Applications to Landslide Monitoring

Fig. 22: GPS reference station in the Alps (Foto: Wunderlich, TU München)

Landslide monitoring by means of GPS system developed rapidly in the past few years. GPS measuring has proved to be an effective and reliable tool especially for measuring surface deformations on large and slow-moving landslides (see Table 4). Brunner et al. (2007) describes a long perience of monitoring a deep seated mass movement in Gradenbach (Austria) with RGPS. The authors name motion cies (1σ) of ±4 mm in horizontal direction and ±8 mm in vertical direction during the last seven years[32]. The application for small and/or fast moving landslides is not so widespread up to now. Each GPS ing system consists of a number of benchmarks on the landslides. Their positions are measured vs. the positions of some reference benchmarks located off-slide. The ideal number of reference points should be four, geometrically disposed around the slide, but the usual number is two or three. Since locating off-slide reference points is no easy matter, the presence of permanent GPS stations (within 7 to 10 km from the landslide to me monitored) can greatly help. It is very important to introduce redundancy into the network that is being measured. This involves measuring points at least twice during one epoch and creates safety checks against problems that would otherwise remain undetected.

The measurements are usually of manual type with removable GPS stations (measuring epochs). Currently, the costs for a realization of an automatic GPS network are still high. They are however justified to ensure the monitoring of phenomena which generate risk for the population, when measurements cannot be done easily with others techniques. Monitoring with low-cost GPS receivers is currently object of research.

[32] Including 17 GPS surveying campaigns with at least 48 hours of observation; choke-ring antenna with a radome protection to avoid/reduce multipath effects, post-processing software Bernese 5.0.

6.3 Geotechnical Monitoring of Deformations

6.3.1 Crack Monitoring

6.3.1.1 Basic Principle

Surface cracking can be one of the first indicators of landslide deformation. The development and displacement of cracks commonly reflects the behaviour of the landslide at depth, particularly in the upper half to two thirds of a landslide area (Keaton and DeGraff, 1996). Careful measurement of fracturing can therefore provide important information on the mechanics and activity of a landslide.

6.3.1.2 Measured Parameters

The parameters relevant to a particular crack development depend on the material and mechanism of fracturing. Commonly recorded parameters include propagation, extension, vertical offset, shear, and rotation. Propagation of a crack is often the most visible sign of ongoing fracture development. However, as it provides very little information on the nature of the ongoing instability, measurement is typically limited to identification and visual observation. Relative displacement provides the most information on the nature of the deformation; this may be quantified by installing fixed reference points on either side of the crack and measuring the leg lengths.

6.3.1.3 Installation Considerations

The susceptibility of reference pins to disturbance by processes other than landslide activity is often the greatest difficulty in crack monitoring. Examples of such processes include:

- accidental damage by construction equipment, animals, and people,
- vandalism,
- surface creep,
- thermal contraction and expansion of the rockmass and
- extreme weather such as frost heave.

Factors such as vegetation growth and topography should also be considered to ensure good access to the pins, easy relocation, and accurate measurement. Pins are typically set at 1-3 m apart but may extend to 20 m across a single discontinuity or series of discontinuities (International Society for Rock Mechanics, 1984).

6.3.1.4 Measurement Interval / Frequency

Frequency of measurement is largely dependant on factors such as the activity and assumed failure style of the landslide. While indicators such as debris and surface morphology provide an indication of these important factors, initial readings need to be taken with a frequency to enable the establishment of trends, and quantify the degree of movement. Long term monitoring of slow movement may require monthly or quarterly measurements, while fast moving slides may require several readings per day (Cornforth, 2005).

6.3.1.5 Typical Methodology

6.3.1.5.1 Crack Propagation

a) Glass Plates or Plaster Patches

For accurate measurement of crack propagation on hard rock slopes a thin glass plate or gypsum plaster patch may be cemented across discontinuities or the tip of propagating fractures to observe breakage. Glass plates should be approximately 80 × 20 × 2 mm³, and installed on the clean rock surface using an epoxy resin. Measurements of the extension, length, and direction of propagation of fracturing in the material may be taken with a ruler or calliper. Details of the procedure are described by the International Society for Rock Mechanics (1984), and Dunnicliff and Green (1993).

b) Crack Tip Record

Where only moderate accuracy is required, paint or broad tipped pens may be used to mark the terminus of the propagating crack, different colours or symbols may be used for consecutive readings and the distance between successive marks can be measured. This is most effective on paved surfaces or bedrock exposures, though is also useful on soil slopes with rapidly developing failures (Keaton and DeGraff, 1996). Environmental effects will lead to deterioration of the marks, and they should be regularly checked.

6.3.1.5.2 Crack Displacement

Displacement can be measured using strain meters. These typically span in the order of 1m or less and have a high accuracy, generally limited by the sensitivity of the instrument (Keaton and DeGraff, 1996). There's a wide range of equipment available for measuring crack displacements, below is an overview of the most common:

a) Survey mark

The simplest form of strain meter simply consists of pins installed on either side of the discontinuity; a steel tape can be used to monitor the separation. The selection of pins and their installation should be appropriate to the ground conditions; it is important that they are rigidly affixed to the surface and will not move or loosen with time or repeated measurement. When the surface is strong rock or concrete unaffected by local cracking, pins may be approximately 2 cm long, 5 mm dia with a tapered point at one end and a welded base at the other. Epoxy resin can be used to fix the base to the surface, or a concrete rivet gun may be used to embed pins. For soils or soft rocks, larger pins up to 50 cm in length and 1.5 cm diameter can be driven into the surface to gain a good seating. A special sleeve type anvil may be required to drive them into the ground without damaging the measuring heads (Keaton and DeGraff, 1996). Alternatively, pins may be grouted into a drilled hole. The pins should have pointed tips or filed cross-lines on the head to allow accurate re-measurement (International Society for Rock Mechanics, 1984).

b) Quadrilateral survey

Quadrilaterals provide a simple method of determining extension, shear, and tilt across a discontinuity. They consist of an approximately square array of benchmarks that lie in a plane (Baum Rex et al., 1988), and installation is similar to that for survey marks (described previously). They may straddle a discontinuity, be installed on the lateral flank of a landslide, or in areas of differential surface displacement. An example of a quadrilateral is provided in Fig. 23.

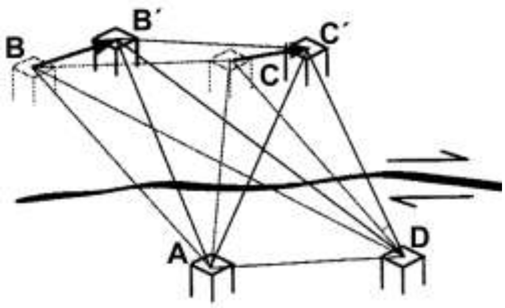


Fig. 23: Quadrilateral survey network (Keaton & DeGaff, 1996)

Measurement involves determining the relative elevation of the four marks, the 6 distances between the marks, and the azimuth of a pair on one side of the discontinuity. The relative motion of three marks with respect to the fourth can then be determined by solving three point problems for triangles defined by the network. A detailed description of the method can be found in Baum et al. (1988).

The accuracy of deformation measurement is limited by errors and inconsistencies in the measurement process (commonly resulting from a change of staff). Tape and hand level measurements will not resolve small movements. Measurement of movement in the order of 1mm or less requires stable benchmarks and precision length measurement, commonly with a mechanical gauge.

c) Tensioned wire

A tensioned wire extending between pins installed on either side of a discontinuity can provide a continuous measure of strain. The wire should be attached to an anchor on one side of a discontinuity and mounted across a pulley on a measuring station on the other (Fig. 24). Tension is maintained by a weight suspended from the wire beneath the measuring station pulley, and extension can be measured from a fixed point attached to the wire where it passes a graduated scale on the measuring station. The primary benefit of this method is that the continuous measure of extension allows a simple alarm system to be installed. A trip block fixed to the wire can be set to trigger an electronic switch at a pre-

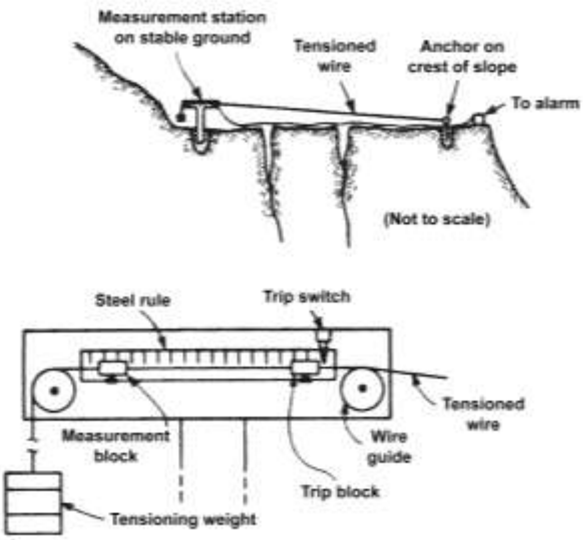


Fig. 24: Tensioned wire strain meter (Dunncliff & Green, 1993)

determined displacement; this may be attached to a visual or audio alarm system. The precision of tensioned wire crack meters is limited to approximately ±3mm (Dunnicliff and Green, 1993). Significant errors may be associated with stretch or expansion of the wire, wind or precipitation, or variation in gauge readings.

d) Portable mechanical

Portable mechanical strain meters are particularly useful on sites with easy access where small movements are expected (in the order of millimetres). The design of meters varies markedly; however, in general they consist of fixed length metal bars which are slid past each other to enable the gauge to be positioned on reference pins installed on either side of a discontinuity (Fig. 25). Very accurate measurements of strain can be made using callipers, or a gauge affixed to the strain meter. While some strain meters may allow large adjustments using a calibration jig, typically measurement pins should have a fixed separation specified by the meter range and a setting tool is required to accurately position the holes.

Precise reproducibility of measurement is critical when assessing such small strains, accurate positioning on the reference pins is therefore essential. A common method is to form a ball and socket connection with hemispherical depressions machined into the head of the monitoring pins and matching spherical connections on the strain meter (International Society for Rock Mechanics, 1984; Willenberg, 2004). Mechanical strain meters typically have measurement repeatability in the order of ± 0.1 mm (Willenberg, 2004).

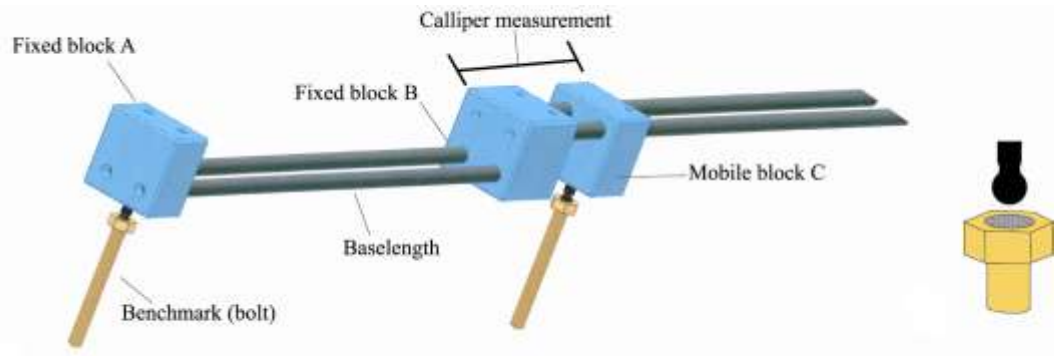


Fig. 25: Portable mechanical strain meter (Willenberg, 2004)

e) Electrical

Electrical strain meters are primarily used on sites with poor access, or where a continuous record of strain is required. The strain meter is installed permanently across a discontinuity, commonly with ball joints that are grouted into the substrate on either side (Fig. 26). While there are a number of electrical methods available to continuously measure strain, two of the most common include vibrating wire transducers or resistance strain gauge transducers.

The strain meters are designed by manufacturers to accurately measure displacement over specific ranges. Most manufacturers offer a series of instruments that measure ranges of between 3 mm and 150 mm. The resolution reduces with increasing range, but is generally between ±0.001 mm and ±0.13 mm (±0.1% of the full measurement scale (FS)). For examples see Geokon Incorporated (2007), RST Instruments Ltd (2007) and Slope Indicator (2006).

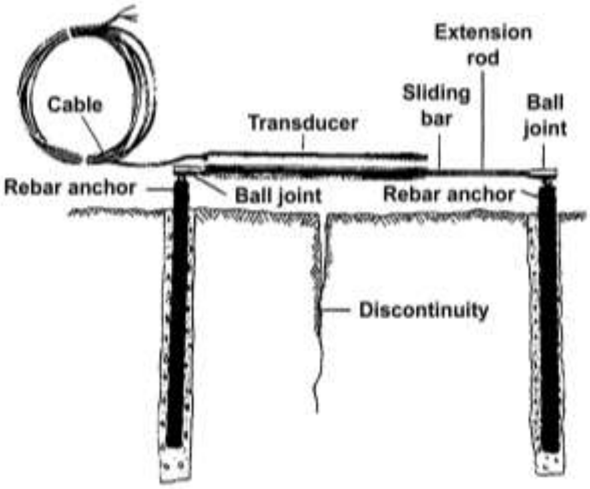


Fig. 26: Electrical strain meter (International Society for Rock Mechanics,1984)

Vibrating wire instruments have two principal advantages over other electrical measurement devices in the field:

- The instrument output is a frequency signal rather than a resistance or voltage. Frequency signals are very stable in transmission, and errors associated with signal cable resistance, contact resistance, leakage to ground, and the length of signal cable may be ignored (Dunnicliff and Green, 1993).
- There is a wide range of vibrating wire instrumentation available for field applications. Selection of instruments with the same output signal allows a multi channel datalogger to be used, and can reduce complexity and cost in installations where several parameters are to be measured.

Sources of error associated with particular electrical measurement techniques should be considered prior to undertaking an installation; some examples include (Dunnicliff and Green, 1993):

- corrosion
- temperature variation (including diurnal and seasonal)
- lead wire effects (resistance)
- moisture and electrical connection (resistance)

- ground vibration (vibrating wire)
- zero drift (vibrating wire)

6.3.2 Tiltmeters

6.3.2.1 Basic Principle

Subsurface movement in rotational or toppling slope failures is commonly reflected in the increasing inclination of features on the ground surface. Measuring the changing surface inclinations with a tiltmeter can provide valuable data on the mechanics and activity of the instability. They are particularly applicable in situations where discrete features such as readily observable surficial cracking are not present. These are usually a more reliable and representative indicator of movement and monitoring is discussed in the previous section. Areas where tiltmeter monitoring may be particularly useful include:

- developing failures where discrete surface features may be diffuse or not yet present,
- in the toe region of landslides where incipient bulging may take place, or,
- in areas where ground cover or topography limits observation.

6.3.2.2 Measured Parameters

Tiltmeters very accurately measure inclination relative to gravity, either at a discrete point or along a baseline. Units of measurement vary, but are typically expressed as arc-seconds – 1/3600 of a degree. Other units of measurement are also used, these are listed in the below table:

Table 5: Conversion of angular dimensions

Convert from	to	multiply by
Arc-second	Degrees	1/3600
Micro Radian	Degrees	$180 \times 10^{-6}/\pi$
Percentage	Degrees = arctan(percent slope/100) 1% = 0.57°, 5% = 2.8°, 10% = 5.7°, 15% = 8.5°	
Gon	to degrees	360/400

6.3.2.3 Installation Considerations

Tiltmeters provide a secondary measurement of ground deformation by very precisely measuring minor variations in ground tilt in response to subsurface displacement. The requirement for sensitive and precise measurement means correct installation and recognition of possible tilt “noise” sources is important. These may include:

- thermo-elastic strain induced by daily or seasonal heating of topography,

- water table changes,
- surficial creep or
- contrasting atmospheric conditions (for long baseline horizontal tiltmeters).

These effects may be reduced by minimizing climatic variations and deep referencing sensors, preferably to depths of 15 m or more to negate thermo-elastic effects.

6.3.2.4 Measurement Interval/Frequency

Frequency of measurement is largely dependant on factors such as the activity and assumed failure style of the slope. While indicators such as debris and surface morphology provide an indication of these important factors, initial readings need to be taken with a frequency to enable the establishment of trends, and quantify the degree of movement.

Long term monitoring of slow movement may require monthly or quarterly measurements, while toppling or rapidly deforming slopes may require constant readings.

6.3.2.5 Typical Methodology

6.3.2.5.1 Horizontal Tiltmeters

Horizontal tiltmeters are used to measure tilt by comparing fluid pressure or levels in hydraulically communicative standpipes at two locations separated along a fixed baseline (Fig. 27). The devices are particularly versatile as they may be manufactured on site using readily available low cost materials. They can achieve relatively high accuracy (a few millimetres) in areas where surficial material is unstable by considering tilt over long distances (Cornforth, 2005).

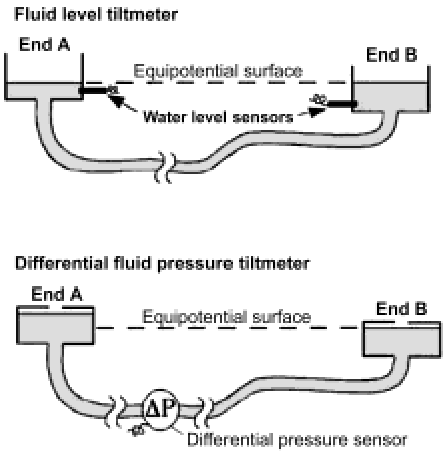


Fig. 27: Horizontal tiltmeters (Cornforth, 2005)

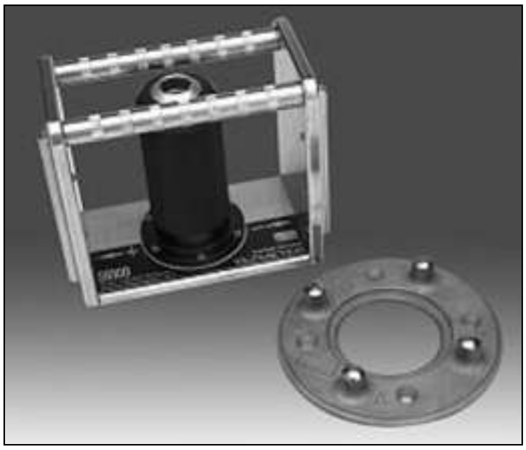


Fig. 28: Portable tiltmeter (Slope Indicator, 2004)

6.3.2.5.2 *Vertical Tiltmeters*

Tilt at discrete locations is best measured with vertical tiltmeters (Fig. 28). These operate with either a bubble or pendulum mechanism and may be mobile or fixed in place, the latter allowing automated or remote measurement.

Bubble tiltmeters electronically measure the position of a 5 mm (diameter) bubble in a curved glass tube. The sensors can be uniaxial or biaxial, have a full scale range up to -± 30° and an accuracy of. ± 0.1% F.S. These are generally robust and reliable instruments as they have no moving parts; however they can be sensitive to temperature fluctuations.

Pendulum tiltmeters can either measure the deviation of a pendulum from vertical, or the force required to hold the pendulum in place (i.e. force-balance accelerometers). These have a similar range and accuracy as bubble tiltmeters.

6.3.3 Extensometers

Crack monitoring may not provide an accurate indication of displacement in areas of extensive cracking, plastic surface deformation, or areas of developing (or retrogressing) instability. Extensometers are used to measure strain over distances greater than 1 m (Mikkelsen, 1996), and measurement distances are commonly in the order of tens of meters (i.e. Okamoto et al., 2004; Reid et al., 2003).

While installation and operation is similar to that of crack displacement monitors (described in → 6.3.1), the increased monitoring range and site exposure results in lower sensitivities. Geodetic methods are also suitable for measuring the distance and scale of slope movement monitored by extensometers. However, these either require site visits to undertake re-surveys at discrete intervals, or expensive in situ monitoring equipment. The ability to use simple mechanical or electrical extensometers to continuously monitor slope displacement has lead to these becoming one of the most commonly employed tools for the development of landslide early warning systems (i.e. Fujisawa et al., 2007; Okamoto et al., 2004; Reid et al., 2003).

6.3.4 Borehole Inclinometers

6.3.4.1 Basic Principle

Slope instability creates differential subsurface movement. Quantifying this movement can provide important details regarding the depth, rate of movement, and internal kinematics of the instability. Inclinometers provide a measurement of time dependant differential subsurface displacement in a near vertical borehole. They have been described as "... probably the most valuable tool available to a landslide analyst" (Cornforth, 2005).

6.3.4.1.1 *Borehole Probe Pipe*

A basic inclinometer is one of the simplest subsurface devices. Known officially as a borehole probe pipe, or occasionally as a "poor boy" or "slip indicator", this typically consists of a thin (25 mm) plastic pipe installed in a vertical borehole in the slope. A series of metal bars of varying length are lowered down the pipe and the rod length that is just unable to pass a given depth provides an indication of the curvature of the pipe at that point. If there is complex internal deformation within the moving slope, or a thick shear plane then a metal rod attached to a wire can remain at the bottom of the pipe and be raised to determine the base of the shear zone (Dunnicliff and Green, 1993; Mikkelsen, 1996).

Curvature is given by the relationship:

$$R = \frac{L^2}{8(D_1 - D_2)}$$

Where:

R	=	radius of curvature of tubing or pipe
D_1	=	inside diameter of tubing or pipe
D_2	=	outside diameter of rod
L	=	length of rod

(Dunnicliff and Green, 1993)

6.3.4.1.2 *Standard Inclinometer*

A standard inclinometer is comprised of a guide casing installed in a near vertical bore-hole, a portable probe, a portable readout unit with power supply, and a graduated signal cable to link the probe to the readout unit (Fig. 29).

The guide casing is typically a plastic or aluminium tube with an approximate outer diameter of 85, 70, or 50mm (Slope Indicator, 2006) with two sets of grooves oriented so that the inclinometer can be drawn through the pipe measuring either of two planes oriented 90° to each other. The probe has wheels that track along the diametrically opposite grooves, and an accelerometer (commonly force balance or vibrating wire type) is used to measure the inclination of the instrument at discrete depths.

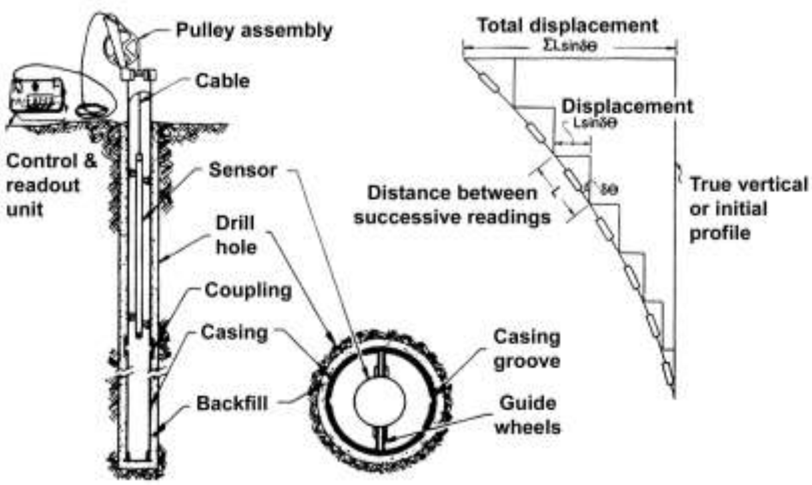


Fig. 29: Standard inclinometer arrangement (Mikkelsen, 1996)

6.3.4.1.3 *In-Place Inclinometer*

Where continuous monitoring or greater sensitivity is required, inclinometers can be installed semi-permanently in a standard guide casing. This is a more expensive option than standard inclinometer measurements as a number of probes are required for each borehole, and in addition an automated data logger is needed to record the data.

6.3.4.2 Installation Considerations

The accuracy of inclinometer measurements is usually limited by the quality of guide tube installation and repeatability of measurement. The casings should be seated in bedrock well beneath the shear zone of the landslide to provide a stable reference point to compare readings. Mikkelsen (1996) and Cornforth (2005) recommend extending boreholes at the time of drilling if there is any doubt regarding the stability of the strata, for example installations of +200m are not unheard of. Alternatively, the position of the guide tube can be surveyed relative to a stable benchmark (Mikkelsen, 1996), however this increases error and the remeasurement time.

Careful positioning and backfilling of the guide tube is important to reduce scatter in readings and ensure deformation of the tube accurately represents slope movements. Sand, pea gravel, or bentonite/grout mixes can be used as backfill material, the selection of which depends on factors such as (Mikkelsen, 1996):

- substrate strength,
- permeability and voids,
- borehole stability (i.e. collapsing without mud),
- groundwater conditions, and
- the drilling technique used.

The 3D trajectory and rotation of inclinometer tubes installed in deeper boreholes (>50m) should be carefully recorded after installation.

Inclinometers can become inoperable if internal shearing is greater than the difference between the probe and borehole diameters.

6.3.4.3 Data Reduction

The interpretation of inclinometer data is subject to the identification and elimination of numerous random or systematic error sources (Cornforth, 2005; Mikkelsen, 1996; Mikkelsen, 2003; Moormann, 2003; Willenberg et al., 2003).

Random errors can stem from sensor noise (ie. the precision of the probe) and other environmental factors (Dunnicliff and Green, 1993). Moormann (2003) and Mikkelsen (2003) estimate the standard deviation of random error in vertical boreholes to be between 0.1mm and 0.16mm/measurement interval. When undertaking cumulative displacement measurements the estimated random error e_r may be defined as:

$$e_r = 0.16mm\sqrt{n}$$

Where n is the number of measurement intervals (Willenberg, 2004).

Systematic errors are compounded at each interval measurement, and are therefore usually greater than random errors for the same survey. These mostly relate to the inclination and curvature of the inclinometer casing, Mikkelsen (2003) suggests the four main systematic error sources are:

- depth-positioning error (casing settlement and depth measurement error)
- rotation error (shift or rotation of the accelerometer sensor axis)
- bias shift (calibration error, easily eliminated)
- sensitivity shift (change in amplification of probe signals, rarely significant)

Mikkelsen (2003) suggests systematic errors may be as large as 0.11 mm per measurement interval. Careful data analysis is required to reduce the systematic error if very small deformations are to be observed, such as across discontinuous zones in progressively failing crystalline rock (Willenberg et al., 2003).

6.3.5 Borehole Extensometers

6.3.5.1 Basic Principle

Slope instability creates differential subsurface movement. Quantifying this movement can provide important details regarding the depth, rate of movement, and internal kinematics of the instability. Extensometers installed in boreholes can provide information that, when combined with other monitoring data, allow a more accurate quantification of this movement (i.e. 3D displacement when combined with inclinometers as described in Willenberg et al. (2003)).

Borehole extensometers measure extension parallel to the borehole axis by means of permanently installed rods or wires, or with a probe capable of measuring fixed points within the borehole. Due to several significant uncertainties associated with installing and observing extension parallel to the borehole axis (e.g. the orientation, depth, and number of deformations in the borehole), it is difficult to derive slope activity based solely on borehole extensometer readings.

6.3.5.2 Installation Considerations

Borehole extensometers may either be permanently installed fixtures in the slope, or probes used to measure known reference points installed within the slope. They most accurately reflect displacements when the borehole is drilled parallel to the failure direction.

Fixed extensometers generally require rods or wires to be permanently installed in the borehole. These enable continuous automated monitoring of extension, and alarm systems to be installed; however fixed installations prevent the combination of additional monitoring equipment in the borehole. Probe-type monitoring systems require periodic site visits by technicians to undertake measurements, but the less obtrusive permanently installed components provide the opportunity to undertake additional monitoring in the borehole, potentially providing a much more accurate interpretation of subsurface displacements. The main installation options are discussed further below:

Fixed rod and wire extensometers can be used to monitor the change of distance between two or more points in a borehole.

- Rod extensometers are installed with one end of a steel, alloy, fibreglass, or invar rod anchored in natural ground in the borehole. The position of the outer end of the rod can be monitored relative to a fixed collar on the slope face. Rod extensometers are usually simpler instruments than wire types and are more easily installed; they are often the preferred method for measurement intervals of up to 45m (Slope Indicator, 2006).
- Wire extensometers operate by a similar principal to the rod extensometers, but use a single strand stainless steel wire (0.5-1.3mm in diameter) to determine displacement. Wire tension may be maintained with a spring, or more preferably, a weight suspended from the wire outside the borehole. Both rod and wire extensometers are sensitive to temperature fluctuations and shear within the borehole, however, wire extensometers are the only devices that may continue to be operated once shear on a discrete plane exceeds the borehole width.

Probe extensometers require reference markers to be installed in a cased borehole (Fig. 30). The markers may be physical stops within the casing (ie. a sliding micrometer (Dunnicliff & Green, 1993; Kovari & Amstad, 1982)), or steel or magnetic rings installed outside the casing. Measurement is undertaken by lowering a probe down the hole and measuring either the incremental or total change in marker spacing. Aside from leaving the casing free to accommodate other sensors, this installation often also has the advantage of allowing measurement to be undertaken over any number of set intervals. Accuracy is typically 3 to 5 mm, though the Slope Indicator Increx system offers similar accuracies as mechanical methods (± 0.01 mm per metre) (Slope Indicator, 2006) (Dunnicliff & Green, 1993; Mikkelsen, 1996).

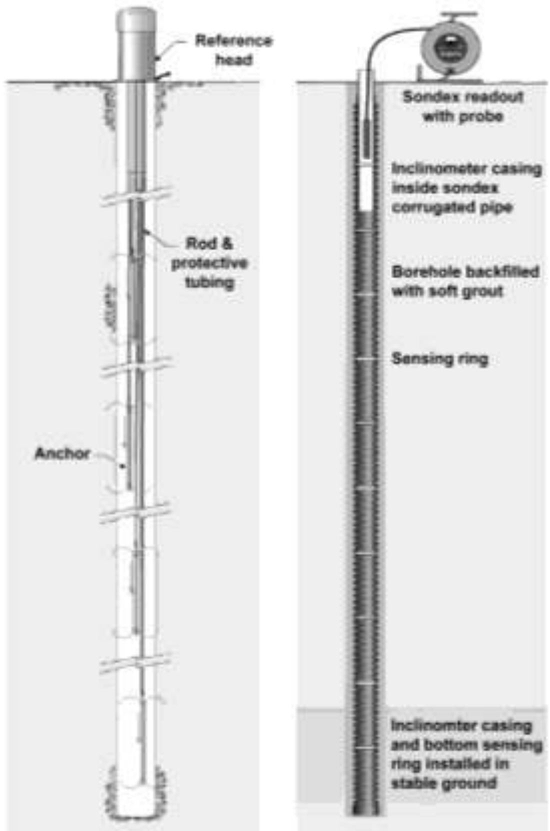


Fig. 30: Examples of multi level rod and probe extensometers (Slope Indicator, 2006)

6.3.6 Piezometers

6.3.6.1 Basic Principle

Slope instabilities can be very sensitive to changes in groundwater re-gime, rapid water table drawdown can increase shear stresses in low permeability slopes, and high water pressures associated with precipitation events or inundation of the toe can reduce effective strength of saturated slope materials and trigger landslides (Wieczorek, 1996). Monitoring of groundwater conditions within a landslide can therefore provide important quantitative infor-mation on the stability state of the slope, and unlike most other factors monitored on landslides, can be coupled with environmental information to predict failures prior to displacement taking place (Corominas et al., 2005).

Piezometers are instruments installed in the ground to measure water pressures. Dunnicliff (1993) describes some of the many types of piezometers available for geotechnical monitoring. However, three types are commonly used for landslide monitoring applications; standpipe, pneumatic, and electric (Cornforth, 2005; Mikkelsen, 1996). These piezometers vary in the way they sense pressure variation, and as for most monitoring techniques, proper installation is vital to achieve meaningful results.

6.3.6.2 Measured Parameters

6.3.6.2.1 Standpipe

Open standpipes are the simplest and most common means of measuring groundwater pressure. The Cassagrande type standpipe has proven to be the most successful (Fig. 31). It consists of a thin plastic tube with a porous tip installed in a borehole so that the tip is hydraulically communicative with the surrounding soil or fractured rock. A sand filter is usually used to ensure communication, and should be approximately 1m thick to ensure suitable response times (Mikkelsen, 1996).

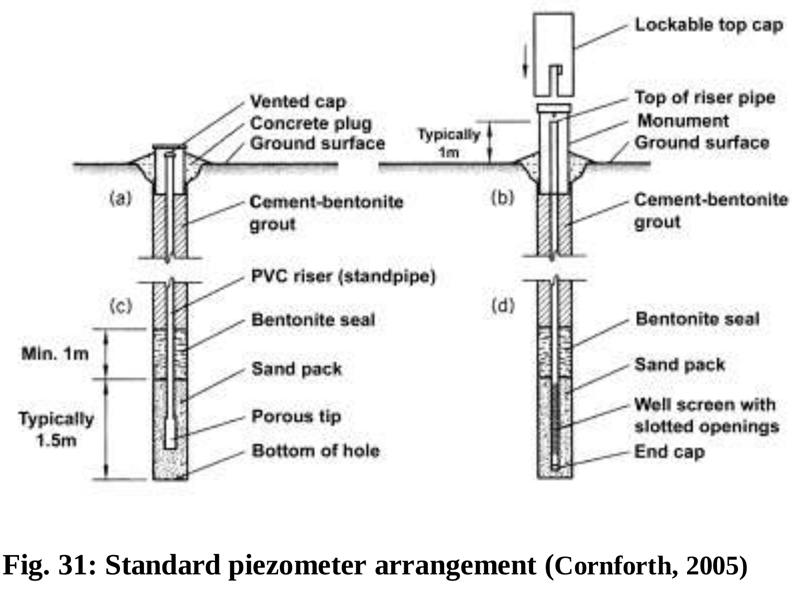


Fig. 31: Standard piezometer arrangement (Cornforth, 2005)

The water level in the tube is manually measured by lowering a graduated low-stretch tape with a tip-mounted electronic water sensor (Slope Indicator, 2006). Peak groundwater levels may be estimated by suspending a series of small "buckets" on a line within the standpipe. As the water level rises it progressively fills each bucket and is retained until the line is removed for monitoring, the highest filled bucket indicates the approximate maximum water level. Such a system may require a larger diameter standpipe, which can significantly reduce response times (Cornforth, 2005).

The relatively slow response times for standpipe piezometers means they are not suitable for installation in low permeability soils. Cornforth (2005) demonstrates that achieving a 99% response in a 1 inch diameter standpipe in soils with permeabilities under 10-6 cm/sec can take over 1 day.

6.3.6.2.2 Pneumatic

Pneumatic piezometers have been used as lower cost alternatives to electric methods and are preferred by many practitioners because of their reliability and rapid response (Cornforth, 2005; Mikkelsen and Green, 2003). They are operated by measuring the gas pressure required to dilate a diaphragm installed in a borehole. They are inherently free from drift, corrosion free, and are not subject to freezing (Cornforth, 2005; Slope Indicator, 2006), which makes them particularly suitable for long-term monitoring (Mikkelsen, 1996). However, they require gas to be carried to the site, are sensitive to intrusion or dirt, require good operator skills, and are impractical for automation (Cornforth, 2005). In addition, Mikkelsen and Green (2003) point out that it is very difficult and time consuming to obtain stable and reliable pore water readings in materials such as low permeability clay.

6.3.6.2.3 Electric

Electrical piezometers measure the deflection of a diaphragm in the piezometer tip, typically with a vibrating wire or strain gauge. Time lag for these systems is negligible and sensitivity is excellent – high end systems can have accuracies as high as 0.01% F.S. (Paroscientific Inc., 2005), traditional vibrating wire piezometers commonly have accuracies of 0.1% F.S (approx. 0.05 mm) (Geokon Incorporated, 2007; RST Instruments Ltd, 2007; Slope Indicator, 2006). The various merits of vibrating wire or resistance systems are briefly discussed in section → 6.3.1.

Multipoint electric piezometers may also be installed to monitor compartmentalised groundwater in compound slides and fractured rock at intervals as small as 0.5m (Solexperts AG, 2006) in deep landslides (Mikkelsen, 1996). The requirement for several piezometers in a single hole, and increased difficulty of installation in some cases make this a somewhat expensive option (Mikkelsen, 1996). The following section has further details on piezometer installation in compound slides and fractured rock.

6.3.6.3 Installation Considerations

6.3.6.3.1 Simple slides

When installing piezometers in simple soil slides it is important to ensure that the tip (sensor) can be at, or very close to the slip surface of the landslide. The piezometer will reliably measure the groundwater pressure at the sensor over an extended time period (Cornforth, 2005).

Ideally the sensor should be installed just above the basal shear zone of the landslide with the sand filter extending into the shear zone without passing through it. This will enable the piezometer to provide data on pore water pressure at the failure surface without being damaged by ongoing ground displacement.

The base of slope failures commonly marks a significant change in groundwater conditions; it's common for the strata beneath landslides to have significantly lower groundwater pressures than in the slide mass. Installations that are too deep and extend into this stratum may not reflect groundwater conditions within the slide.

Cornforth (2005) shows that shallowly installed piezometers that do not reach the base of the slide may reflect a higher groundwater level than would be indicated by one installed at the slip surface, particularly on steep slopes. In soft and medium-stiff soils, piezometers may be driven into the slope; this installation is self sealing and rapid.

Traditional methods of installing multiple piezometers involve the emplacement of sand filters separated by bentonite seals and a grouted length of borehole around the piezometer sensor. Mikkelsen (2003) states that this method "... is at best a laborious process and can in the worst case be so difficult that the whole installation becomes a total failure".

In saturated soil slopes, a fully grouted installation is recommended for diaphragm (pneumatic and electric) piezometers (Fig. 32) instead of the traditional sand and bentonite method (Cornforth, 2005; Geokon Inc., 2007; Mikkelsen, 1996; Mikkelsen & Green, 2003; Slope Indicator, 2006). Mikkelsen & Green (2003) state that a fully grouted diaphragm piezometer is more reliable and simple to install, which reduces costs and field installation time.

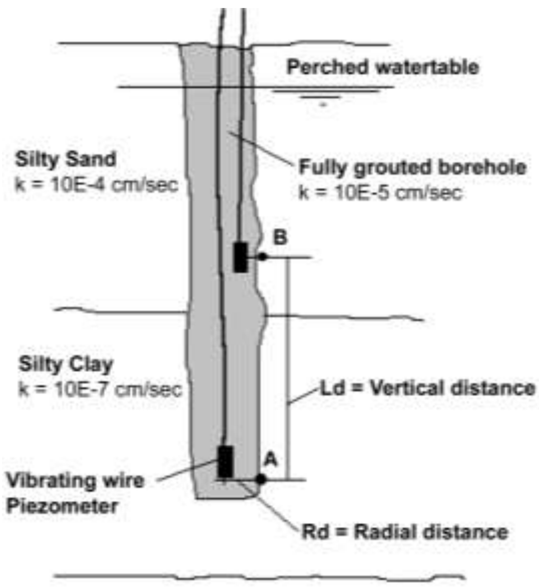


Fig. 32: Example of a multi level piezometer arrangement (Mikkelsen & Green, 2003)

6.3.6.3.2 Compound Slides

Piezometers installed in deep compound slides and fractured rock require multipoint sensors in order to isolate confined water pressures at the base of the instability, or to observe perched water tables identified during drilling. Core and drilling fluid losses should be studied carefully, and additional downhole investigations such as pressure tests using packers, flow logging, sonic velocity profiles, and optical and acoustic televiewers may be required. It's important to ensure adequate hydraulic conductivity between piezometers and the adjacent strata or fracture system to be monitored, while preventing vertical fluid migration between aquifers, or within the borehole.

Traditional multiple piezometer methods, as described for simple slides, may also be applied for compound slides and fractured rock. These can be difficult to install. Sand filter zones a few meters in length provide transmissivity between the aquifer or fracture network and the sensor.

Hydraulic, pneumatic, or chemical packer systems developed specifically for the isolation of groundwater in boreholes may be used as an alternative to traditional methods. These are relatively simple to install, and can be used to test a large number of zones (Dunnicliff & Green, 1993; RST Instruments Ltd, 2007).

Specialised multiple piezometer monitoring systems such as those produced by Westbay or Waterloo Systems (Schlumberger Limited, 2007; Solexperts AG, 2006) can provide detailed information on groundwater networks by allowing the installation of measurement port couplings in the piezometer casing wherever groundwater pressure measurements are required. The Westbay System allows installation to depths of up to 1000m, and may be combined with sections of telescopic casing and inclinometers to facilitate and monitor deformation within the slope (Dunnicliff & Green, 1993; Schlumberger Limited, 2007).

6.3.7 Time Domain Reflectometry

Time Domain Reflectometry (TDR) is an electrical measurement technique used to determine the degree and spatial location of cable deformation. In concept, it is similar to radar along a cable (O'Connor & Dowding, 1999; Dussud, 2002) and can be descried as "cable-based radar". A TDR system consists of two basic components: a combined transmitter/receiver (TDR cable tester) and a coaxial cable (Fig. 33). The TDR cable tester produces electric impulses, which are sent down the coaxial cable. When these pulses approach a deformed portion of the coaxial cable, an electric pulse is reflected and sent back to the TDR cable tester. The reflected signals are collected and analysed. The distance to the disruption can be calculated knowing the propagation velocity of the signal and the time of travel from the disruption to the receiver. Furthermore by analysing the reflected pulse (amplitude, width and form) information about the type and amount of deformation can be obtained (Fig. 34). The experiment shows a TDR measurement series during the forced shearing of the cable under laboratory conditions. By interpreting the collected waveforms, the shearing zone can be located; the amount of shearing also increases with the amplitude of reflection (Singer & Thuro, 2006).

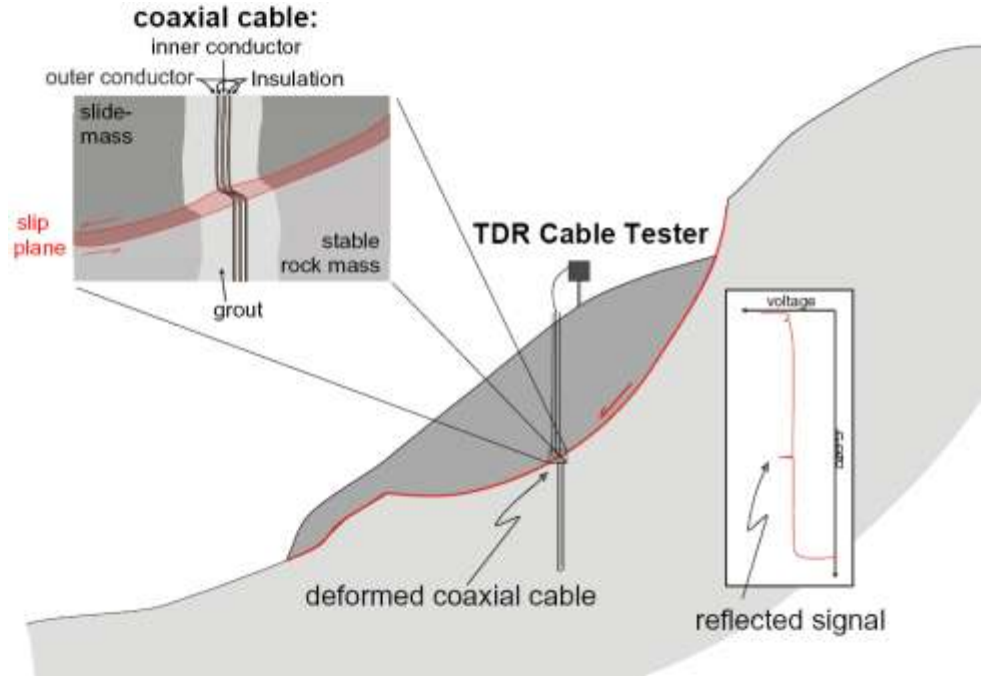


Fig. 33: Basic setup of a TDR measuring site (Singer & Thuro, 2006)

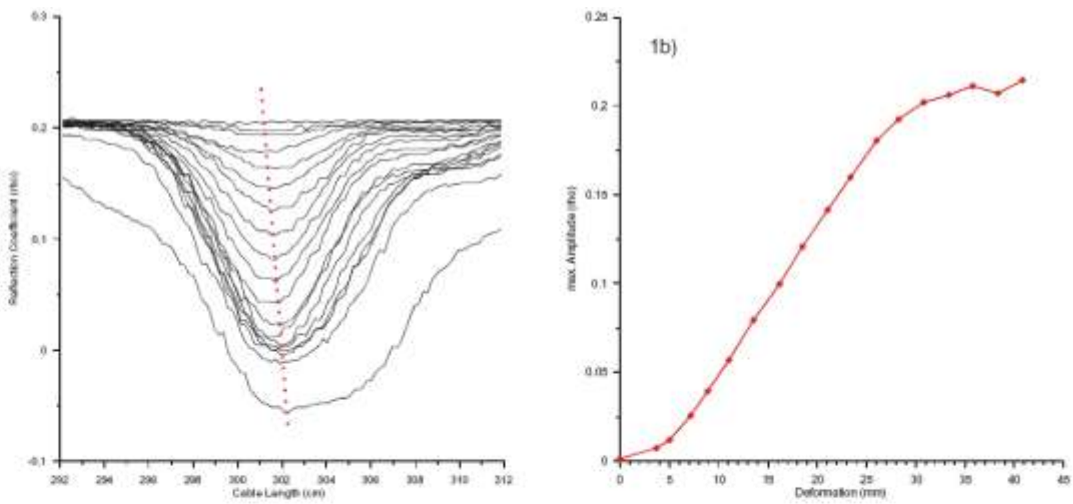


Fig. 34: Experimental TDR measurement series (Singer & Thuro,2006)

For landslide monitoring the coaxial cable is installed into a borehole (→ 6.3.4 and → 6.3.5) and connected to the rock mass with grout. Some experiments of installation were made in Piemonte by grouting a TDR coaxial cable in between the open hole and the inclinometer casing. The aim was to prolong the life of the installation by taking TDR readings after the inclinometer is not usable any more due to deformation. Overall results are quite poor which is possibly due to poor grouting (the TDR cable remained loose and did not react to deformations) and the usage of low diameter flexible TDR coaxial cables instead of proper large diameter (about 2 cm) semi-flexible cables. But there are cases that show very good matching between inclinometer and TDR readings as well, which seems to indicate that, if proper cables are used and a proper installation is made, the system may well be used.

In a recently started research project (alpEWAS[33]) attempts were made to define several different TDR measuring-system configurations (especially cable and grout type) where each is designated for a specific geological environment (Thuro et al., 2007). These configurations were calibrated in laboratory shear tests and will now be tested in the field by comparing them with inclinometer measurements. By combining several of these calibrated TDR measurements positioned in a pattern or along a profile within a landslide, better knowledge of the position, width and type of deformation zone can be achieved. Since TDR data can be acquired remotely, a continuous collection of data is possible. Thereby, external influences (e. g. rainfall) on the landslide can be observed in real-time (Singer & Thuro, 2007).

Table 6: Advantages and disadvantages of TDR

Possibilities	Problems & limitations
• cost effective installation • prolong the lifetime of inclinometers • Continuous data collection possible • remote data collection • measurement of subsurficial deformations delivers a insight (surface of rupture/position of slip plane, width and type of deformation zone)	• proper grouting (especially in soil) • only applicable to localized shearing deformation (narrow shearing zone) • quantitative measurements are still a challenge (movement rates > 2 cm/a) • no information on direction/orientation of deformation • combination with surface measurements necessary

6.3.8 Fibre Optics

During the past decades new sensory capabilities to measure the internal parameters of structures have been developed. As part of so-called smart civil structures small fibre optic sensors (FOS) are embedded and spatially distributed in the structure. FOS have originally been developed do detect variations in crack formation, strain, temperature and corrosion for industrial applications. But other parameters such as displacement and acceleration are possible as well and current FOS systems are applicable for health monitoring in the field of constructive engineering. Habel et al. (2007) gives a large overview of FOS applications in civil engineering and geotechnics showing the potential of this technology.

[33] alpEWAS: Development and testing of an integrative 3D early warning system for alpine instabile slopes. Geotechnologien – Forschungsschwerpunkt Frühwarnsysteme im Erdmanagement. 2007-2007. http://www.geotechnologien.de/forschung/forsch2.12k.html

Many different fibre optic sensor technologies exist and offer a wide range of performances and sustainability for different applications (Inaudi & Glišić, 2007). The most widely used sensing techniques include point sensors (Fibre Bragg Gratings and Fabry-Perot interferometers), long-gauge sensors (SOFO) and distributed sensors (Ramann and Brillouin scattering sensors). A detailed explanation of established technologies is not possible within this report; the authors refer to further reading, e. g. Udd (2006) and Glišić & Inaudi (2007). Nevertheless, the basic measurement principle shall be introduced on the basis of one particular but representative sensor: the SOFO displacement sensor which was developed at the Swiss Federal Institute of Technology Lausanne (EPFL) and is now commercialised by Smartec[34], Switzerland.

6.3.8.1 Measurement Principle

The following description is based on the description by the manufacturer. For further details see the website given in the footnote.

The SOFO measuring system is based on the principle of low-coherence interferometry (Fig. 35). The infrared emission of a light emitting diode (LED) is launched into a standard single mode fibre and directed, through a coupler, towards two fibres mounted on or embedded in the structure to be monitored. The measurement fibre is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fibre, called reference fibre, is installed free in the same pipe. Mirrors, placed at the end of both fibres, reflect the light back to the coupler which recombines the two beams and directs them towards the analyser. This is also made of two fibre lines and can introduce a well known path difference between them by means of a mobile mirror.

On moving this mirror, a modulated signal is obtained on the photodiode only when the length difference between the fibres in the analyser compensates the length difference between the fibres in the structure to better than the coherence length of the source (in our case some hundreds of mm).

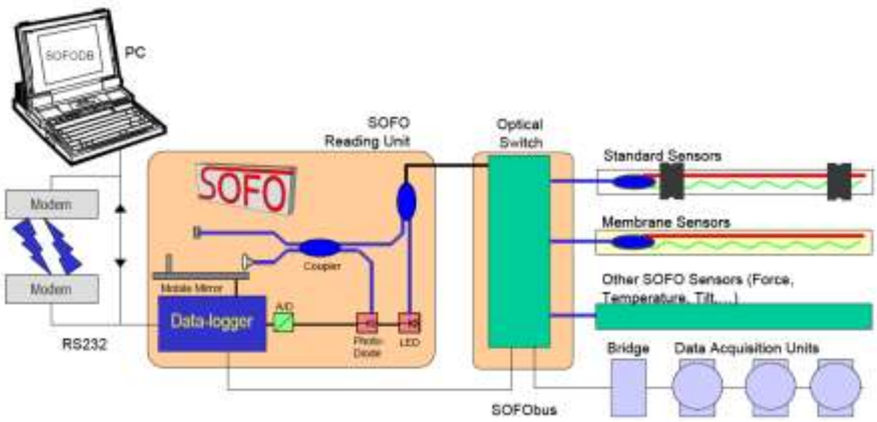


Fig. 35: The SOFO system architecture (Smartec SA)

[34] Smartec SA, http://www.smartec.ch/

Each measurement gives a new compensation position reflecting the deformation undergone by the structure relatively to the previous measurement points.

The Reading Unit can therefore be disconnected and used to monitor other fibre sensors and other structures. If multiple sensors need to be measured automatically, an optical switch is installed.

6.3.8.2 Intelligent Geosynthetics

The reinforcement application of geosynthetic is used as the reinforcing element to provide tensile resistance for the strengthening of the soils as adopted for slopes or retaining walls. Geosynthetic reinforced soil retaining structures are therefore more economical in saving land space and construction materials. With more structures being constructed, monitoring the behaviour of the engineering structures is becoming increasingly important demandingly during heavy rainfall intensity areas, over soft foundations or when poor soils are used as construction materials (Abidin et al., 2007).

Monitoring the behaviour of geosynthetic reinforced soil structures by measuring strains in the geosynthetic reinforcement can be practically made simple by the invention of intelligent geosynthetic known as Geodetect. Geodetect is an innovative geotextile-based monitoring system developed in cooperation with ID-FOS Research, Belgium (Briançon et al, 2005). It consists of Rock PEC geotextiles, equipped with optic fibres linked to a monitoring device (FBG[35]-Scan) and a PC or laptop that measures changes in wavelength versus real time. Any stresses exerted in the geosynthetic incorporated fibre optic, will cause a wavelength shift in the sensor that can then be related to a corresponding strain. Constant monitoring and management of a structure can be implemented via telemetry for remote data acquisition and early warning system. Once the change in wavelength or strain limit threshold is reached, a warning system will be activated prior to failure of the structure.

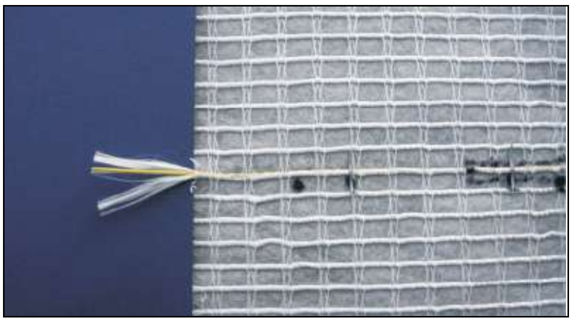


Fig. 36: Rock PEC geotextile with optical fibre (Briançon et al, 2005)

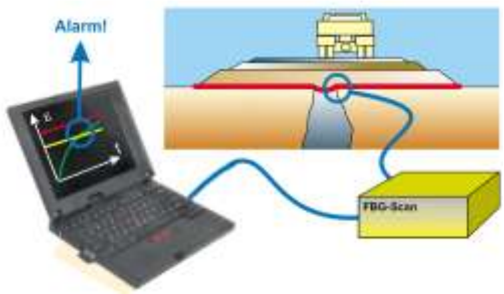


Fig. 37: Geodetect system configuration (Illustration: Polyfelt Geosysnthetics)

The system is designed to increase the safety of civil-engineering infrastructure through cost-effective predictive maintenance, especially in sensitive areas. Possible application ar-

[35] Fiber Bragg Gratings

eas are roads and railways, retaining walls, tunnels and other underground structures, like pipelines (Voet et al., 2005).

6.3.8.3 Application for Landslide Monitoring

Already in 1999 two 10 m SOFO sensors were installed on the active fault of the landslide Eiblschrofn (Austria). They were connected to a measurement station in the safe area where the movements were recorded at 5 minutes intervals. As far as the authors found out, the system was strongly influenced by several circumstances and therefore results remained non-satisfying.

A more promising example can be found be at the Gradenbach landslide in Carinthia, Austria. For the past 30 years, the landslide has been investigated using geodetic, geotechnical and seismic surveys. The GPS results suggest that the velocity pattern of the deep-seated mass movement is not uniform but rather intermittent, i.e., highly accelerated motions are followed by periods of creeping. The causes for this pattern are unknown. For a summary of these investigations and an interpretation of the kinematics of this landslide reference is made to Brunner et al. (2007).

For the investigation of the mechanics of this phenomenon a “strain rosette” for in-situ measurements of local distance changes is being developed. It consists of three embedded extensometers at a separation in orientation of 120°. The sensors are long gauge (5 m) fibre optical interferometers of SOFO type yielding a precision of 2 µm for absolute length changes and 0.01 µm for relative length changes with a data rate of up to 10 kHz over short periods. The future aim of the rosette is the detection of vibratons (dynamic measurements) and strain changes (static measurements) generated by a landslide.

A first installation was implemented at a test site to investigate the process of embedding the sensors. According to Brunner et al. (2007) the connection of the SOFO sensors to the soil and their protection against loose material is one of the most critical parts in this process.

Since the test site is located in a very stable region only little deformations should appear. However, control measurements for the highly precise SOFO data are nearly impossible using an independent technique. Temperature and moisture of the soil as well as the air temperature are measured and used for meteorological correction of the data. Magnitude of the overall correction is about 18 µm for a change of the soil temperature of -15°C and a change air temperature of -7°C with respect to the used reference temperature. The influence of soil moisture on the measured length changes is still being investigated. After full installation, the movements are in between 0.2 mm and 0.5 mm.

Furthermore, artificial agitations (5 kg hammer, 30 m apart from the strain rosette) were used to investigate whether strain waves can be measured with the strain rosette. Several experiments were carried out with a sampling frequency of 1 kHz. First results on a test site show that strain waves can be detected with small amplitude which correlate with geophone measurements. The system seems to be adequate for observing micro-earthquakes as well. Currently a similar strain rosette is embedded in the Gradenbach landslide area.

6.4 Geophysical Methods

6.4.1 Direct Current Geoelectric

The determination of the distribution of the subsurface resistivity is the purpose of direct current (DC) geoelectrical measurements. The aim is the correlation of ground resistivity with geological parameters.

The specific electric resistivity is a physical property of a material. All components of a material contribute to this characteristic value. In earth-moist mineral materials the ionic conductivity dominates the thermionic conductivity. That means low resistivity is caused primarily by the water content respectively the salts (ions) solved in the water. The water content therefore leads to a wide range in the resistivity of one and the same material.

6.4.1.1 Principle of the DC resistivity technique

DC resistivity measurements determine the distribution of specific electrical resistivity within the subsurface. The electrical resistivity is primarily affected by porosity, degree of water saturation, conductivity of pore fluid and clay content and to a minor extent by particle shape and pore geometry. Combining this information with those gained from geology and/or boreholes, reliable conclusions about the composition of the subsoil can be deduced. Additional application of borehole geophysics (→ 5.3.1) may facilitate the interpretation of geoelectrical results. Thus a good correlation between the geoelectrical scheme and the geological units can be expected.

The basic theory of the geoelectrical method has been established in the early 1900 and can be found e.g. in Koefoed (1979).

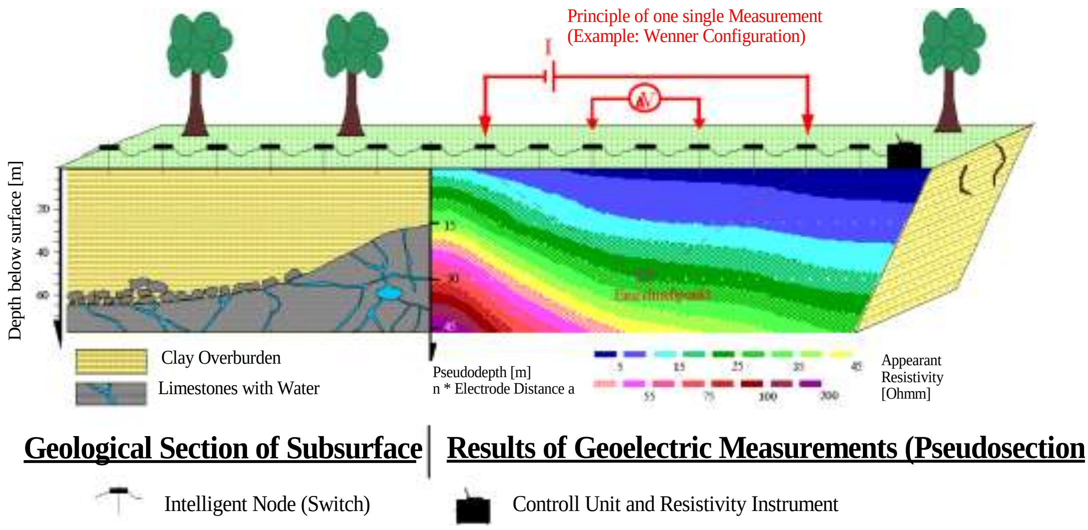


Fig. 38: Principle of a 2D-measurement with a multi-electrode system

The variation of the spacing of the outer electrodes allows measuring the apparent resistivity for different depths. Whereas in former times 1D measurement were taken manually, nowadays automatic gained 2D geoelectrical profiles with up to 100 electrodes (max. depth ~ 200 m) with a few thousand data points are common. To obtain the subsurface structure, a 2D-inversion of the data is carried out. The measured values are figured as a pseudosection[36]. The apparent resistivity data are plotted in combination with the "depth of investiga-investigation". The 2D-inversion divides the subsurface into rectangular blocks. With an algorithm the best fitting resistivity value will be assigned to the measured value. Resistivity data are inverted using the "modelling" process: A hypothetical model of the earth and its resistivity structure (geoelectric sections) is generated. Based on this model, the theoretical electrical resistivity response is calculated. The theoretical response is then compared with the observed field response and differences between observed and calculated will be minimized by an iterative procedure. It remains the interpreter's task to evaluate the reliability of these models and to produce a plausible geological model from the geoelectrical data. In combination with local geological knowledge (e.g. from boreholes) the interpretation of the inverted section can give a picture of the earth subsurface (Fig. 38).

6.4.1.2 DC-Geoelectric used as a Monitoring System

2D-Geoelectric surveys have been used for many years now to investigate the structure of landslide areas, thus gaining the status of a state of the art method in civil engineering for this application. Many applications showed that repeated DC-geoelectric measurements can be used to detect changes in the subsurface structure. As the electrical resistivity of the subsurface mainly depends on porosity, saturation, pore fluid conductivity and clay content, the geoelectric method can be a reliable tool for observing these changes. Changes in the resistivity are mainly caused by changes in the water content, which is an important criterion for a sliding process. Changes in the resistivity thus can be an indirect indicator for sliding processes. Preconditions for a recordable measuring result are:

- The resistivity of the matrix has to differ from the resistivity of the pore water.
- Porosity has to be great enough to cause significant changes in resistivity
- The saturation has to change significantly during the measuring period.

The process that leads towards triggering of a landslide is built up gradually or sudden. Therefore a monitoring system for surveillance of these processes has to be capable of surveying long period changes (within months) as well as short sudden developments (within hours). It should provide a point shot of the current system status, which practically means that data acquisition time should be much less than the period of possible changes. As these changes could be very small, the system used must provide high resolution data. This can be reached by keeping the error of each single measurement low and/or information of electric noise is available and by using many different possibilities of configurations. Due to the fact that each single measurement is afflicted with a different amount of noise, not only linearly independent configurations should be measured. Repeating the measurements at short time

[36] A pseudosection is the distribution of the apparent resistivity obtained along a given electrode profile with all possible configurations of a given array geometry, e. g. Wenner-Layout, Dipole-Dipole or Pole-Pole.

intervals allows determining a base level of possible changes due to noise and inversion error. Therefore online access to the observation system, short processing time of data, permanent availability of actual information and definition of critical values for pre-alarm is necessary.

In 2001 no commercially available geoelectrical instrument met the requirements of high resolution monitoring (high resolution data, direct noise control, short acquisition time, permanent remote access and automatic data broadcasting), so a completely new, high speed geoelectrical data acquisition system, called GEOMON^{4D}, was developed by the Geological Survey of Austria for the Forest Engineering Service in Torrent and Avalanche Control of Vorarlberg and the County of Vorarlberg (Supper et al., 2007; Supper et al., 2005).

6.4.1.3 Characteristics of the system:

- Low acquisition time for a single potential measurement. Therefore a big number of potential measurements, including unusual unsymmetrical configurations, can be taken for one current injection position. Thus only high quality data points can be selected for the inversion without any loss in resolution. Consequently a subsurface coverage about ten times higher compared with conventional arrays is reached within a much shorter time. E.g. a Wenner-Schlumberger section, measured with a conventional system (390 measurements) takes 1.6 h of acquisition time, whereas the new system (3000 measurements) requires 20 min. acquisition time. The high acquisition speed combined with few current injection points limits also power consumption thus allowing power supply by solar panels.
- The high acquisition speed combined with few current injection points limits also power consumption thus allowing power supply by solar panels.
- System operation and data download is done remote controlled by GSM module.
- All samples of the single measurements are saved, allowing full information on the contained noise and noise filtering in a post-processing step. Therefore sampling intervals can be adapted to detected noise frequencies.

6.4.2 Microseismic Monitoring

6.4.2.1 Basic Principle

Slope instabilities are accompanied by microseismic emissions generated by cracking, fault propagation, and shearing of the substrate. Microseismic monitoring involves the installation of passive acoustic receivers (geophones) on a slope to provide a record of the energy release and spatial distribution of these acoustic events (Fig. 39). It has been used to identify active areas of slope deformation and provide details on the precursors to failure (Amitrano et al., 2007; Amitrano et al., 2005; Meric et al., 2007).

Microseismic monitoring is unique in that it can provide information on the entire subsurface volume. This makes it a particularly useful aid when comparing data from separate monitoring systems usually associated with discrete features on the site (i.e. geodesy, crackmeters, tiltmeters, extensometers and inclinemeters).

Fig. 39: Seismic array (Roth et al., 2006)

While primarily applied to instabilities in rock slopes, acoustic monitoring has been proven to be useful in soil slides. In this function however, it is hampered by the low power of acoustic emissions and high attenuation in such failures. Proper site selection and equipment installation is therefore particularly critical for soil slopes (Rouse, 1991).

6.4.2.2 Measured Parameters

Microseismic monitoring techniques have been widely used to monitor rockmass deformation in applications ranging from volcanic monitoring (De Natale et al., 1998; Lippitsch et al., 2005; Lomax, 2005; Presti et al., 2004; Vilardo et al., 1996), fracturing and fluid flow in hydrocarbon reservoirs or hot dry rock systems (Evans et al., 2005; Oye and Roth, 2003; Rutledge et al., 1998; Vecsey et al., 1998), mining-induced earthquakes (Trifu and Urbancic, 1996), and major tectonic faulting (Malin et al., 1989; Schorlemmer and Wiemer, 2005).

The application of this method to the monitoring of unstable natural slopes has been limited to date. Though as evidenced by recent studies it is becoming an increasingly popular tool (Amitrano et al., 2007; Amitrano et al., 2005; Eberhardt et al., 2001; Roth et al., 2006; Rouse et al., 1991; Spillmann et al., 2007). Amitrano et al. (2005) and Amitrano et al. (2007) have shown a relationship between slope acoustic events and landslide velocity or degree of slope instability. As brittle deformation (cracking, fault propagation and shearing of the substrate) is required to generate microseismic signals, this is more applicable to developing rotational or toppling failures than translational slides with well developed, pre-existing failure surfaces.

Microseismic data may be used to monitor the temporal and spatial evolution of slope instabilities. The versatility of event information is highly dependant on the sensitivity and layout of the geophone array, and interpretation can be limited by poorly considered installations. Three principal degrees of installation and analysis are common; for each refinement the complexity, and therefore cost, of monitoring can increase by an order of magnitude. These are described below:

- Relative energy release – Monitoring of event occurrence and amplitude is the simplest form of data collection. Relative variation in energy release can provide a qualitative indication of temporal slope instability.

- Spatial assessment – Spatial location of microseismic events can provide important information regarding the location, propagation, and mechanics of unstable areas. Even the simplest form of event location requires active seismic trials in order to determine subsurface conditions and calibrate the installation.
- Moment tensor and source location – The most detailed data from microseismic investigations can provide information on individual microseismic events and aid the interpretation of the instability mechanism (i.e. Spillmann et al., 2007). This requires active seismic trials, along with borehole geophone installation, and careful 3-D tomographic modelling and processing of the data.

The importance of the network installation is evident in Roth et al. (2006), who recorded an increase from 3 to 50-100 events per day by upgrading to a more sensitive seismic network on a slide moving up to 15cm per year. The processing of signals also has a significant effect on the identification of true slope noise events; of over 66,000 files recorded over a 31 month period, Spillmann et al. (2007) was able to identify 223 local signals (average of 0.5 events per day) on a slope moving 1-2cm/yr. Monitoring by Amitrano et al. (2005) recorded acoustic noise events in a cliff over a six month period prior to collapse. This showed an average of 1.7 events per day until the 2 hours prior to collapse when the rate increased by 3 orders of magnitude, and was accompanied by an increase in the average size of seismic events.

6.4.2.3 Installation Considerations

"Principles and applications of microearthquake networks" (Lee and Stewart, 1981) is an excellent reference to gain an initial understanding of microseismic techniques. However, it is essential that an expert is consulted at an early stage in order to gain meaningful and useful results from a microseismic monitoring system.

A microseismic monitoring system uses sensitive geophone arrays, usually connected to a central seismic acquisition system to sense and record microseismic emissions as well as ambient noise in the environment. In order to maximise signal response the geophones should, whenever possible, be installed on firm rock. Along with desirable slope instability signals, noise sources can also include:

- human activities (e.g. foot and vehicle traffic, machinery, or construction),
- atmospheric effects (e.g. wave action, wind, and lightning) or
- unrelated geological processes (e.g. rockfalls and earthquakes).

While it is possible to filter out most undesirable signal sources, this process inevitably reduces the resolution and quality of records associated with slope instability. Consideration should be given to the expected strength and travel distance of signals relative to that of background noise. Porous and fractured rockmasses are very good attenuators of seismic energy and reduce the depth from which signals can be resolved (Amitrano et al., 2005; Rouse et al., 1991). Spillmann (2007) noted that attenuation may have limited the recognition of events at depths greater than 100m in highly fractured and faulted crystalline rocks.

Microseismic monitoring systems generate a significant quantity of data, in the order of 1Gbyte per day (Roth et al., 2006; Spillmann et al., 2007). Data storage issues for these systems therefore require very good data transmission capabilities, commonly a radio link from the seismic acquisition system to a wired internet connection. Issues associated with operating such electronic equipment in adverse environments can limit operational time. A system used by Spillman et al. (2007) incurred 20% downtime over 31 months of service, and Roth et al. (2006) removed temporarily installed equipment prior to winter conditions restricting access.

Network layout plays an important role in determining the applicability of recorded data. Optimally geophones should be evenly distributed on the site and centred on the area of interest. For spatial location of signals, the minimum geophone spacing should be less than the minimum expected hypocenter depths. In areas of shallow instability this requires a dense grid of sensors and on sites of deep failures geophones should be located a significant distance outside of the unstable area.

Borehole microseismic monitoring can significantly aid the location of hypocenter depth and origin time (Spillmann, 2007), particularly in the highly fractured heterogeneous materials common in landslides. It is important that geophones installed in boreholes have positive contact with the borehole walls, and, if cased, the casing should be grouted in place to maximise signal response.

6.4.2.4 Measurement Interval/Frequency

Microseismic monitoring may be undertaken continuously, or with an event-triggered recording system. Both options generate a stream of data which needs to be automatically filtered in real time and regularly analysed (Roth et al., 2006). As the application of seismic techniques for monitoring natural slope instability has to date, been limited, determination of appropriate analysis intervals and markers to trigger early warnings is still highly dependant on the particular site requirements.

6.5 Remote Sensing

Remote Sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in physical contact with the object, area, or phenomenon under investigation.

6.5.1 Photogrammerty

Photogrammerty is a remote sensing technology that determines location and geometric properties of objects from images. Images can be acquired with different sensors (film cameras, digital cameras, scanners, etc.) from satellites (6.5.1.5), aircrafts, helicopters or even remote-controlled flying objects (6.5.1.4) as well as from a terrestrial viewpoint (6.5.1.3). Depending on exposure conditions, size, velocity of landslides, and the type of study (hazard monitoring or scientific purpose), one or combination of several techniques and data can be used. They are characterized by resolution, accuracy, surface coverage and revisiting time (Table 7, Delacourt et al., 2007).

Table 7: Characteristics of optical sensors in Photogrammerty

	Fixed Camera	**Remote-controlled**	**Aerial Photo-grammetry**	**Satellite Imagery**
Measurement Type	2D horizontal displacement or 3D if DEM available			
Spatial Resolution	~ cm to ~ m	< mm to 1 m	0.5 m to 2 m	0.6 m to 80 m
Accuracy	1/5 pixel	a few pixels	2-3 pixels	~ 1/5 to 1 pixel
Covered Area (per image)	10 × 10 m² to 1 × 1 km²	10 × 10 m² to 300 × 300 m²	5 × 5 km²	10 × 10 km² to 60 × 60 km²
Temporal Resolution	1 sec to 1 day	on request	5 – 7 years	~ 30 days
Archive	–	–	1950 - ongoing	SPOT1-4 (1986); SPOT5 (2002); IKONOS (1999); QuickBird (1999)

6.5.1.1 Basic Principle

A line of sight can be constructed from the camera location to any point on the object (image). By constructing two homologous rays in two stereoscopic images (images of the same area acquired from slightly different standpoints), their intersection determines the three-dimensional location of the point (Fig. 40). If more image locations of object points are identified on each image of a pair of stereoscopic images, three dimensional Digital Terrain Models (DTM) and afterwards orthoimages can be extracted. The allocation of homologous rays can be done manually or automatically (by image correlation). Automatic processing allows fast production of dense DTMs and orthoimages.

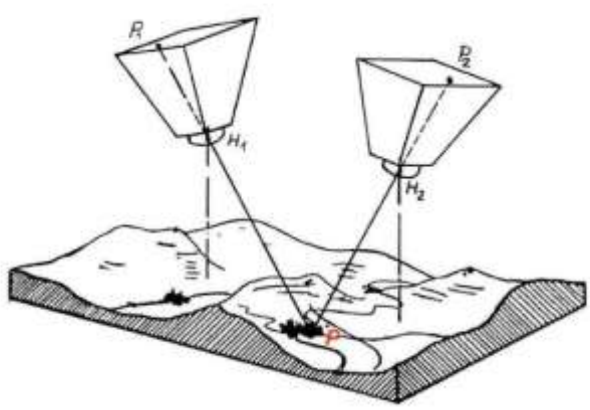


Fig. 40: Principle of aerial stereoscopic photgrammetry (Hoffmann, 1990)

Digital orthophotos (orthoimages or orthorectified images) are georeferenced images of the terrain equivalent to maps: the image row and column directions are aligned to East, North directions and pixels have associated map coordinates. This is achieved, after image orientation, by geometric-ally correcting the original image for displacements caused by camera altit-ude, terrain relief and optical distortions.

The usage of orthoimages is essential in case of large events, such as floods, to quantify damages but also for landslide mapping in large geographic areas or for the creation of landslide inventories integrated in Geographic Information Systems (GIS).

This technique requires knowledge of the optical characteristics of the camera, which are called internal parameters (e.g. focal distance), and knowledge of external parameters like the position and orientation of the camera at the time of acquisition. The internal parameters are the principal distance of the lens, the principal point coordinates in the image system which is the projection of the lens optical centre on the image and the distortion parameters of the lens. The external parameters of the camera are defined for each image. They are the spatial coordinates of the optical centre of the camera and the orientation angles of the image frame with respect to an external reference frame.

6.5.1.2 Principle of Image Correlation

A two dimensional displacement field can be derived by correlating two optical images obtained at different times. To find the ground displacement which occurred between two epochs a correlation window and a search window are defined in the former and latter image. By maximizing the correlation function in the correlation window shifts in pixels are deducted. If orthoimages are used, the shift obtained corresponds with planimetric displacements. Altimetric displacements are measured by using two multi-temporal DTMs.

6.5.1.3 Fixed Camera Photogrammetry

The main problem of data sets acquired by flying platforms as descried in the following sections (→ 6.5.1.4 and → 6.5.1.5) is that images cannot be obtained in exactly the same geometry and that temporal resolution depends on flying conditions. The DEM construction requires that the position and the orientation of the cameras are computed.

Since the middle of the 90's, the development of digital cameras equipped with sensors of more than 6M pixels and high quality lenses, has permitted the growth of new remote sensing technologies. Digital cameras can be placed in front of landslides and programmed to take images with a constant time step (Fig. 41). In that case, images are exactly in the same geometry due to the fixed camera position and can be directly correlated.

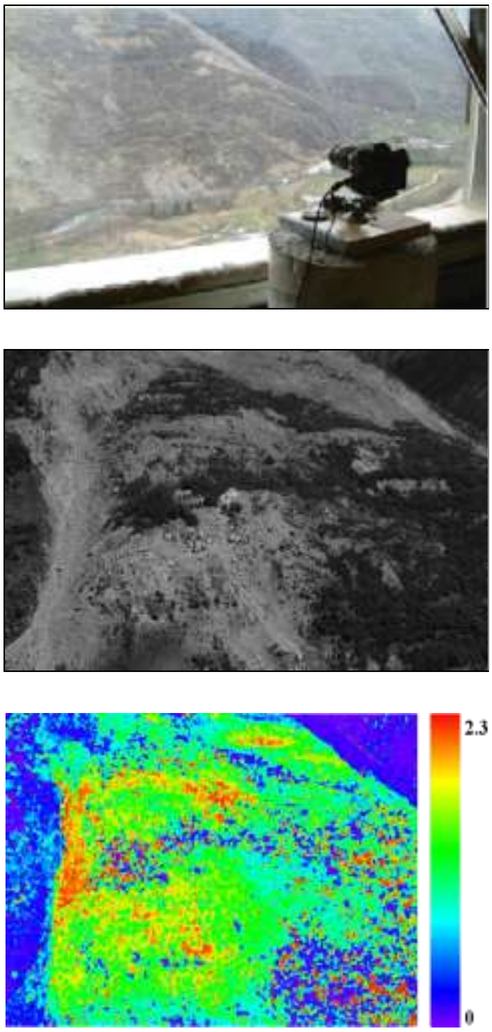


Fig. 41: Fixed camera installed in front of the "La Clapière" landslide. Photograph and displacement map (in pixels) derived from two images (Delacourt et al., 2007)

The precision of the correlation is controlled by a) the correlation algorithm, b) the movements of the camera due to thermal distortion, c) the change in the refraction indices of the atmosphere between the camera and the landslide and d) the change of sun illumination. The effect (a) is negligible as the correlation can be realized with sub pixel accuracy. The second one (b) can be avoided if the camera is fixed on a rigid stand. Experiments show that (c) can produce apparent shift, up to 2 pixels, if the camera equipped with a 22 mm focal lens is placed at 1 m of the landslide.

In order to minimize these artefacts, the images need to contain a stable area that will be used as a reference. As no displacement is expected within this area, the maximum displacement calculated using the correlation method will give an upper boundary for the error on the unstable domain. In order to reduce sun illumination effects, only the images obtained at the same time on two successive days are correlated with a preference for images acquired when the sun elevation is maximal. The correlation works also well on images acquired at the same solar time with one year interval.

Another problem comes from the size of the landslide compared to the image swath width. Generally, only the lower part of the landslide can be imaged. There are also technical constraints inherent to these methods. Systems of image transmission need to be associated to the acquisition process in order to quickly process the data. Another problem is more conceptual: if no DEM is used, the resolution of the image depends on the distance between the landslide and the camera. Then, the displacement, which is evaluated in pixels by the correlation, cannot be translated in distance. This problem can be circumvented if a high spatial resolution DEM is available. This technique can be used to observe both very fast and very slow landslides, by adapting the time span between two acquisitions. Another strong constraint is the surface changes, which have to be low enough so that the correlation remains possible.

6.5.1.4 Aerial Photogrammetry

Aerial images obtained from national geographic institutes or land surveying offices associated with image correlation are very useful for scientific studies. The cheap archive of images covers a history of fifty years with an average time span of five years. The spatial resolution is around or better than one meter and the detection threshold for monitoring purposes is around two or three pixels. The development of high resolution digital cameras fixed on unmanned platforms (Fig. 43) that are radio controlled by an operator permits high resolution acquisitions with an adapted temporal frequency.

Fig. 42a/b: Airplane and photogrammetric camera (Fotos: Genth, Hansa Luftbild)

Fig. 43: Remote-controlled platform (Delacourt et al., 2007)

Analysis of aerial photos is very useful for

(1) recognizing and mapping geomorphologic features of landslides (both in areas where landslides already have occurred and where they are likely to occur) and

(2) mapping the real extension of phenomena. Some kind of potential landslides can only be identified from geomorphological features (e.g. trenches and double ridges) which can be recognized from aerial photos easily.

Furthermore, combining image data with Digital Elevation Models (DEM) or point clouds (→ 6.5.2), photorealistic 3D models of the terrain can be produced and 3D measurements can be performed on the object; the real extension of phenomena and various features (e.g. volumes, displacement, length of fractures, orientations, etc.) can be measured; to this purpose, software has been specifically developed in the last years.

6.5.1.5 High Resolution Optical Satellite Imagery

Earth observation satellite imagery exists for about 25 years. However, the spatial resolution of optical satellite imagery systems is typically not adequate for landslide studies until the recent improvements of optical sensors, such as the ones on-board IKONOS, QuickBird or SPOT5.

Fig. 44: QuickBird Satellite (Courtesy of DigitalGlobe Inc., 2007)

Fig. 45: QuickBird Satellite image (Courtesy of DigitalGlobe Inc., 2007)

This technique has been successfully applied to French Alps landslides (Delacourt et al., 2007). As the spatial resolution of very high resolution satellite images is close to the aerial ones (→ 6.5.1.4), correlation of the two types of data can be realized (Delacourt et al, 2004). Joined hyperspectral and high resolution images (Fig. 46) have been used to predict landslide susceptible areas in Slovenia (Komac, 2006).

One way to overcome some limitations of aerial approach is to use satellite images with a revisit period of 20 to 30 days. A new generation of high resolution satellites (Ikonos since 1999 and QuickBird since 2001) provides high resolution (0.6 m to 1 m) data covering areas with 10 × 10 km² in size. The SPOT5 satellite (launched in 2002) has a lower ground resolution (2.5 m) in Very High Resolution mode, but the wide footprint of 60 × 60 km² is useful for regional scale studies. Furthermore, precise orbital ephemeris and attitude descriptions are provided with the images. Without any ground control points, an image is located on the ground with a precision of 30 m RMS[37]. Although earth observation satellites are sun-synchronous, the change of illumination between acquisitions can induce significant variations in the length and the direction of shadows. This will even be stronger in the case of images acquired during different seasons. High resolution optical satellite images associated with image correlation techniques are useful for both scientific and hazard purposes. These images have a ground resolution of 1 m and the time span between two acquisitions is around 20 days, which can be reduced to three or four days in case of specific orbit cycles. Thus, these images are suitable for high velocity landslides (at least 1 meter per day) if the time span is equal or less than three days. For medium velocity landslides (at least 2 or 3 meters per month) a time span of 20 days is required. They are suitable for low velocity

[37] Root Mean Square is a statistical measure of the magnitude of a varying quantity (e.g. measurements)

landslides (2 or 3 meters per year) for a time span of one year. High resolution images coming from different sensors can be combined. The archive of these images is however very limited – less than 6 years of record are available.

Data is available as raw image format or existent in a processed (georeferenced[38], noise-reduced /removed) form. Images can be processed using various classify-cation methods where signal or digital number/information from sensors is analysed to obtain surface specifics and/or anomalies. Using high resolution satellite images detection of local and regional landslides (territorial expansion from small scale with less than 1 km² up to large scales with more than 1000 km²) with displacement rates of 1 pixel per epoch (~20 days) is possible. The main advantages are broad cover-age (also hardly accessible areas), constant periodic monitoring, possible panchromatic/multispectral imagery and relatively easy comparison of observed areas of mass movements with stable areas.

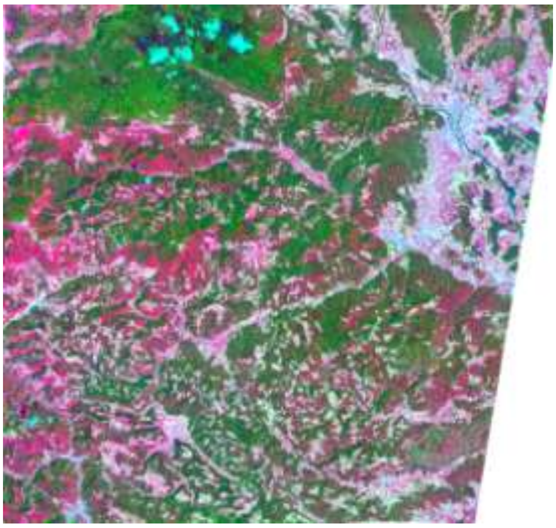


Fig. 46: Colour composite image (Landsat-5) joined with the first principal component of satellite image Resurs-F2.

The main disadvantages or restraints are low accuracy of monitoring displacements. In addition only horizontal changes are detectable – no information on vertical component can be provided. Optical sensors are passive ones hence other source of energy is needed (usually solar). Therefore, monitoring is governed by weather and lightning conditions (sky cover, daylight). Uncertainties in the geometrical parameter of the images as well as changes in vegetation, length of shadows and other radiometric differences influence results.

6.5.2 Airborne Laserscanning

Airborne Laserscanning (ALS), also known as Light Detection and Ranging (LIDAR), is a rather young technology opening new possibilities for qualitative and quantitative determination of surface elevation changes. Its rise was possible through the combination of several modern measuring methods and sensors, such as:

- Distance measurements to non-cooperative targets (main component of ALS-sensor).
- High-precision DGPS (→ 0): used in kinematic mode to record the coordinates of the sensor almost continuously (Fig. 47) and

[38] Georeference is an imperative process to establish a relation between images to map projections and/or coordinate systems.

- Inertial Navigation Systems (INS): used to describe the orientation of the sensor and for track densification.

Airborne Laserscanning enables remote capture of the terrain surface. The system has the advantage of delivering good results for areas which are difficult to penetrate, such as forests and wooded areas (Kraus & Pfeifer, 1998). ALS is the only cost effective method available for capturing elevation data from forest areas. In addition the active sensor allows operation independent of solar illumination, which takes a great advantage in comparison to optical photogrammetry (→ 6.5.1).

6.5.2.1 Basic Principle

The system is operated from a plane or a helicopter. The laser scanner is installed in an opening in the floor of the aircraft. It determines the distance to the earth's surface by measuring the time-of-flight of a short flash of infrared laser radiation. In order to figure out the exact geographic 3D coordinates (latitude, longitude, elevation) of any surface spot that was hit by a laser pulse it is necessary to know two more items in addition to the distance: the location of the aircraft from which the measurement was made, and the direction in which the laser altimeter was ‘looking‘. These values are usually obtained through a dynamic position and orientation system (POS) consisting of Global Positioning System (GPS) receivers (in the aircraft and, for reference, on a known location on the ground) and an Inertial Navigation System (INS) onboard the aircraft (Fig. 47). Data from those instruments are combined to compute the 3D coordinates of the features from which the laser beam has been reflected (Fig. 48). For this purpose all components have to be time-synchronized.

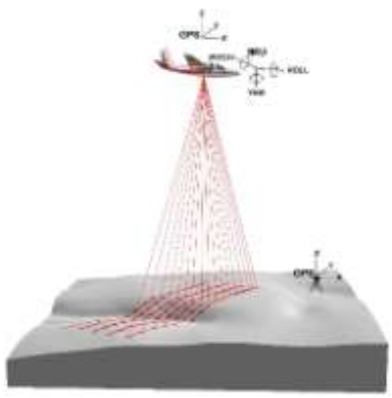


Fig. 47: Prinzople of ALS (Source: USDA Forest Service)

Fig. 48: DTM derived from ALS data (Source: Schäfer, TUM)

6.5.2.2 Accuracy and Geomorphologic Quality of digital terrain models (DTMs)

The elevation accuracy of Laserscan DTMs depends on the operating altitude, the terrain slope angle and the average number of points per square meter which is depending on the surface condition (Pfeifer, 2003). Contrary to aerial photogrammetry (→ 5.5.1.2) its elevation accuracy is considerably higher than the accuracy of the position and lies within some decimetres. A combination of both methods is strived for the future. The crucial parameter for the geomorphologic quality of the DTM also is the number of points per square meter and the used method to identify breaklines (Briese, 2004).

6.5.2.3 Application of ALS in landslide/rockfall areas

ALS therefore can be used for the monitoring of inaccessible or difficult accessible slopes especially slopes covered with vegetation. One of the most important outputs is information about the volumetric changes in the landslide area by comparing a set of DTMs from different acquisition dates. Vertical and horizontal changes of the terrain can also be observed. Precondition for the application of ASL are high movement rates. The advantages of ASL compared with TSL (→ 5.2.2) are

- applicability under all terrain conditions
- applicability in areas covered with shrubs and trees
- high homogeneity of the density of terrain points (in TSL data gaps as a result of shadowing effects due to vegetation and artificial objects) (Briese & Kraus, 2005).

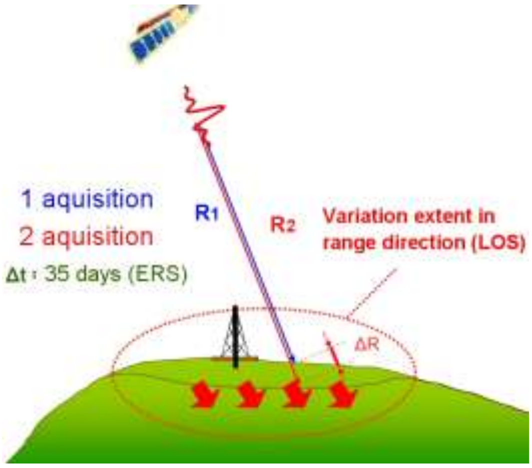
6.5.3 Satellite-born Radar Interferometry

The use of satellite mounted radars for Synthetic Aperture Radar Interferometry (InSAR) and Differential Interferometry (DInSAR) has been made operational with several platforms (ERS 1-2, ENVISAT, Radarsat, JERS-1). Conventional spaceborn SAR interferometry has proven a remarkable potential for applications such as reconstruction of topographic digital elevation models (DEM) and the detection of surface deformation phenomena (Ferretti et al., 1996). Landslide monitoring applications of the techniques includes Differential SAR Interferometry (DInSAR) and a group of recently developed techniques, generally named “persistent scatterers” methods.

6.5.3.1 Differential SAR Interferometry (DInSAR)

DInSAR measurements provide a unique tool for low-cost, large-coverage surface deformations monitoring (Colesanti & Wasowski, 2004). The interferometric technique involves phase comparison of synthetic aperture radar (SAR) data between two images, gathered at different times with slightly different looking angles. The phase subtraction between two images (one called master and the other called slave) generates an interferogram, which can provide a representation of the ground displacements which occurred in the time span between the two radar surveys.

The displacement measurement accuracy that can be achieved with differential interferometry along the LOS direction (Line of Sight; i.e. the line connecting the satellite radar sensor and the ground radar target) is in the range of less than the radar signal wavelength. Usually the dimensions vary from several millimetres to several centimetres. The high accuracy is the consequence of observing the difference of interferograms and not the actual elevation models or their changes. This enables the highly accurate target motion detection. To achieve such high accuracy of motion detection, a good knowledge about topography and the position and direction of the antennas is necessary. Only one-dimension measurements are a substantial drawback of this technique, while the big advantage is the possibility of spatial coverage of the observed area. Combining the radar data from ascending and descending orbits in analyses would enable the definition of two components of movement, which is usually sufficient for analyses.



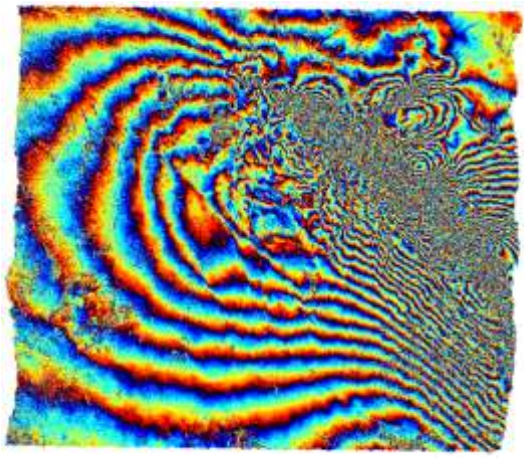


Fig. 49: Simplified scheme of DInSAR (Courtesy of TeleRilevamento Europa)

Fig. 50: Differential interferogram of the Landers earthquake. The interferogram has been generated by means of two ERS-1 images taken before and after the earthquake. The main fault is displayed along the main diagonal of the image in correspondence of the very dense fringe pattern. (Courtesy of TeleRilevamento Europa).

Motion measurements with radar interferometry depend upon the nature of the motion. There are two basic conditions for satisfactory results (Oštir & Komac, 2007):

- Changes during the acquisition of images must not be too big. This applies especially to their gradient, which should not be too big within a pixel. Usually this condition doesn't pose major problems.
- Radar scattering within a pixel at the time of acquisition must be as equal as possible. More precisely, the position of emitters within the observed resolution cell should not change more than 20% of the wavelength of the used micro-wave radiation. When it is not fulfilled this condition can pose bigger problems – time decorrelation. Time decorrelation is minimum observation of the surfaces that are not covered with vegetation, e.g. desert or urban areas. In general bare areas are more adequate than vegetated, dry areas are better than wet and radars with a larger wavelength are more appropriate than those with smaller. The difficulties with decorrelation can be solved by persistent scatterers technique, which takes into account only those areas (points) which are coherent (i.e. phase stable).

Differential interferometry has two very important limitations (Oštir, 2000; Hanssen & Ferretti, 2002; Oštir & Komac, 2007). The reflected radar radiation of all three images must be in correlation – there must be no time decorrelation. The second, more important limitation is that interferogram phases have to be developed prior to their comparison. Only then can the second interferogram be used to detect small changes in the surface. This problem may well be solved by having a digital elevation model and by having sufficient knowledge of recording geometry. However, in this case a differential interferogram is obtained, for which later a phase must be unwrapped in order to be able to determine absolute movements. Therefore the movements of at least a few points on the Earth's surface have to be known.

Main advantages are:

- high accurate surface measurement discontinuity (millimetric target displacements)

Main limitations are:

- measurements over longer period of time are mostly not possible due to decorrelation,
- loss of coherence,
- undesired atmospheric influences are not eliminated and
- sensitive to the geometry of image acquisition.

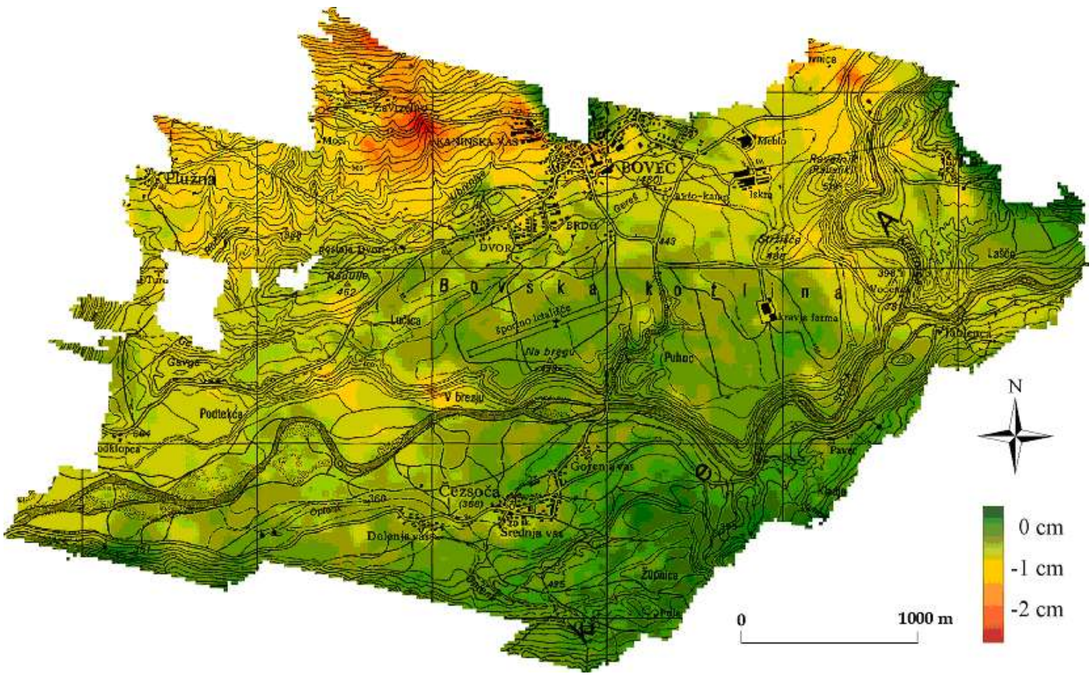


Fig. 51: Vertical movements recorded at the Bovec basin, an area struck by an earthquake on 12th April 1998. The model was produced with controlled merging of image interferograms acquired on 20.3., 24.4., and 29.5.1998 (Oštir, 2000).

6.5.3.2 Persistent Scatterers Methods

The Persistent Scatterers Methods are applications which allow the use of DInSAR techniques for precise detection of ground deformations including landslides detection and Persistent Scatterers Methods

Persistent Scatterers SAR Interferometry is still a recent, innovative and somehow experimental method (Ferretti et al., 1999, 2001). The next paragraph deals with Permanent Scatterers SAR Interferometry (PSInSAR™) for the authors have experience in this particular technique. All over the world a limited number of companies, universities and research centres provide products (e.g. IPTA™ and SPN™) based on very similar techniques with general features equal or very similar to the one described below.

A recent project by ESA, the PSIC4[39] compares all the existing persistent scatterers methods, in order to produce reliable information about the accuracy and dependability of these methodologies. The project is divided in two parts: the first concerns parallel processing of identical stacks of data by the different contractors; the second is an independent validation of the results, carried out by a separate consortium of experts.

6.5.3.2.1 Generalities

PSInSAR™ Technique is a registered patent of Politecnico di Milano (Italy). The Permanent Scatterers (PS) technique overcomes the main limiting factors of conventional Differential SAR Interferometry (DInSAR): atmospheric phase screen (APS), loss of coherence and baseline-dependent revisiting time.

PS Technique takes advantage of long temporal series of SAR data over an area, acquired by the satellite on the same orbit, to filter out the atmospheric artefacts. It does so by generating multiple differential interferograms from a set of radar scenes and it processes them by means of numerical and statistical analyses from which a sub-set of image pixels are identified. The latter allows high precision measurements to be performed. These pixels, virtually unaffected by temporal and geometrical decorrelation, are referred to as Permanent Scatterers (PS).

The PSInSAR™ analysis is based on the processing of long series of SAR data (min. 25-30), acquired in the same geometry over the same area, in order to single out those pixels, the Permanent Scatterers (PS), that have a "constant" electromagnetic behaviour in all the images.

PS can be rock outcrops or large boulders, metal or concrete power poles, buildings, manufactures, to mention but a few; PS are absent over vegetated areas and water bodies, for these surfaces quickly change their shape, hence the way they appear in radar images. For each identified PS it is possible to calculate the displacements occurred in the time span considered.

[39] Persistent Scatterers Interferometry Codes Cross-Comparison and Certification, http://earth.esa.int/psic4/

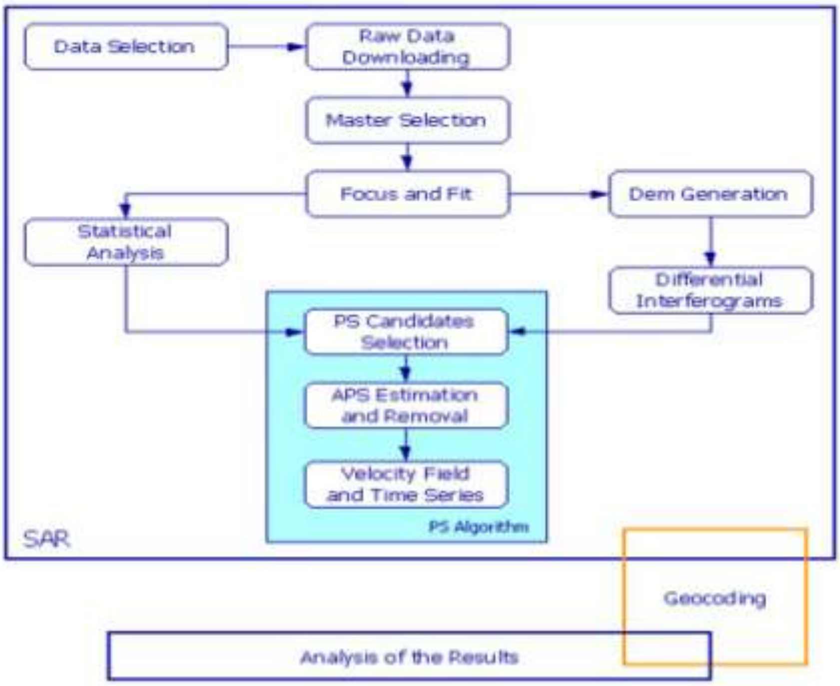


Fig. 52: Flowchart of the Permanent Scatterers Technique processing steps

If the PS can be traced over a long image series (> 30), processing of ESA-ERS archive allows, once the APS are estimated and removed, to evaluate PS displacement velocities (along the LOS) with a precision in the order of 0.1 mm/a.

The final results of this multi-interferogram approach are:

- a map of the PS identified in the image and their coordinates;
- their average LOS velocity (in mm/a);
- the estimated motion component of each PS as a function of time.

Common to all differential interferometry applications, the results are evaluated with respect to a ground control point (GCP) supposed to be stable.

6.5.3.2.2 PSInSAR™ for landslide investigation

The development of this new robust technique based on the interferometric analysis of radar images, and the possibility of integrating these data within a Geographical Information System (GIS) strongly increased the potential of remote sensing for landslide investigations (Mantovani et al., 1996).

The PSInSAR™ application on landslides up to now, based on the experience of the project partners, allow highlighting important result.

The application scale range is very wide, from regional to local, depending on data availability. The displacement velocities recordable with the PSInSAR™ technique are very low, generally less than 5-6 cm/a. the computational process in the Standard PS Analysis

(SPSA) gives a linear value of displacement up to the annual average calculated along the available time span.

The main information provided from this methodology is:

- discrimination between stable and unstable areas;
- landslide's kinematic mechanisms;
- displacement velocity;
- forerunning signs analysis (expected deformation).

The main feasible applications of the PSInSARTM analysis are:

- landslide inventory maps (at a regional scale), with possibility of future periodical upgrade (depending on data availability);
- single landslide monitoring, through comparison of PS time series with classical monitoring systems available;
- possibility to define, in large landslides, homogeneous sectors that have similar kinematic mechanisms (landslide sectors in the same deformation range).

Main limitations are:

- The method records only one component of the displacement, along the line-of-sight between the satellite and the PS. The determination of total 3D displacement, although possible in principle, using a combination of PSInSAR™ data from ascending and descending orbit, is not straightforward and may be troublesome;
- The technique works as long as good radar reflectors are present (buildings, bare rocks, infrastructures etc.), in wooded or grass-covered areas it is not applicable;
- Since satellite orbits are NS oriented, displacements along EW oriented slopes are difficult to detect;
- The surficial PS-related displacement may not be solely due to landslide's activity;
- Linear tectonics drifts (or by any other source) blur the displacement measurements. This effect is especially obvious in steeper areas.
- Areas affected by rapid displacements (rockfalls, fast moving landslides) or strong and rapid subsidence can not be detected, because during analyses of SAR images and extraction of PSInSAR™ data these areas are automatically eliminated from the results. Displacements prior to major collapse could, however, be detected, providing that only the data concerning the time span from the first image available to the last image before the collapse are processed. This, however, has some drawbacks: minor precision, because not all the available images are used and extra costs, for it is a custom-made additional analysis normally not included in PSInSAR™ ordinary data processing.

The interpretation of PS deformation on a densely-populated slope (where SAR targets mainly are buildings and human-made structures) may be difficult, for the recorded displacements may be due to the combination of several processes, both natural and anthropogenic. In this case, landslide-related displacements must be discriminated from PS-related displacements due to:

- damaging of anthropogenic structures;
- collapse of engineering manufactures;
- volumetric change of the terrain or structure materials;
- subsidence or uplift/heave due to natural or human process.

Since the maximum velocity detectable by PS analysis is about 5-6 cm/a (if radar C-band is used; use of other radar band, such as the X-band, may incline the maximum detectable velocity to 10-12 cm/a), information by this technique is available for just some landslide type:

- large, slow-moving landslides *(*e.g. deep-seated-deformations);
- slow, permanent, translational or rotational slides;
- slow flows;
- rockfalls themselves are very rapid and instantaneous and therefore can not be directly detected by PS analysis. Rockfall source zones, however, consisting of multiple-attitude bare rocky slopes, are PS-rich and the analysis points out significant displacement for all the slopes which are common rockfall sources.

There are experiences of placing artificial metal corner reflectors (dimensions about $1 \times 1 \times 1$ m³) on some landslides in order to create artificial and very clear PS in areas which do not host natural ones. In this case however, the observations are only possible for the future events (post artificial PS installation) and not for the past, as in natural PS observations.

6.5.4 Ground-based Radar Interferometry

6.5.4.1 Basic Principle

Ground based synthetic aperture radar interferometry (GB-InSAR) is an innovative remote sensing method that allows very accurate measurement of ground displacement across wide areas. The principal is similar to that of satellite-born radar interferometry, discussed in the previous section. Instead of a satellite-based radar source, GB-InSAR consists of a portable radar unit that slides along a 1 to 5 m long rail while taking measurements (Antonello et al., 2004; Rudolf et al., 1999). The resulting data can achieve a resolution equivalent to or even better than traditional geotechnical and topographic instrumentation.

The installation of ground based SAR equipment has a number of advantages over satellite-born techniques (Corsini et al., 2006):

- ground displacements can be derived from just a couple of images,
- the frequency and geometry of acquisition is more flexible,
- the system is relatively easy to install and quick to set up,
- and measurements can be undertaken in “near real time” with repeat observations possible in a matter of minutes

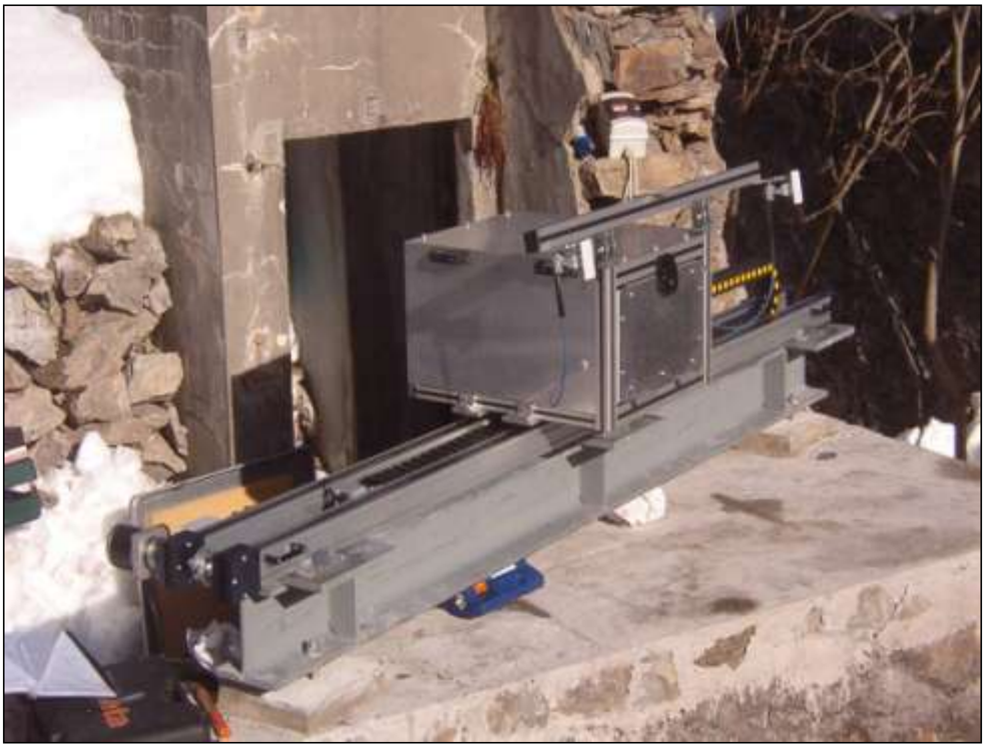


Fig. 53: Ground-based InSAR-System

6.5.4.2 Measured Parameters

Ground-based synthetic aperture radar (GB-SAR) allows the calculation of the line of sight distance between the system and natural reflectors within its field of view. It uses Ku, C and L frequency band radar emitted from a portable Linear SAR (LISA) system. The system was developed by the Joint Research Centre (JRC) of the European Commission (Antonello et al., 2004; Corsini et al., 2006; Rudolf et al., 1999). These frequencies are in the microwave portion of the electro-magnetic spectrum with a longer wave length than that of visible light so that the system is less sensitive to fog, rain, and snow than optical and laser methods.

By using interferometric processing of consecutive surveys to identify differences in the phase of the returned radar wave, GB-InSAR can provide a measure of ground displacement toward the sensor with a precision in the order of 0.3 to 0.7 mm (LiSALab srl, 2007). These measurements can be obtained over ranges of a few meters to several kilometres. The extent of the target area is defined by the radar antennas which have a 3dB beam width of approximately 20°; the area therefore varies with increasing target distance from the radar (Antonello et al., 2004).

6.5.4.3 Installation Considerations

GB-InSAR installation requirements depend largely on the purpose of the investigation. Applications of this technique to date have ranged from:

- rapid deployment (within 4 days) and emergency monitoring of a reactivated rotational-translational earth slide over a period of several days (Corsini et al., 2006),
- temporary setup and intensive monitoring of an existing landslide's response to rainfall over a short period (Antonello et al., 2004; Barbieri et al., 2003; Pieraccini et al., 2003)
- semi-permanent installation and continuous monitoring of a slope over several months to determine residual risk following a disastrous landslide (Antonello et al., 2004; Casagli et al., 2003)
- permanent foundation construction and long-term periodic re-survey of large, slow-moving slope instabilities (Noferini et al., 2005), and
- permanent installation of a continuously active GB-InSAR to monitor activity of a hazardous slope instability (Antonello et al., 2004; Casagli et al., 2004).

Due to the very high accuracy of GB-InSAR systems it is essential that the SAR is mounted on a stable platform, and in the case of long-term surveys, reasonable steps should be taken to ensure the platform is sited on a stable foundation. Where the instrument is to be repositioned for repeat surveys, a solid frame should be installed to ensure accurate repositioning.

GB-InSAR surveys have been shown to be sensitive to environmental factors, these include vehicle traffic between the SAR and the target, humidity variations, and decorrelation (a random change of the position and physical properties of the scatterers on the slope) due to vegetation (Corsini et al., 2006; Noferini et al., 2005). The effect of these factors can reduced through careful installation and processing.

6.5.4.4 Measurement Interval/Frequency

The re-measurement interval of GB-InSAR surveys depends largely on the rate of ground deformation and the time required to physically undertake a single survey. The maximum re-measurement interval should be programmed so that the magnitude of the expected ground deformation between measurements is less than the wavelength of the radar. Technical constraints restrict the minimum measurement interval to a few minutes, and therefore limit the maximum observable deformation rate to a few decimetres per hour (Antonello et al., 2004).

7. BENCHMARKING

Chapter 6 introduced a large variety of methods and sensors that are suitable for slope monitoring in some way. The parameters that can be measured differ significantly: relative changes of distances, absolute coordinates of single points, area-wide rates of subsidence just to mention a few. In addition, accuracy depends on many factors such as hardware, observation techniques, data processing and experience.

All theses circumstances make it impossible to directly compare methods or even to create a guidebook that decides which system is the best solution for a particular problem. Since requirements change on every specific slope it is rather necessary to understand the basic principle and the differences to be able to do an appreciation of values. Nevertheless, the following tables shall provide a quick overview over the possible field of application. At this juncture a classification was mainly done by introducing characteristics such as surface extension, coverage and predominantly morphology. Fitting methods are named as well as the achievable accuracy of the measured quantity. Some comments shall support first considerations. The methods are, as mentioned above, explained in detail in the last preceding chapter. Moreover ANNEX B summarizes many methods in terms of specification sheets.

Table 8: Monitoring Methods for small surface extension (< 1 km²)

Morphology	Coverage	Monitoring Method	Quantity measured	Accuracy	Comments
predominantly flat	single point(s)	**RTK-GPS**	3D relative or absolute single point movements	P[40]: 2 - 4 cm H[41]: 4 - 8 cm	Real time monitoring requires a GSM/UMTS connection or a radio link.
		R/DGPS	3D relative or absolute single point movements	P: 0.5 - 2 cm H: 1.0 - 4 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the institution of an elaboration centre connected in real time to the sensor.
		Tacheometry	3D relative or absolute single point movements	0.5 - 2 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the installation of automatic total stations connected in real time to the elaboration centre.
		Precise Levelling	single points altitude movement	0.15 - 3 mm/km[42]	For high precision survey fixed levelling points are needed in a stable position
		Geotechnology	various		In general relative measurements
	area-wide	**Terrestrial Laserscanning**	changes in volume & topography	2.5 - 7 cm	It is possible to install an automatic scanner. The real time monitoring is affected by the elaboration time.
		Geoelectric	changes in electric resistivity of subsurface		Distribution of resistivity changes indicates changes in landslide water regime and can be seen as evidence for changes inside a landslide
		Microseismic	magnitude of acoustic signals		Correlation of slope acoustic events and landslide velocity/degree of slope instability. This is more applicable to developing rotational or toppling failures than translational slides.
predominantly vertical	single point(s)	**Tacheometry**	3D relative or absolute single point movements	1 - 4 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the installation of automatic total stations connected in real time to the elaboration centre.
	area-wide	**Terrestrial Photogrammetry**	difference along a prefixed direction between surfaces	~ (1.5 - 4) × camera distance	This method allows the construction of 3D movement vectors.
		Terrestrial Laserscanning	changes in volume & topography	2.5 - 7 cm	It is possible to install an automatic scanner. The real time monitoring is affected by the elaboration time.
		Ground-based InSAR	change in line-of-sight distances	0.3 – 0.7 mm	

40 Position (2D)
41 Height/Altitude (1D)
42 Accuracy for Precise Levelling dependant on distance between 2 control points

Table 9: Monitoring Methods for medium surface extension (1 – 25 km²)

Morphology	Coverage	Monitoring Method	Quantity measured	Accuracy	Comments
predominantly flat	single point(s)	**RTK-GPS**	3D relative or absolute single point movements	P: 3 - 4 cm H: 6 - 8 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Real time monitoring require a GSM connection or a radio link
		R/DGPS	3D relative or absolute single point movements	P: 1 - 2 cm H: 2 - 4 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the institution of an elaboration centre connected in real time to the sensor
		Tacheometry	3D relative or absolute single point movements	1 - 4 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the installation of automatic total stations connected in real time to the elaboration centre.
		Precise Levelling	single points altitude movement	0.15-3 mm/km	For high precision survey fixed levelling points are needed in a stable position
		Geotechnology	various		In general relative measurements
	area-wide	**Geoelectric**	changes in electric resistivity of subsurface		Distribution of resistivity changes indicates changes in landslide water regime and can be seen as evidence for changes inside a landslide
		Microseismic	magnitude of acoustic signals		Correlation of slope acoustic events and landslide velocity/degree of slope instability. This is more applicable to developing rotational or toppling failures than translational slides.
		Aerial photogrammetry(helicopter)	difference in altitude between surfaces	~ (1.5 - 4) × camera distance	This method allows the construction of 3D movement vectors.
		Direct aerial photogrammetry (helicopter)	difference in altitude between surfaces	~ (1.5 - 4) × camera distance, min. 15 - 25 cm	This method allows the construction of 3D movement vectors.
		Airborne Laserscanning (from helicopter)	difference in altitude between surfaces	15 - 25 cm	-
predominantly vertical	single point(s)	**Tacheometry**	3D relative or absolute single point movements	1.5 - 7 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the installation of automatic total stations connected in real time to the elaboration centre.
	area-wide	**Aerial photogrammetry(helicopter)**	difference along a prefixed direction between surfaces	~ (1.5 - 4) × camera distance	This method allows the construction of 3D movement vectors.

Table 10: Monitoring Methods for large surface extension (25 – 225 km²)

Morphology	Coverage	Monitoring Method	Quantity measured	Accuracy	Comments
predominantly flat	single point(s)	**R/DGPS**	3D relative or absolute single point movements	P: 1 - 3 cm H: 2 - 6 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the institution of an elaboration centre connected in real time to the sensor
		Tacheometry	3D relative or absolute single point movements	1.5 - 7 cm	For high precision survey fixed points are needed with centring forced and vertex in a stable position. Continuous monitoring requires the installation of automatic total stations connected in real time to the elaboration centre.
		Satellite-born DInSAR/PS	Movement of single points along a prefixed direction	2 - 4 mm along the direction of acquisition	It gives the movement of PS points (surfaces reflecting radar impulses). Low planimetric accuracy. If reflecting point moves can't be used again.
	area-wide	**Aerial Photo-grammetry**	Difference in altitude between surfaces	~ (1.5 - 4) × camera distance	This method allows the construction of 3D movement vectors.
		Optical Satellite Imagery	Difference in altitude between surfaces	min.: 0.7-1.5 m	This method allows the construction of 3D movement vectors.
		Airborne Laserscanning	Difference in altitude between surfaces	20 - 45 cm	-

Table 11: Monitoring Methods for very large surface extension (> 225 km²)

Morphology	Coverage	Monitoring Method	Quantity measured	Accuracy	Comments
predominantly flat	single point(s)	**R/DGPS**	3D relative or absolute single point movements	P: 1 - 3 cm H: 2 - 6 cm	
	area-wide	**Aerial Photo-grammetry**	Difference in altitude between surfaces	~ (1.5 - 4) × camera distance	This method allows the construction of 3D movement vectors.
		Optical Satellite Imagery	Difference in altitude between surfaces	min.: 0.7-1.5 m	This method allows the construction of 3D movement vectors.
		Airborne Laserscanning	Difference in altitude between surfaces	20 - 45 cm	-
		Satellite-born DInSAR/PS	Difference in altitude between surfaces	15 - 25 m	-

8. CONCLUSIONS

The topic of WP6, monitoring of slope deformations, was chosen as representative for one element of a comprehensive hazard management. The detailed report shows the broad variety of approaches to slope monitoring.

As almost each hazardous site shows specific problems, a standardised proceeding will not be possible. In general the time for a comprehensive monitoring is restricted but the time span observed can be extended by the inclusion of historical data. Longer observations are necessary to determine the probability of an event.

Monitoring may serve as an early warning system, but the results of WP6 show that this is only possible in special cases and with a high technical and socio-political effort. Landslide warning systems (i.e. monitoring systems in which data is collected and analysed continuously and civil protection procedures are activated when a definite threshold is exceeded) are extremely appealing to manufacturers of geotechnical instruments, professionals and sometimes to local authorities. The huge progresses of electronics seems to indicate that a wide application of electronic devices to slope monitoring is logic and straightforward. Good and useful as they may be, however, these systems may be difficult to use, complex and troublesome to operate and maintain over long time spans. So their use should be carefully evaluated and limited to the most critical cases only.

The monitoring methods are evolving rapidly, especially those based on remote sensing. Further improvements are to be expected in many fields and the knowledge is changing constantly. In some questions, there is special need for further research and development. The following actual problems can be enumerated:

- Radar methods as e.g. PS-DINSAR still have to be verified and crosschecked in the field, the software for deformation analysis must be developed further.
- The exposition problem for deformations parallel to the radar satellite tracks should be solved
- GPS high precision methods must be developed further to reduce costs and the manpower needed for each campaign.
- In deformation analysis, due to the large variety of new monitoring techniques and sensors, the creation of hybrid spatial and time-dependent analytic and stochastic models should be encouraged and explored in detail.
- As there is still a great uncertainty about hardware and data collection, it is necessary to compare different approaches. Independent validation scenarios should also include methods that are not related to the one tested. Therefore cross-validation systems have to be taken into account.
- The analysis of multi-sensory time series must to be able to detect erroneous data instantly to avoid false alarm. Besides advanced filtering techniques, fuzzy logic seems to be an adequate assessment tool and should be developed further.

The findings of Work Package 4 (WP4 – Information and Publicity Activities) within this project indicate that the Alps will be hit in a differentiated way by the consequences of climate change: some places and areas can even benefit, others might suffer severely. It is now essential to find out the risk-areas in order to start or enhance preventive measures. Slope monitoring as described within this report are a crucial element of prevention and prediction. The importance of prevention is fully recognised by the practitioners and by the scientists, but not yet in the public awareness. Prevention costs money and will not show immediate results. Nevertheless, on the long term it is often the cheapest and most sustainable way to save lives and goods.

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ANNEX A BEST PRACTICE EXAMPLES

A1. The Arpa Piemonte Landslide Monitoring Network

Author: Carlo Troisi (Arpa Piemonte)

Abstract: The Arpa Piemonte Landslide monitoring network can be regarded as an example of managing at a regional scale. It was devised for the specific Piemonte requirements, but its philosophy can be easily exported do suit other situations. Regione Liguria (Italy) is currently creating a similar network based on Piemonte experience.

Weblinks: http://www.arpa.piemonte.it
http://gisweb.arpa.piemonte.it/arpagis/index.htm

More detailed description

In Piemonte (Italy), remedial works, river training works and landslide monitoring systems are usually made by local authorities (communes), by means of financial resources from the Regional government. Piemonte has a large number of communes, about 1200. Most of these are small: about 1000 have less than 3000 inhabitants and about 350 have less than 500 inhabitants.

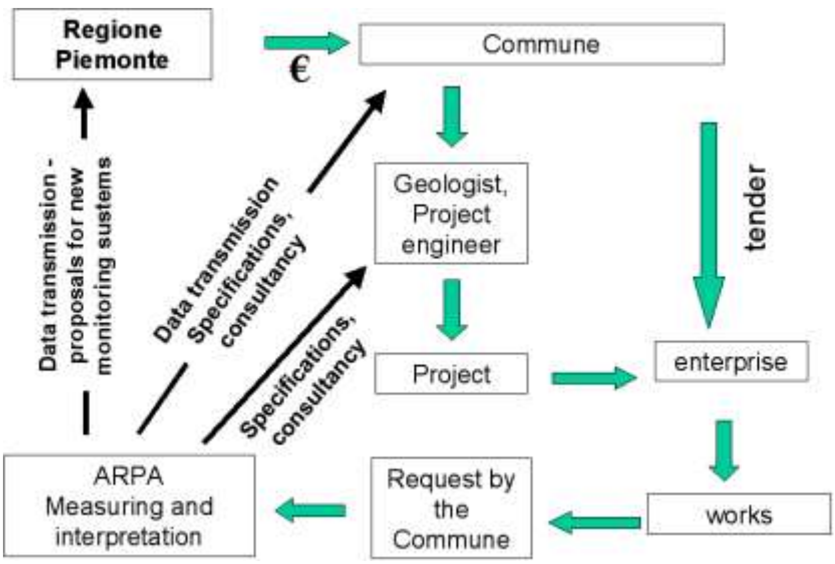

Fig. 54: Flow-chart of Arpa's role in managing landslide monitoring systems in Piemonte.

Small Communes have very limited budgets and very limited technical structures; often with a strong turn-out rate. Landslides monitoring, on the other hand, requires economic resources, specific know-how and constant attention over long time spans (several years at least) that communes can rarely provide. Given this framework any landslide monitoring systems is likely to go stale prematurely, cease to operate and suffer early abandonment.

To solve the problems, starting from the nineteen-eighties a specific unit of the Regional Geologic Survey (now part of Arpa Piemonte) is active in order to take in charge the landslide-monitoring systems and carry out all the connected activities all-over Piemonte (Fig. 54).

Site Information, Instrumentation	#
Observed sites	300
Sites with detected displacements	~ 150
Inclinometers	~ 700
Inclinometers (meters of casing)	~ 23.000
Piezometers	~ 400
Extensometers	~ 100
In-place inclinometers (automated data recording and GSM or GPRS data transmission)	21
Automated data recording units	~ 120
Automated data transmision units	~ 50
GPS monitored-landslides	~ 20
Conventional topographic surveys	~ 10

Table 12: Composition of the Monitoring Network of ARPA Piemonte

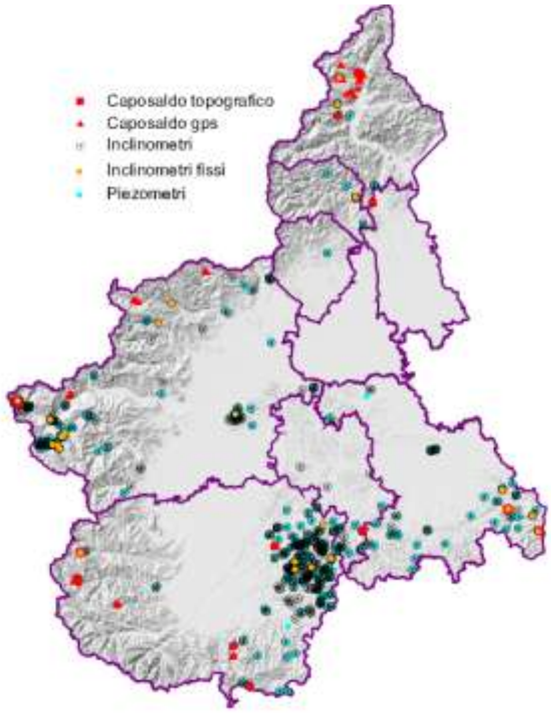

Fig. 55: Monitored landslides in Piemonte

The monitoring network now consists of about 300 sites. Each site includes an active, suspended, dormant or simply suspected landslide with one or more instruments (Table 12). Displacements from some millimetres per year to 20 cm per year are recorded at about 150 sites. The ARPA monitoring network is "soft" and extensive rather than intensive, i.e. it includes many sites, each one with few instruments, and no warning systems.

The goals of the monitoring network are:

- to ensure that all landslide - monitoring devices installed by public agencies in Piemonte are properly measured and maintained;
- evaluate the state of activity and the rate of movement of monitored landslides;
- update the conceptual model of monitored landslides;
- provide local authorities/civil protection agencies with information on landslide evolution;
- support of local authorities in the aftermath of major calamities.

Two contractors, with Arpa specifications, provide (with an annual total cost of about 300.000 €):

- manual measuring of inclinometer casings (one to four measurements per year);
- manual measuring of GPS benchmarks (one-two measurements per year);
- data off-loading from automated recording units (two to four times per year);
- maintenance of automated recording units, in-place inclinometers, extensometers etc.

Activities of Arpa unit (5 members of staff) include:

- direct measurements of some of the instruments;
- storage of all the data in a tailor-made GIS-based data bank;
- data interpretation;
- Integration the data of the Arpa-made regional landslide inventory;
- Transmission of the interpreted data to whom it is concerned; more than 500 reports are drawn-up each year.

Such a monitoring approach has many positive aspects and some drawbacks:

- any monitoring instrument installed in Piemonte is properly measured and maintained;
- monitoring results are examined by competent personnel;
- the procedure is uniform over the entire regional territory;
- all institutions (region, provinces, communes, civil protection etc.) are regularly informed about monitoring results;
- centralized management provides a strong cost reduction.

Main drawbacks are:

- great variety of monitoring schemes designs;
- great variety of instruments;
- being service-free and "automatic" many communes simply don't care much of the whole business.

Much information concerning the Arpa landslide monitoring network are available on the internet by means of a Web-GIS-service, which also includes the landslide inventory and the geotechnical data-base (see weblinks above).

A2. The case history of Bognanco

Author: Carlo Troisi (Arpa Piemonte)

Abstract: The example of Bognanco is a good example of how a simple and low-cost landslide monitoring system may prove to be an invaluable tool as a decision making tool in case of calamity. Since, all around the alpine area, more and more local laws and programs lead to the production of official classifications of landslide-affected areas, local authorities should be acquainted with this type of approach.

Weblinks: http://www.arpa.piemonte.it

Bognanco is a small town in the northern part of Piemonte, close to the border with Switzerland. Part of the village develops on a ridge which, since the 19th century, shows consistent traces of displacements related to a slow-moving landslide affecting a 20 to 60 m thick detritic and morainic deposits. Since 1992 the former Geological Survey of Regione Piemonte (now part of Arpa Piemonte) worked on the site in order to define a model of the landslide, to help local authorities to cope with the phenomenon and to define general hazard and risk conditions. In this framework the Regione Piemonte financed a monitoring system consisting of four inclinometers and four piezometers (Fig. 56).

Fig. 56: The Graniga ridge in Bognanco. Legend: (1) High risk area in accordance with National Law. (2) Inclinometers. (3) Main slides, mudflows and fractures developing during heavy rains.

In 1999 the ridge was classified, in accordance with National Law 675/98, as high risk area. Starting from October 13th, 2000, the area was affected by heavy rains lasting four days; total precipitation was about 740 mm. Since the very first hours of the rains Bognanco was totally isolated, for the only access road was blocked by a large landslide. During October 13th the ridge was affected by several phenomena:

- development of major fissures in the upper part of the ridge,
- rotational landslides and mud flows,
- collapsing of retaining walls in the upper hamlet, causing the destruction of two buildings,
- development of debris flows and minor rotational landslides in the lower part of the ridge,
- development, in the lower hamlet of a rotational landslide with destruction of two buildings,
- development of fissures of variable size all around the ridge.

The distribution of phenomena, concentrated along the edges of the instable ridge, made the mayor and the municipal technical officer to fear that a failure of the whole ridge was going on. During the night of October 14th the mayor ordered the evacuation of the hamlets and 179 inhabitants moved (in the dark, on feet and through the rain) on a nearby ridge supposed to be safer.

The governmental and regional authorities also feared that a failure of the ridge (besides destruction of the village) would also dam the Bogna stream; breaking of the landslide dam could play havoc on the town of Domodossola, few kilometres downstream. These allegations were widely reported by both local and national media, creating general concern.

As soon as practically possible the four inclinometers were measured with the aid of the army on October the 19th. They all were undisturbed; the data allowed interpreting the observed landslides as a set of surficial phenomena. In other words: no failure of the whole ridge was going on. On October the 20th (just three days after rain stopped) people could go back to their houses on the basis of a technical note prepared by the regional geologists. Such a prompt and effective response was possible only because of the presence of the inclinometers. Without these instruments a much longer time would have been needed to allow people to return on a landslide area officially classified as “high risk area”.

A (possibly optimistic) estimation of this longer time is 60 days; a rough evaluation of the overall evacuation costs of the whole village for this period is around 5 M€; this is a purely economic evaluation, which do not take into account important human and social factors which are as (or even more) important as the purely economic elements. Since the costs of installing, measuring and maintaining landslides monitoring system over the entire region in the period 1993-2000 were about 7 M€, it is possible to state that the four inclinometers of Bognanco almost repaid the costs of the whole business.

A3. Erosion and Deposition at the landslide "Galierm" – Experiences with TLS

Author: Alexander Prokop (BOKU Vienna)

Abstract: The landslide "Galierm" was surveyed within a period of 18 months by terrestrial laser scanning and tachymetry. A unique post-processing methodology was established. Within this comparison of methods it could be shown that terrestrial laser scanning will, among others, be an important method for monitoring landslides in the future.

Weblinks: http://www.baunat.boku.ac.at/h871_einheit.html?&L=1

"Galierm" Landslide

The "Galierm" landslide is located north-east of the town of Schruns in the area of Montafon (Vorarlberg, Austria) above the bank of Litz stream. A high water event in 2005 caused significant erosion to the stream bank. A weak section of the stream bank started significant movement of the slope above. The dimensions of the moving slope section are approximately 100 x 100 m.

To monitor the movement patterns of the slope, terrestrial laser scanning (device: Riegl LMS z420i) was applied due to the following site characteristics:

- the distance between scanner position and the slope monitored is in a range of 100 m (expected accuracy of the measurement in a range of 5 cm)
- the expected movement rate within the test period is > 15 cm
- the test area is easy reachable by car, power supply and protection of the laser device against external forces does exist
- the monitored slope is 70% free of vegetation
- the incident angle of the laser beam on the slope is within a reasonable range
- a comparison of terrestrial laser scanning measurement method with tachymetry could be executed

Data acquisition

Between March 2006 and September 2007 several monitoring activities of the moving slope Galierm were executed using both measurement methods, terrestrial laser scanning and tachymetry. The laser data acquisition steps included:

- Localisation of a stable scanner position allowing reasonable angles of incidence on the target surface
- Installation of a rigid geodetic network allowing both registration of laser scanner position and tachymetry (registration using tie point targets).
- Laser scanning process including image acquisition that is collected by cameras that are mounted on the scanning device for the creation of orthophotos.

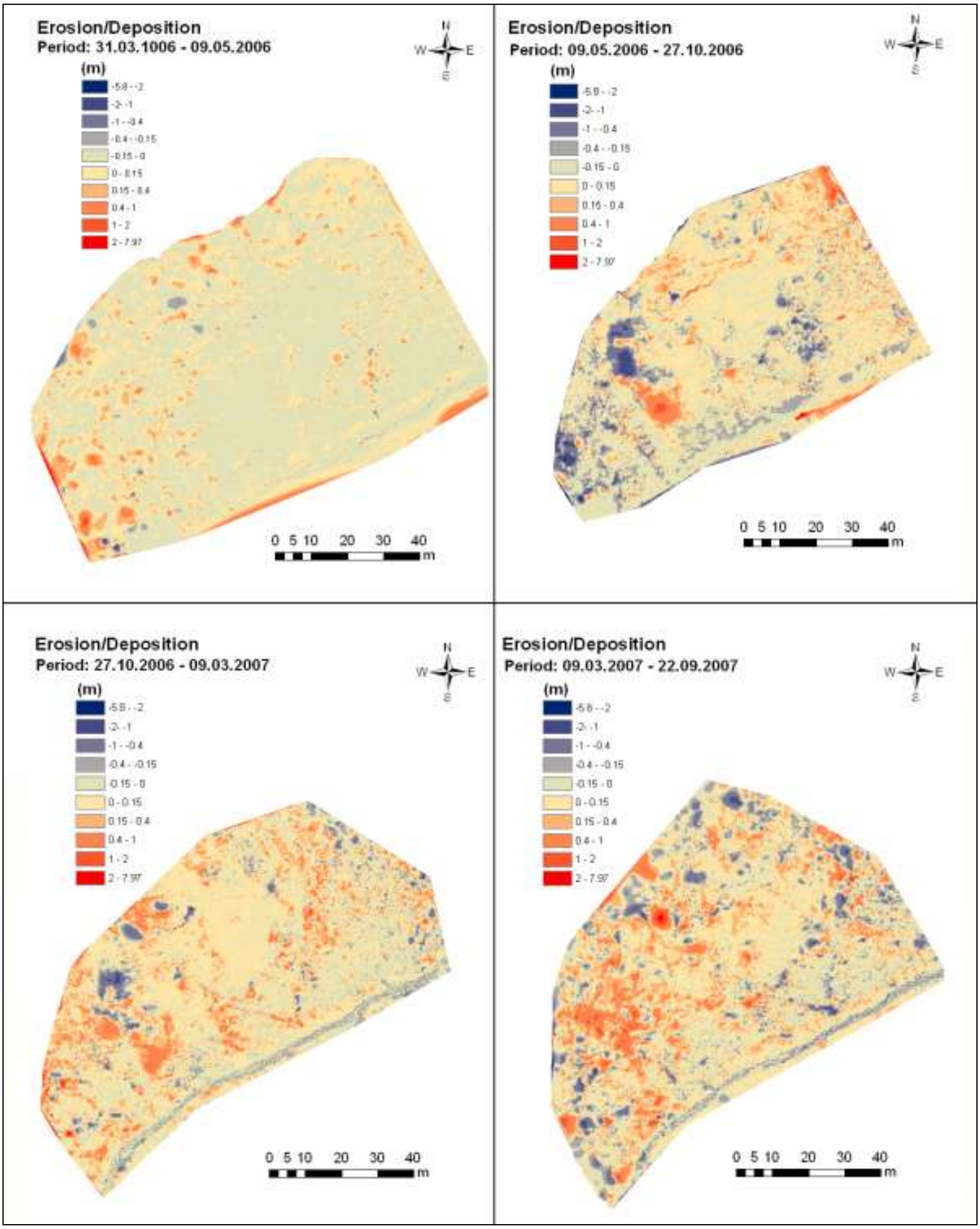

Fig. 57: Determination of erosion and deposition behaviour of the moving slope with TLS

Post processing

Depending on the characteristics of the laser scanned target (e.g. different distances and angles of incidences) the point cloud is inhomogeneously distributed. Furthermore vegetation and objects within the scanned area create points that do not belong to the surface of the investigated slope. Following every target surface that is laser surveyed, a unique post processing method needs to be established, which included the following steps for the Galierm landslide:

- Data quality check (Reproducibility tests, in case of misalignment of scans with respect to each other, scans are sorted out)
- Filtering of point cloud data (Separation of the favoured laser points on the terrain surface (ground points) from the topographically irrelevant points (non-ground-points))
- Interpolation of point data and creation of DSMs (After using different types of geo-statistical methods, Natural Neighbour was considered to be the optimal method concerning the existing sources)
- Creation of orthophotos (Colour information from the digital pictures was used to texture the surfaces of the DSMs)

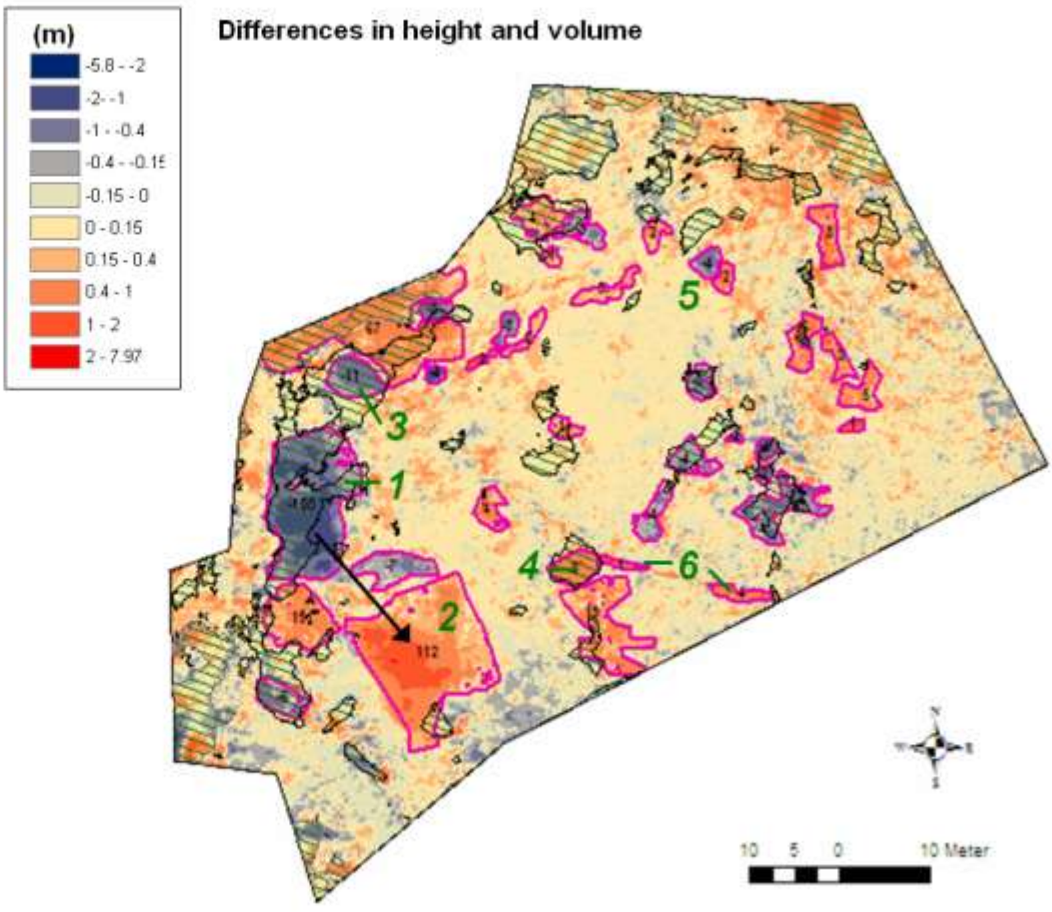

Fig. 58: Significant mass movements in the western part of the slope (1→ 2)

Calculation of slope movement patterns

After the creation of DSMs, zones of erosion and deposition of mass were detected by calculating differences in height (h-axis) or volume between two surface hulls. But to determine slope parallel movement patterns it is necessary to create orthophotos to localize the same point positions on different surface hulls. After the localisation of the same points (e.g. stones and rocks) their position change between two monitoring activities is described by 3D vectors. The 3D vectors were then compared to the tachymetry measurement to validate the laser data quality.

Results and Conclusion

The big advantage of the laser measurement is its ability to provide data with high spatial information. In the case of the "Galierm" landslide, moving parts of the slope could be detected as seen in the (Fig. 57). Determination of the erosion and deposition behaviour of the moving slope was only possible with the laser measurement, tachymetry failed with regard to this particular application. The accuracy of the investigation of height differences between two surface hulls lies within a range of 50 mm (determined by reproducibility tests). Before concluding movement behaviours, the results need to be interpreted concerning the point density of the zones of interest.

Significant mass movements could be detected in the western part of the slope (Fig. 58). Masses moved (starting at the second monitoring period) downwards. This process continued during the third monitoring period. All other zones of height differences can not be considered as slope moving patterns (3, 4, 5 and 6). Either point density was to low, or significant differences in vegetation caused the differences in height.

After the creation of orthophotos the slope parallel movement patterns were calculated and compared to tachymetry. To measure the difference in position of a single point, the laser measurement lack accuracy in comparison to tachymetry (caused by e.g. larger beam diameter and an imprecise registration process). But still, it was possible to determine a 3D position of a point of interest within an accuracy range of 50 mm (distances to the target < 120 m). Concerning monitoring activities for slopes that are moving with rates > 100 mm per period and can be surveyed from distances of about 500 m, terrestrial laser scanning will, among others, be an important method to monitor landslides in the future.

A4. PROALP – Mapping & Monitoring of Permafrost areas

Author: Andreas Zischg (Autonome Provinz Bozen: Abt. Wasserschutzbauten, Abenis AG)

Weblinks: http://www.provinz.bz.it/hochbau/projektierung/830.asp

Objectives of the project

The main objective of this project was the investigation and the delimitation of the permafrost areas and the monitoring slope movements in the whole mountain area of the Autonomous Province of Bolzano, South Tyrol. The following methods were used and combined:

- inventory of rockglaciers
- multitemporal inventory of perennial
- snow patches
- multitemporal inventory of slope movements in permafrost areas by DiffSAR
- georadar measurements
- GPS-measurements
- hydrological and geochemical analyses
- BTS measurements
- modelling of permafrost distribution
- geomorphologic analyses

Fig. 59: Permafrost localisation

Strategic aspects

With this knowledge about the localization and distribution of evident geomorphic phenomena proving the existence of permafrost in combination with remote sensing and modelling techniques, the permafrost related issues can be considered in land use planning tasks and hazard zone mapping. The multitemporal approach allows the assessment of the changes in permafrost forced by climatic changes. The verification of remote sensing and modelling techniques by on-site geomorphologic analyses and geophysical measurements showed that the combination of remote sensing and field measurements lead to the creation of reliable datasets about the phenomena. With the created datasets, permafrost related issues could be considered in hazard zone mapping and natural hazard and risk management.

A5. PSInSARTM-Technique for landslides monitoring

Authors: Alessio Colombo, Carlo Troisi (Arpa Piemonte)

Weblinks: http://www.arpa.piemonte.it

Main principles

PSInSAR™ is a technique which allows, by means of the comparison among satellite radar images taken at regular time intervals, to evaluate the displacements of some ground points which are good radar reflectors, named PS. PS can rock outcrops (Fig. 60), large boulders, metal or concrete power poles, buildings, manufactures, to mention but a few. PS are absent over vegetated areas and water bodies, for these surfaces quickly change their shape, hence the way they appear in radar images. For each identified PS it is possible to calculate the displacements occurred in the time span considered. The development of this new robust technique based on the interferometric analysis of radar images and the possibility of integrating these data within a Geographical Information System (GIS) strongly I increases the potential of remote sensing for landslide investigations.

Fig. 60 a/b: Example of a natural target in Piemonte Alps.

The application scale range is very wide, from regional to local, depending on data availability. The displacement velocities recordable with the PSInSAR™ technique are very low, generally less than 5-6 cm/a. The computational process in the Standard PS Analysis (SPSA) gives a linear value of displacement up to the annual average calculated along the available time span, since 1992 (year when the first interferometric platform, ERS-1, began to work).

The PSInSAR™ post processing provides detailed information about the kinematics of large and very slow moving phenomena. In some cases the PSInSAR™ data may allow to understand the real displacement of the entire slope without installing any artificial monitoring system. Since PSInSAR™ data are issued by DBF tables (Fig. 61), exportation in a GIS is simple and straightforward.

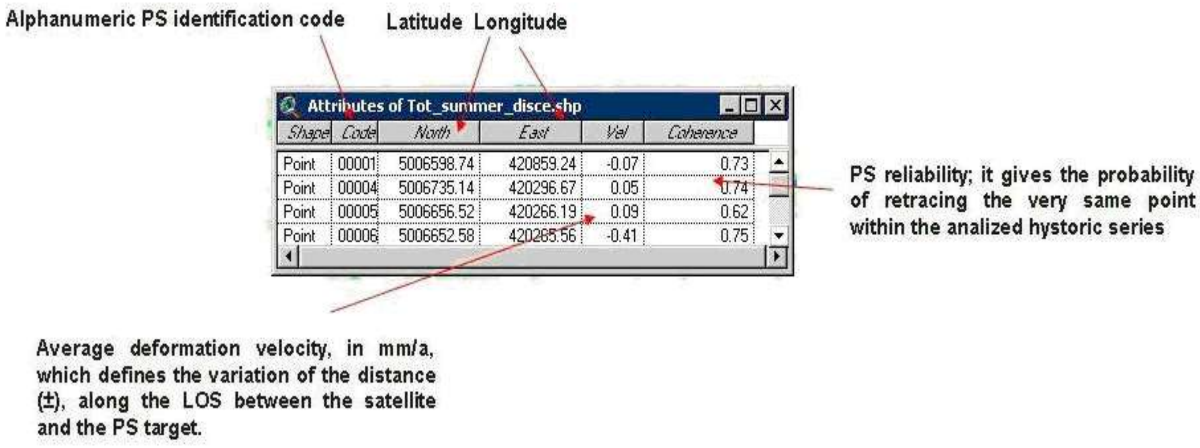

Fig. 61: Description of the PSInSAR™ presentation table

Application References

The system was successfully applied to confirm previous field surveys, to redefine the state of activity of known phenomena, to identify formerly unknown landslides and to detect relevant displacements even where shadowing hampers interpretation of optical images.

The main advantages of the techniques are:

- satellite radar images are available since 1992, so that it is possible to obtain displacement data since that year;
- a large number of slow-moving landslides can be cheaply monitored over a wide area;
- there is no need for any field device, benchmark, monument etc., moreover the monitored area need not to be accessible;
- data can easily be imported in GIS;
- high PS density (up to 1000 PS/km²);
- all-time/weather monitoring possibility.

Evaluation

In 2007 Arpa Piemonte (also in the framework of the ClimChAlp project) compared the results of PS analysis with the results of conventional monitoring.

In the example of Montaldo di Cosola, AL (Italy) (Fig. 62) the comparison of displacements recorded by PS and inclinometers shows an almost perfect dovetailing. PS displacements were projected along the displacement axis drawn from inclinometer readings.

PS interpretation may also be done by use of geostatistic techniques, such as cluster analysis, which produce isovelocity maps which may greatly help landslide interpretation. In the area of Bosia (CN), in Langhe area (Fig. 63), this type of analysis clearly shows how the upper part of the slope undergoes relevant deformation (detension) whereas the toe is more or less stable (Fig. 64). This allows inferring a "confined" landslide, an interpretation which is also suggested by the interpretation of inclinometer readings.

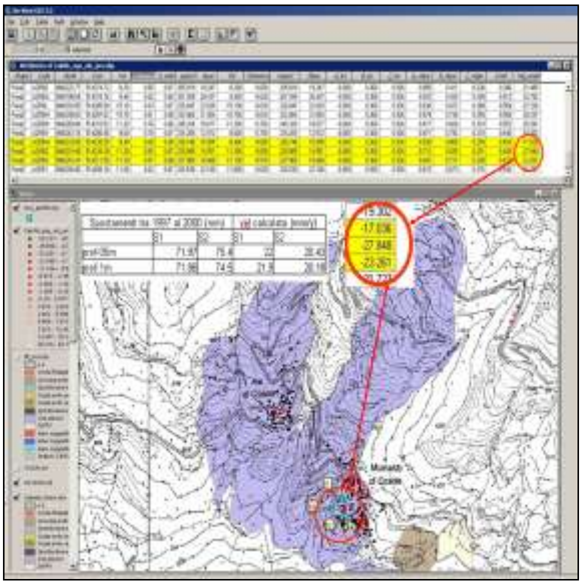

Fig. 62: Qunatity comparison of PSInSAR analysis and inclinometric monitoring

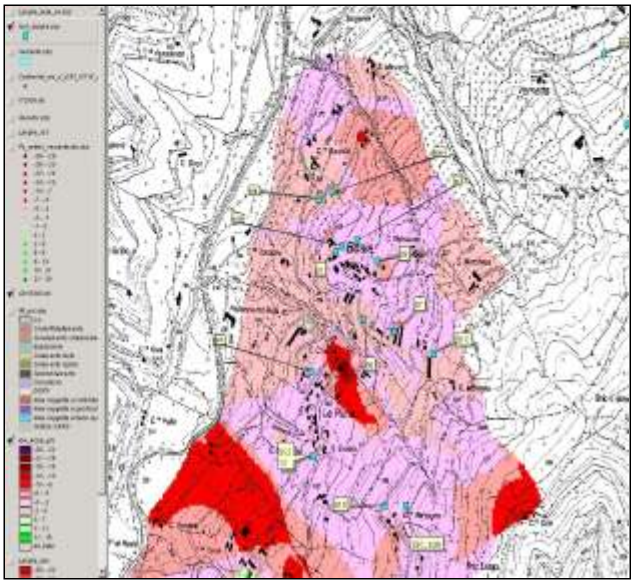

Fig. 63: PSInSARTM data interpolation. Creation of a iso-velocity map

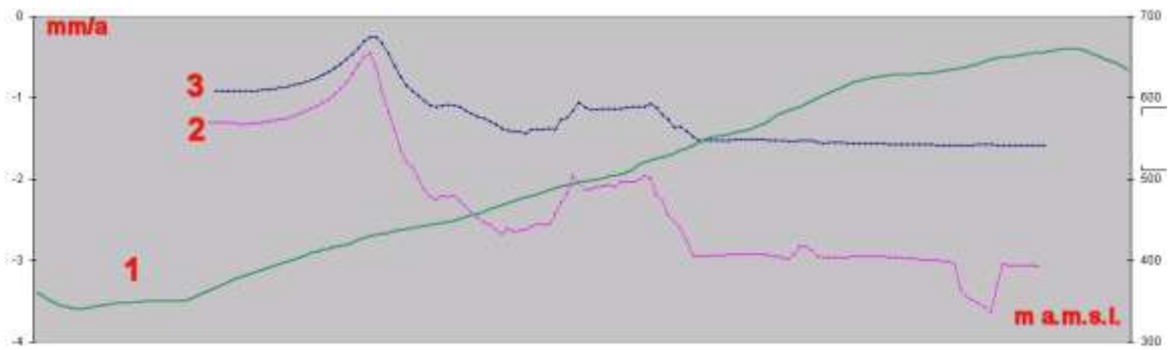

Fig. 64: Correlation between the interpolated velocity and the topographic profile in Bosia landslide. Legend: (1) Topographic profile. (2) PS-related displacement velocity along the LOS (line of sight between the PS and the satellite). (3) PS-related displacement velocity projected along the axis of sliding surface.

A6. 30 years of monitoring of the Sedrun landslide by aerial photographs

Authors: Johan Kasperski (CETE Lyon), Christophe Delacourt (Université Bretagne Occidentale) and Pascal Allemand (Université Lyon 1)

Context

The Sedrun Landslide is located in eastern Switzerland (Fig. 65). The unstable area covers 1.5 km^2 and involves around 100 millions m^3. Some major infrastructures are located in the region of Sedrun such as a construction site for the Gotthard Base Tunnel, an inter-cantonal road and railway connecting Zermatt to St. Moritz. Moreover, the village of Sedrun has been developed extensively over the last few decades, especially as a winter sport resort. The temporal origin of the movement observed is not easy to determine. Up to 1981 no significant motions have been recorded and the occasional snow avalanches originating from Val Strem sparked much greater concern.

Method

The landslide can be monitored by the measurement of reference targets at several epochs. However this technique cannot provide global view of the displacement map. Remote sensing is a powerful tool, because it offers the advantage of global covering. A new technique, called image correlation has recently been developed to derive displacement map from images acquired by airplane or satellite at various epochs. This technique is based on the automatic research of same structure over time-lapsed images. Then, the shift between the positions of the same structure on two images can be associated to surface displacements which occurred between the two dates. It has been successfully applied on various geophysics phenomena leading significant earth surface displacements (earthquake, volcano, glacier flow).

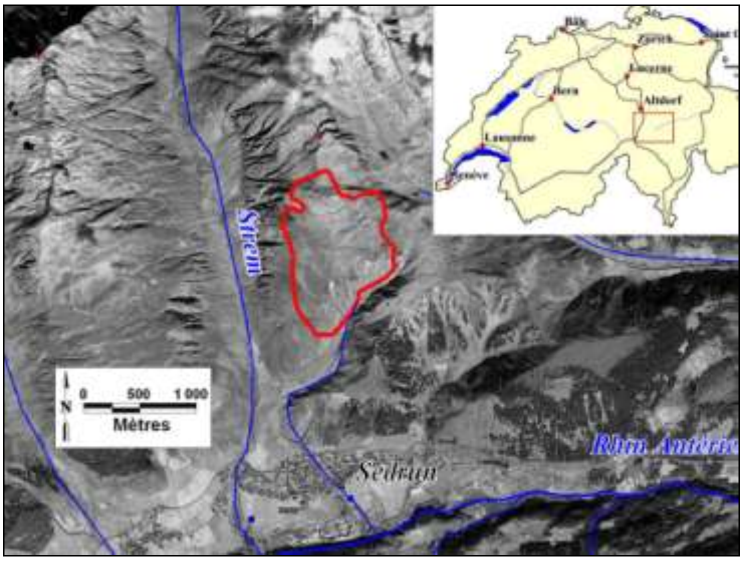

Fig. 65: Location of the Sedrun Landslide

Data

Both satellite and airplane regularly acquire images over Sedrun area. Three aerial images acquired in 1973, 1990, 2003 and three very high resolution images acquired by the QuickBird satellite in 2005, 2006 and 2007 have been processed. The spatial resolution (the size of the smallest object which can be observed on the images) is better than one meter.

Results

In the frame of the ClimChAlp project and for the first time, a displacement map has been derived showing the various parts of the landslide since 1970. The displacement of more than 500 000 points has been automatically calculated. Furthermore, temporal evolution of the landslide has been recorded over 30 years. A significant increase of the velocity of the landslide has been pointed out after 1990 (from 30cm by year between 1970 and 1990 to 50 cm by year after 1990). After 2000 the activity has decreased.

Fig. 66: Major crack at the summit of the Landslide

Conclusion

The image correlation technique is complementary to the present monitoring system which is based on the high repeatable measurement by laser technique of four targets localized in the landslide. Regular aerial and satellite acquisition provide the exact limitation of the sliding area and furthermore detect evolution in the spatial landslide behaviour. This information is a key point to adapt a monitoring system to the landslide evolution behaviour.

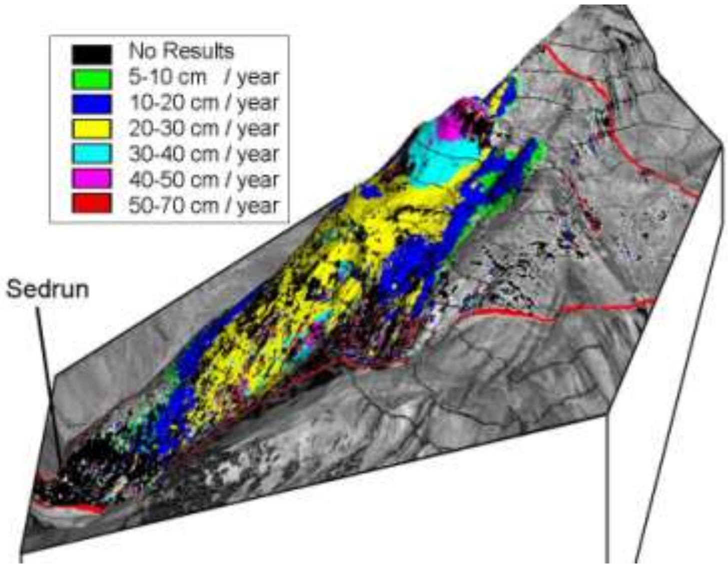

Fig. 67: Surface displacement map calculated by aerial image correlation (1990 and 2003)

A7. Laser/Video-Imaging of a rockfall in Séchilienne: from the precursors to the event

Authors: Johan Kasperski (CETE Lyon), Christophe Delacourt (Université Bretagne Occidentale) and Pascal Allemand (Université Lyon 1)

Context

The Séchilienne landslide (Fig. 68) is located in the Romanche Valley south-east of Grenoble in the crystalline basement of the Belledone massif. The landslide started in the 1980's by rockfalls which became more and more frequent on the road from Grenoble to the winter-sport resorts of the Oisans massif and Briançon region. As the landslide has developed, the road has been redrawn on the other side of the Romanche. At the end of the 1990's, it was obvious that the phenomenon was a deep one and that possibly more than 3 million m^3 could fall causing a natural dam on the river. This dam could break and cause inundation of the downward part of the valley. To prevent that risk, the inhabitants of the IIe Falcon village have been expropriated in application of the Barnier French law.

Actually, the site is monitored under the responsibility of the "Centre Technique de l'Equipement". Deformations, tilts, displacements and meteorological parameters are measured by wire extensometers, tiltmeters, tacheometers, a new technique based on micro wave radar and rain and snow gauges. These data show that the average displacement of the landslide is around of some millimeters per day and is partly controlled by climatic events.

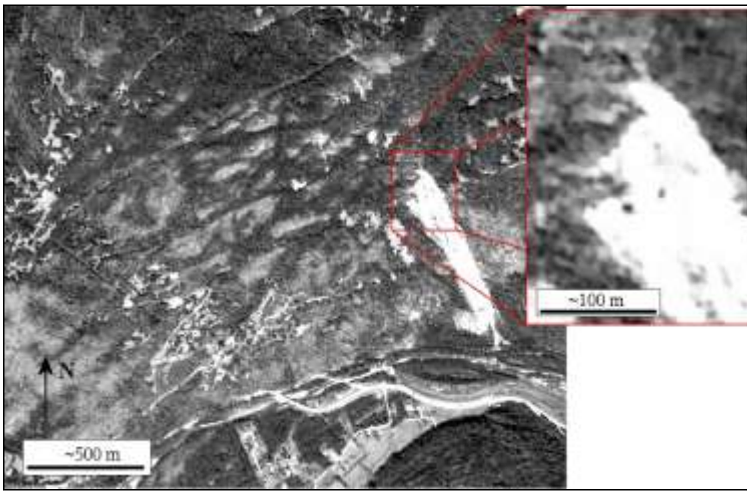

Fig. 68: SPOT image of the Romanche Valley in the Séchilienne area. The landslide extends from the base of the valley, near the river to the top of the Mont Sec which belongs to the Belledonne Massif. The enlargement of the image shows the zone from which the rockfall initiated.

In the frame of the ClimChAlp project, laser scan data of the upper part of the landslide were acquired twice a year. From the laser scan data, Digital Elevation Models (DEM) were built at a resolution of 20 cm for a precision better than 25 mm. Cross section on successive DEM can thus show the horizontal and vertical displacements of the landslide between two laser scan acquisitions.

Another monitoring technique has also been used: photographs from the landslide were regularly acquired from a control station located in front of the landslide on the opposite side of the valley. These images were correlated in order to follow the displacement of the instable areas.

Description of the event

On November 23rd, 2006 at 11:05 pm, upper parts of the landslide fall down. This event has been preceded by numerous small rockfalls of around 100 m^3 which occurred some weeks before. Thus this zone was submitted to an acute observation and a film of the event has been made. This instable surface belongs also to the area submitted to laser scanning. It was possible to measure the volume of rockfall from this laser scan data. In Fig. 69, one can observed cross sections of the successive DEM built from Laser Scan data. At the base of the profiles, the difference in topography before and after the event is clearly visible. The base of the profile of June 2006 is located 20 m under the profiles realized before the event. From parallel differential sections, the volume has been estimated around 39 000 m^3.

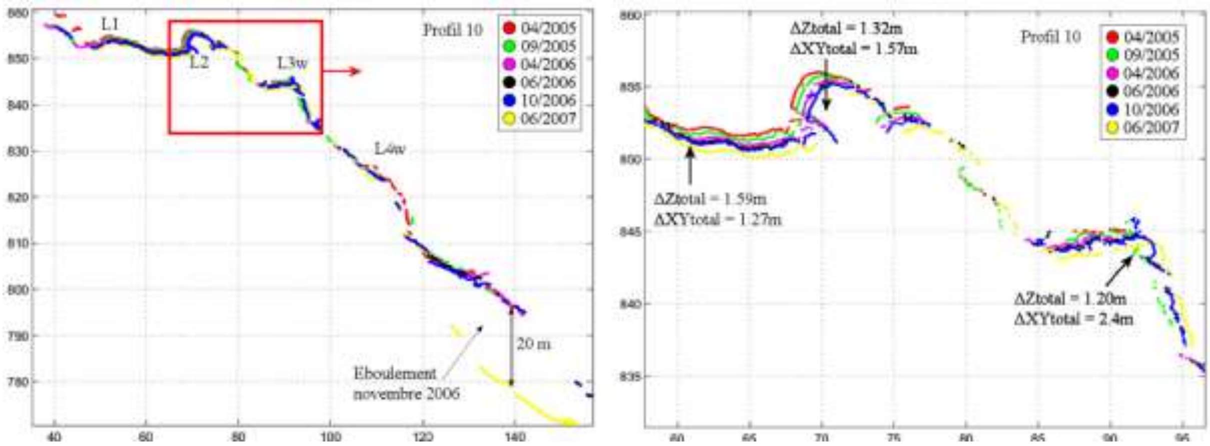

Fig. 69: Successive topographic sections acquired by laser scan The graph shows the topographic sections acquired between April 2004 to June 2007 in the upper part of the landslide. The effect of the rock fall is clearly visible on the lower part of the left image. The 20 m comparison of the June profile and the other one permits to evaluate the volume of the rockfall. On the right image, on can see the progressive translation and subsidence of blocks located above the rockfall. These bocks have been translated for around 2.5 m in 2 years and subsided by more than 1 m during the same period.

More interestingly, this rockfall has been preceded by a clear subsidence and translations which both are visible from the correlation of images acquired some days before the event (Fig. 70). The figure shows the result of the correlation between the images acquired on November 22nd and the image acquired on November 23rd before the event. Within one day the movement (which was classically around some centimeters per day) reached a value from 1 to 4 m. Thus, this technique of correlation of images is promising tool for monitoring instable areas.

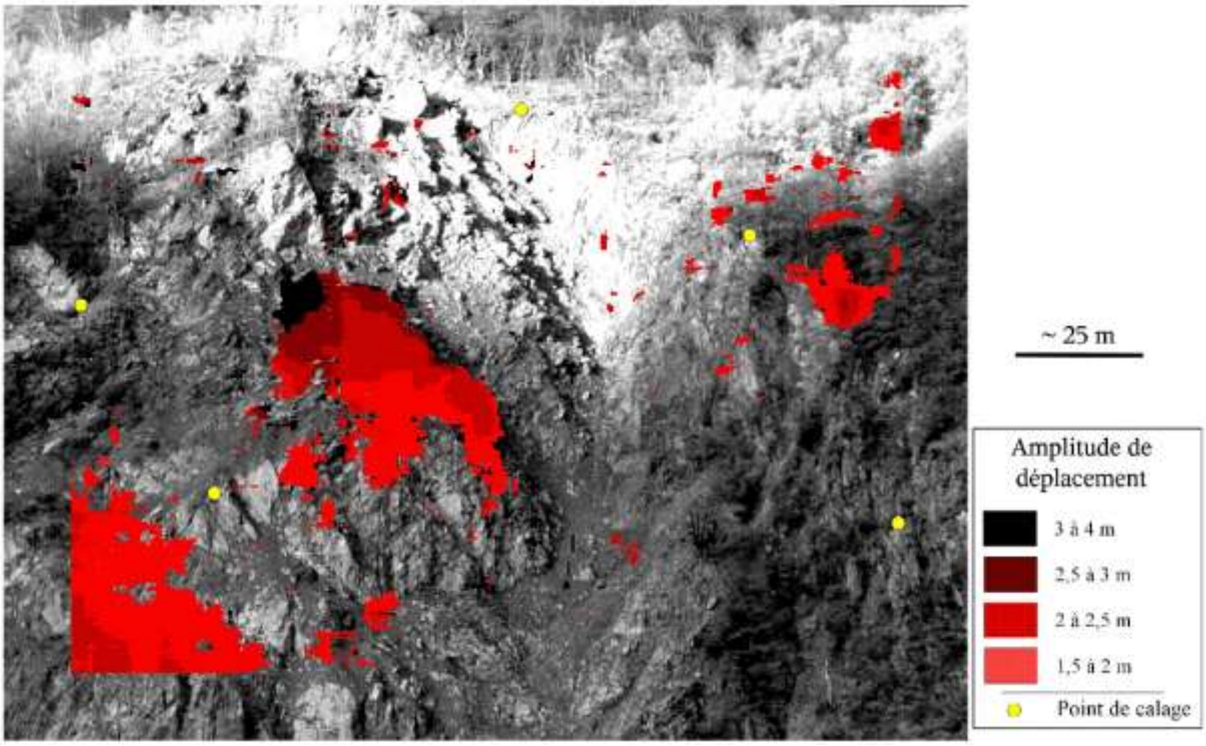

Fig. 70: Image Correlation. Results of the correlation of the photographs acquired on November 22nd and the 23rd, 2006 just before the rockfall. The correlation (colour coded) of the two images is reported on the oldest one. The colours code for the displacement which reached more than 3 m in one day in the upper part of the picture.

A8. The application of Airborne Laserscanning at the landslide "Doren"

Authors: Margarete Wöhrer-Alge

The landslide "Doren"

The landslide area is situated in the northern part of Vorarlberg/Austria on the right flank of the Weißach valley, about 10 km east of the regional capital Bregenz east of the center of the village Doren. The longitudinal extension of the landslide is 700 m and reaches from the river Weißach up to the village Doren (difference in elevation 200 m). The width is approximately 300 m.

Historical data about this landslide go back till 1847. Additional movements could be registered in the years 1927, 1935, 1952, 1954 and 1988. After rather dry weather conditions a strong slope movement occurred on February 18th 2007 and stopped after some days.

During the former landslides (in 1927, 1935, 1988 and 2007) about 2 – 3 million m³ of smooth rock were moved. In 1935 the river Weißach was completely dammed and a lake with a longitudinal extension of 500 m occurred.

Fig. 71 (left): Landslide area of Doren after the event of 1988. At the left side of the upper image border the center of the village Doren is visible. Fig. 72 (right): Landslide area of Doren after the event of 2007

Doren is situated on the fringes of the Northern Alps. Distinct oceanic influence is shown by high rainfall, moderately warm summers and moderately cold winters. The average annual rainfall totals 1875 mm. The Weißach valley was influenced by the Rhine glacier during the last ice age (Würm). Glacial drift and subsequent deglacial sediments were deposited at the slopes and in the valley. After the ice age those sediments were carved and cleared by the river. As a consequence the tertiary bedrock outcrops on the lower slope along the river Weißach. The village Doren is located on a strongly structured terrace with nearly vertical layered tertiary Molasse bedrock which is covered by quaternary sediments.

The landslide area is situated in the tilted and folded Molasse Zone. The lithology of the area consists of interbedded strata of marl, sandstone and conglomerates of the Weißach strata. The Weißach strata are following the slope of the valley and are dipping 50° towards SE. They are spaciously spread or meshed at a small scale. The lithology of the different strata determines the mechanical and hydrogeological characteristics of the landslide area. The layer sequence dominated by marl is steeply inclined, deformed and cut into boulders by fault lines. The bedrock is covered by quaternary sediments with a thickness of some meters. At least three different strata (glacial deposits, coarse clastics and redeposits), which differ in the composition, genesis and age, can be distinguished within the quaternary sediment body.

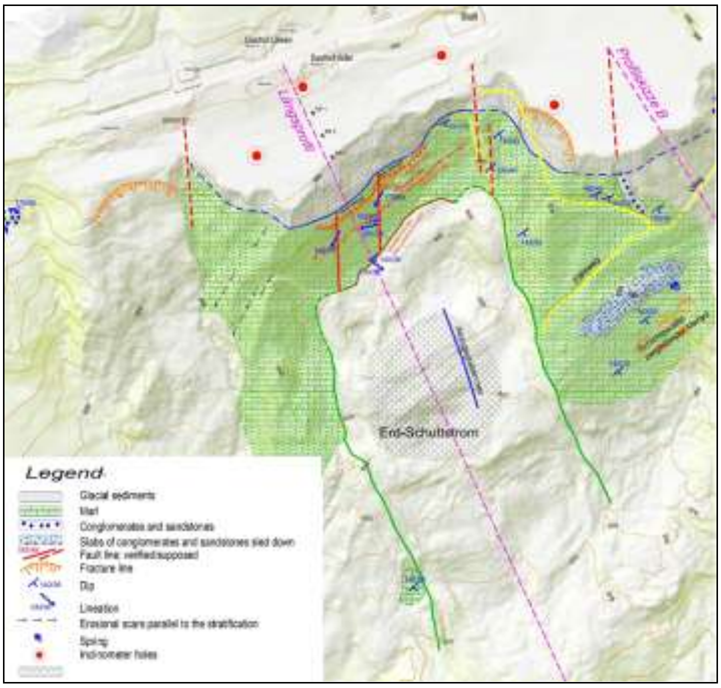

Fig. 73: Geology of the landslide Doren

Primarily the slide affected the bedrock (interbedded strata of clay/marl/ calcareous marl/sandstone), as well as the quaternary sediment cover. Today the landslide scar has the form of a conch and rotational slides are prevailing. The material in the accumulation area is creeping and flowing towards the axis of the river (earth/ debris flow). The quaternary sediment cover atop of the Weißach strata provides supply of material to the earth/debris flow. The earth/ debris flow is periodically mobilised by seeping water in the quaternary sediment cover and surface runoff. To survey the depth and the extent of the impermeable rocks and the depth of the earth/debris flow geoelectrical measures with multi-electrode configuration were carried out.

All profiles on the terrace showed a clear double segmentation in the distribution of resistivity. The depth of the cover which shows high resistiviy (glacial deposits) ranges between 1 m and > 22 m.

According to the results of the geoelectrical measurement, the depth of the actually moving earth/debris flow at the base of the scar is 10 to 15 m. The reason for the “global slide” is a failure of the base of the steep rock layers in the scar (Fig. 74)

- The failure occurs by an overload of the competent parts (sandstone) of the layer.
- The increase of stress up to the failure is caused by the water pressure, which is efficacious along joints and faults. The incompetent layers (marl) are impermeable to water.
- After the failure of the base the sliding mass becomes part of the earth/debris flow. Due to the characteristics of the materials (marl/sandstone = ductile/prattle) and the influx of water the mass is extremely plastified and flows downwards to the river.

Monitoring

The development of the fracture line is already monitored since 1935. For this purpose measurements by theodolite were carried out in the past. Data from aerial photographs and in the last years also data from airborne laserscanning were used to perform this task.

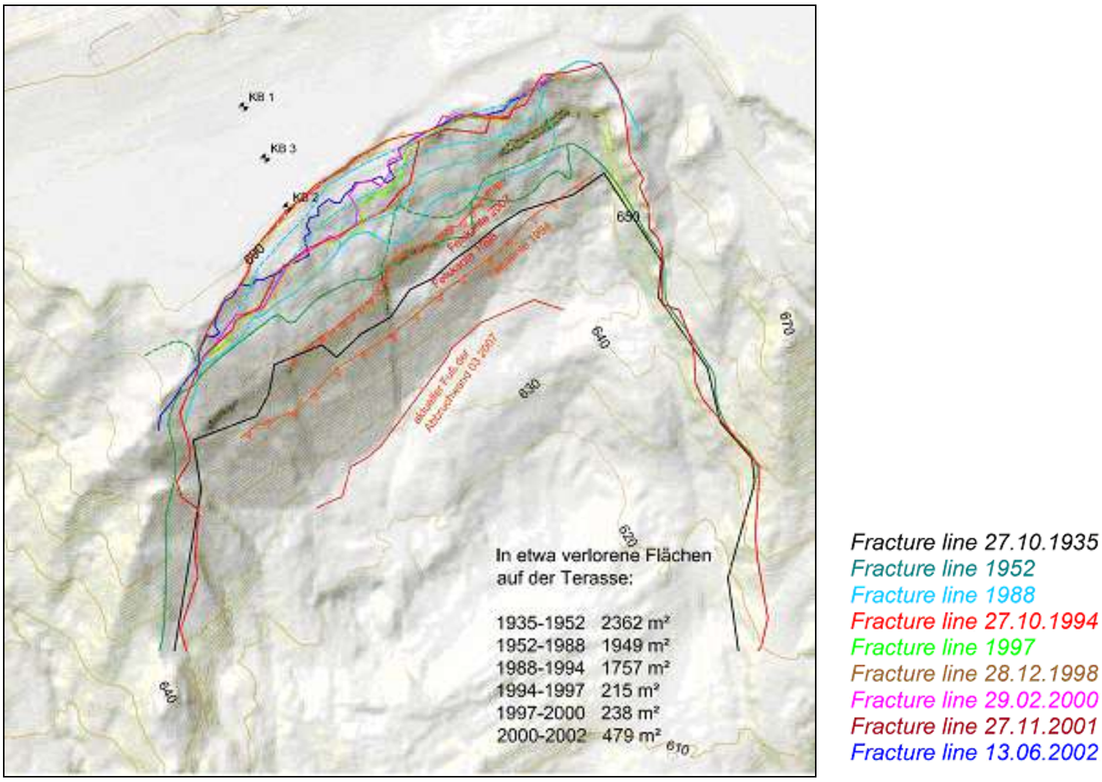

Fig. 74: Development of the fracture line since 1935 (laserscan of March 6th, 2007)

After the event of February 2007 airborne laserscanning was also used to survey the geomorphological changes in the landslide area. Fig. 75 and Fig. 76 show the changes between June 2006 and March 2007. A comparison of the DTMs shows volumetrical changes with a total amount of 206.000 m³. The difference (16.000 m³) between a decrease of the volume (206.000 m³) in some parts of the landslide area and an increase (190.000 m³) in other parts of the landslide area results from mud and debris which was removed by the river Weißach.

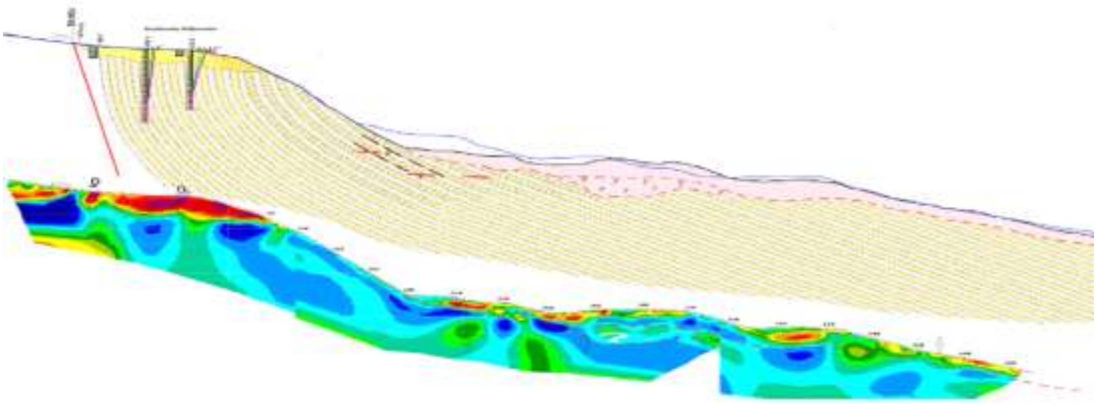

Fig. 75: Geological longitudinal section of the landslide area of Doren

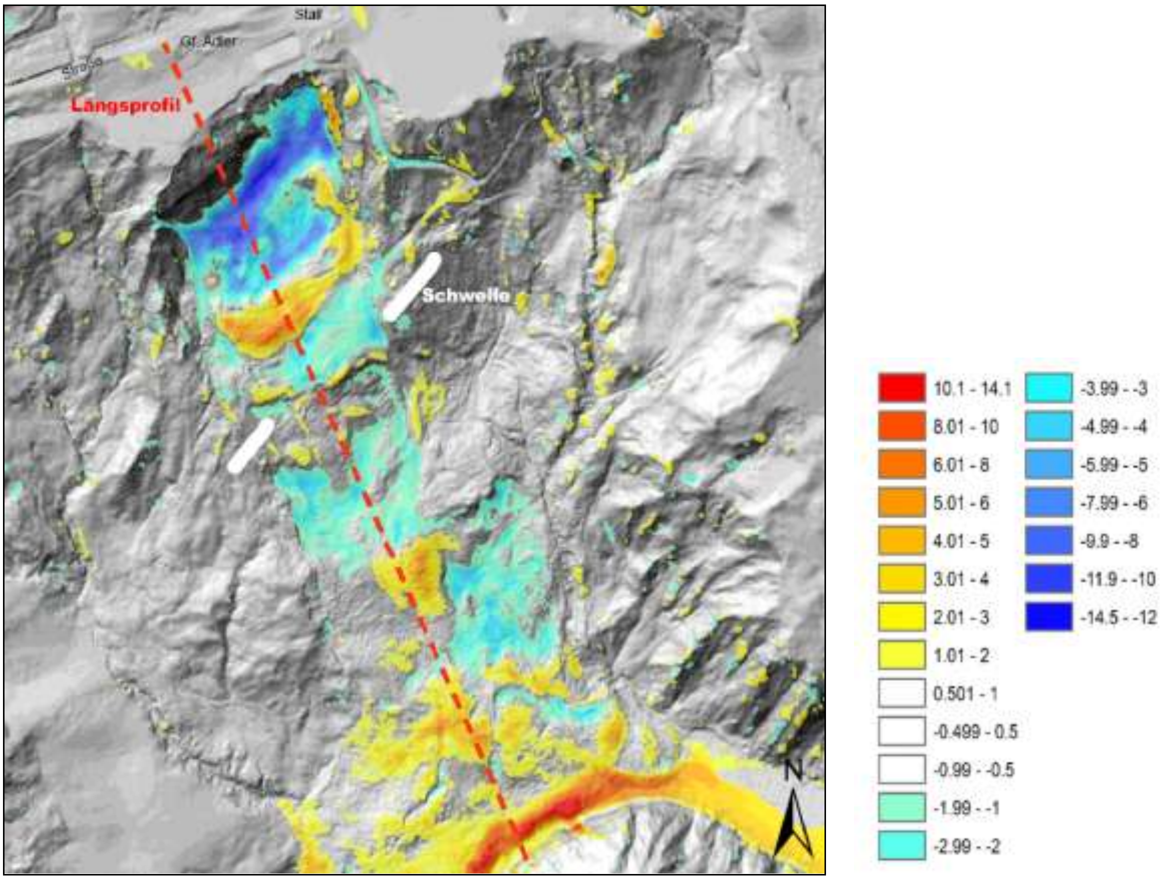

Fig. 76: Differences in the ground height between 12th June 2006 and 6th March 2007 (calculated from airborne laserscan data)

A9. Landslide “Rindberg” and the application of a Geoelectrical Monitoring System

Authors: Margarete Wöhrer-Alge

The landslide event at “Rindberg”

In spring 1999, after a short period of heavy precipitation and the rapid melting of snow, a catastrophic landslide was triggered on the South-flank of the Rubach Valley near Sibratsgfäll in the province of Vorarlberg (Austria). Shortly after the first slide activity was observed, the State Department of Avalanche and Torrent Control authorized preliminary geological investigations.

As a follow up of this first phase of investigation, a complex research program was initiated. The final goal of this study was to develop an operative strategy to optimise measures in case of future events. The applied methods incorporated geo-morphological, hydro-geological and geophysical surveys of the area.

The outcome underlined the importance of monitoring the subsurface water regime for risk estimation. Consequently, a multi-parameter monitoring system was designed, centred on the development of an innovative geoelectrical monitoring system.

The monitoring system

Due to the fact that triggering of movements on this landslide is directly correlated with hydrological processes, geoelectrics seemed to be a promising method for monitoring of similar landslides. In 2001, the starting date of the project, no commercially available geoelectrical instrument met the requirements of high resolution monitoring (high resolution data, direct noise control, short acquisition time, permanent remote access and automatic data broadcasting). Therefore the Geological Survey of Austria (Supper et al. 2002, 2003 and 2004) designed a new, high speed geoelectrical data acquisition system, called GEOMON4D. A first prototype 2d system was installed at the landslide of Sibratsgfäll in spring 2002. This system has been in operation since November 2002, measuring six complete sets of resistivity data, each compromising 3000 single measurements, and 24 self-potential data sets in gradient configuration each day. Since then, daily standard processing of actual data has been performed.

In 2003, the system was completely redesigned according to the experiences derived with the prototype. The instrument now offers a completely open architecture, allowing installation of any number of current or potential electrodes by adding parallel or serial cards. Moreover GPRS (General Packet Radio Service) data transfer was implemented. Therefore maintenance can be performed remote-controlled. Data (measurement results, test sequences and log files, containing information about system and GPRS connection status) are sent automatically every day via email to the data processing centre.

The geoelectrical system was complemented with three soil temperature and soil humidity sensors, rainfall, snow and drainage recording points. Additionally three drillings (equipped with inclinometers) allowed correlation of movement rates with geoelectrical anomalies. To determine values of surface movements, high resolution geodetic surveys were performed almost every two weeks. Selected results of self potential (Fig. 77a) as well as of resistivity time series (Fig. 77b) clearly showed the existence of pronounced anomalies at times of movements of the landslide, whereas during periods of slowdown, hardly any anomalous values were registered. Unfortunately, due to the lack of permanent motion data, no direct correlation with triggering of movements could be derived.

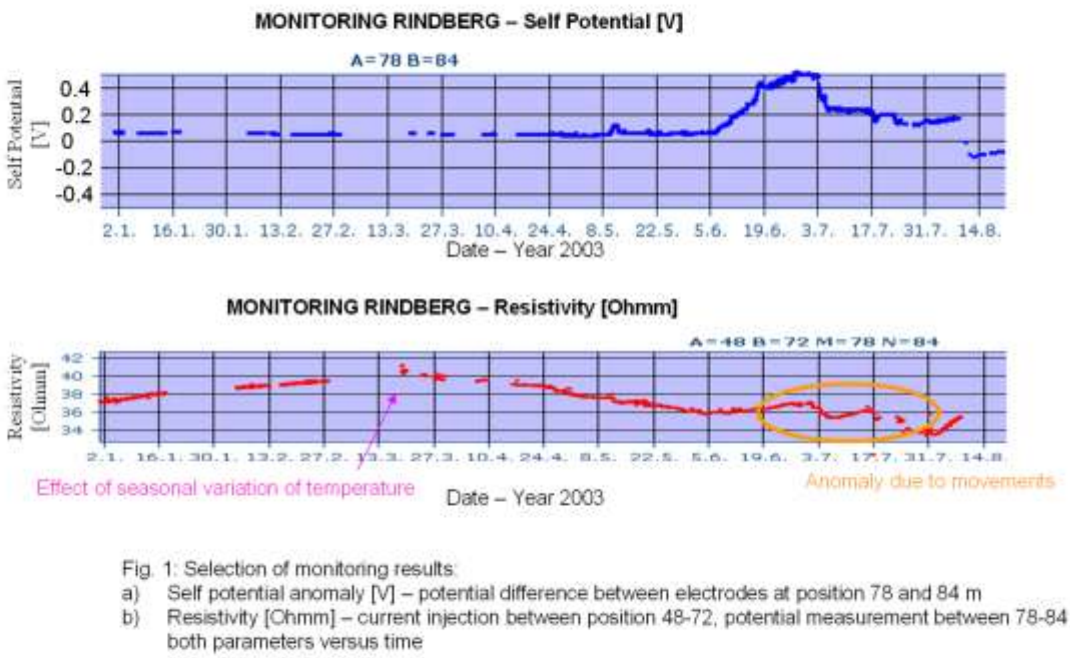

Fig. 77: Selection of monitoring results. (a) Self potential anomaly [V] (b) Resistivity [Ωm]

The geological framework

The landslide area is entirely located within the "Feuerstätter Unit", which is characterized by extensive rock disruption. The landslide area itself is mainly composed of rocks of the Junghansen and Schelpen series. These sub-units consist of marl and schist with highly variable stability as a result of tectonic fracturing. Due to their low resistance against weathering, rocks degrade under the influence of water into deeply weathered granular soils. Within these areas, all primary scarps are located. The Junghansen and Schelpen series are embedded into the more stabile Feuerstätter sandstones and limestones of the Aptychen series. Fig. 78 shows the results of the geological mapping of the landslide area (Jaritz et al., 2004) and surroundings.

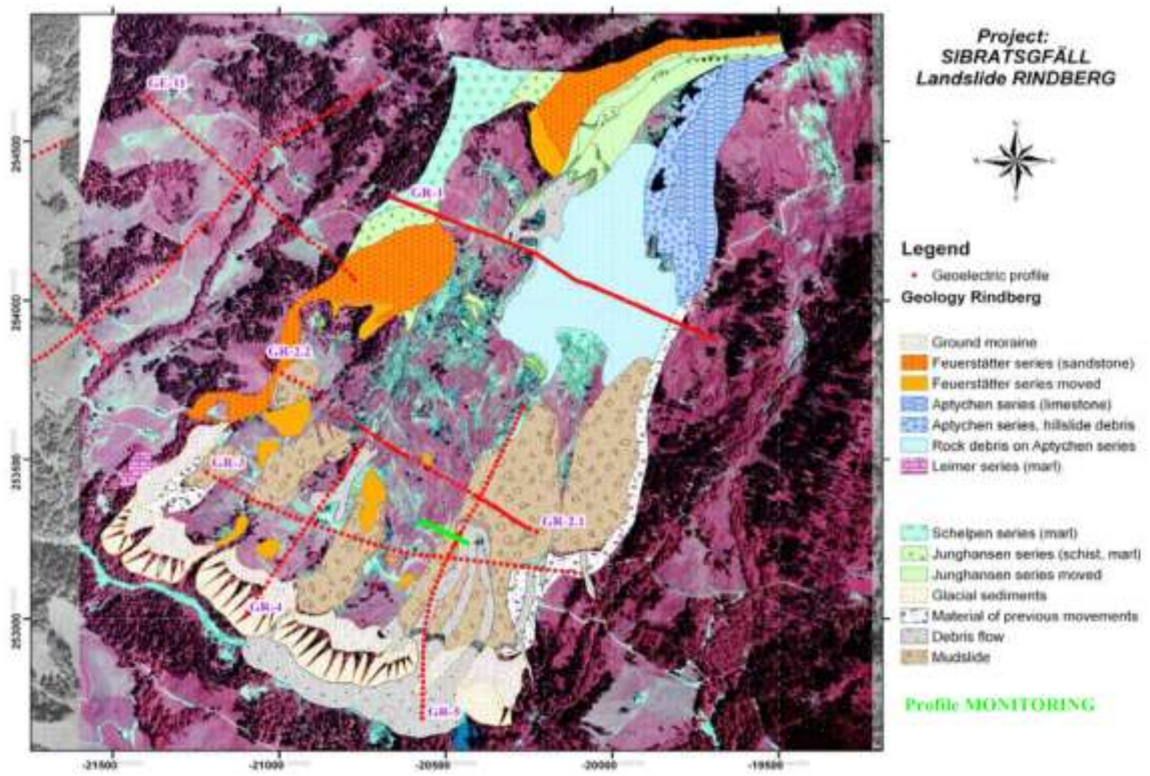

Fig. 78: Geological overview map of the landslide Rindberg

References

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Supper R., Römer A., Hübl G.: Development of a new, fast remote controlled 3D geoelectrical system for subsurface surveillance, Proceedings of the Environmental and Engineering Geophysical Society, 8th Meeting Aveiro, Portugal, 2002.

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Supper R., Römer A.: New achievments in development of a high-speed geoelectrical monitoring system for landslide monitoring (GEOMONITOR2D), Proceedings of the SAGEEP 2004 meeting, Colorado Springs, 2004.

A10. A new database of alpine rockfalls and rock avalanches

Authors: Philippe Schoeneich, Didier Hantz, Philip Deline, François Amelot

Abstract: A new database of Alpine rock falls and rock avalanches has been established, based on the compilation and verification of published inventories, and on additional cases documented by project partners. All data are integrated in a database, with two information levels: basic data for all cases, detailed data for selected cases. The database contains by now around 550 cases, among them round 360 true rock fall and rock avalanche events.

Weblinks: http://www.crealp.ch

Context and goal of the database

The InterregIIIa Rockslidetec project (2003-2006) was designed in order to develop new tools for the detection and the propagation modelling of rock avalanches (Rockslidetec final report). Within this project, a new database of Alpine rock falls and rock avalanches has been established (Action A of the project), with two main goals:

- on short term, provide the experts with a wide set of information allowing an improvement of their analyses based on analogies with known cases. This aspect can be extended to the monitored unstable sites;
- on longer term, set the basis for an advanced statistical analysis of the phenomenon (frequency/probability, susceptibility, triggering and propagation factors).

The database focuses on very rapid to extremely rapid rock movements in the sense of the international classification by Cruden & Varnes (1996), which include: rock falls, very/extremely rapid rock slides, and rock avalanches. For simplification we will use rock fall as generic term.

The database contains two information levels:

- a comprehensive inventory of events of more than 106 m3, covering the whole Alpine range. The threshold of 106 m3 has been considered as a realistic goal to achieve exhaustivity over the entire Alps. At this information level, only limited data are collected like name(s), location, date, type and if possible area and volume, mostly from literature;
- a detailed database, containing also smaller events, and covering mainly the working areas of the project partners (Valais, Aosta valley and Northern French Alps). These data have been collected by field work.

Database structure

The database is designed to allow detailed analysis of susceptibility, triggering and propagation parameters. It contains therefore 38 tables including 305 fields organized in six main domains:

- topographical and geological characteristics of the concerned valley slopes;
- initial profile of the slope;
- post-failure profile of the slope;

- characteristics of the failure, including jointing, triggering factors, …
- characteristics of the deposit;
- references to documents, literature, including reference numbers in the previous published inventories.

All data are organized around the table Rockfall, which contains the identification and the general caracteristics of the event. Fig. 79 gives the basic structure of the database. Fig. 2 shows an example of the user interface.

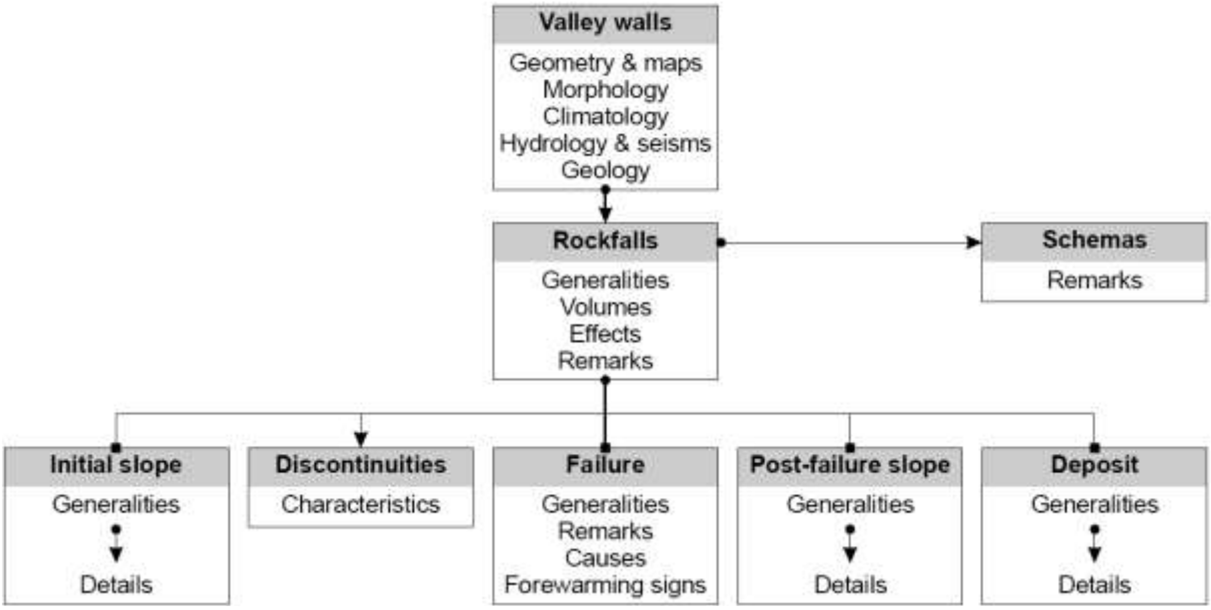

Fig. 79: Overall database structure

The "valley wall" is a relatively homogeneous area from a geological and geomorphological point of view. It extents transversely from the valley bottom to the top of the valley slope, and longitudinally as far as the geological and morphological characteristics remain roughly constant. It makes it possible to calculate a spatial and temporal rock fall density, if a sufficient number of rock falls have occurred in the same valley wall or in valley walls with the same geological and geomorphological characteristics. The rock fall densities for different geological and geomorphological contexts could then be compared (Dussauge-Peisser et al., 2002).

The initial and post-failure slopes are described, as well as the characteristics (attitude, spacing, extension, roughness, filling) and the role of the main discontinuity sets. They are subdivided in slope segments. This description can help the expert to determine the volume, geometry and failure mechanism of a potential failure in similar conditions. Information on the triggering factors makes it possible to know what type of triggering factor is the most efficient according to the geological and geomorphological context, and to the potential failure mechanism. Information on the propagation includes geometrical parameters on the propagation path. It can be used for a better knowledge of the propagation angle (Fahrböschung) according to the geological and geomorphological context, and to the potential failure mechanism.

The description of the deposit includes geometry, geomorphological and granulometrical observations. The description can be subdivided in sub-areas with homogeneous characteristics, in order to account for the complex shape of many deposits. These data serve to interpret the propagation patterns, and to control modeling results. Figures (maps, topographical/geological profiles, photographs, ...) can be added to illustrate any of the described parameters.

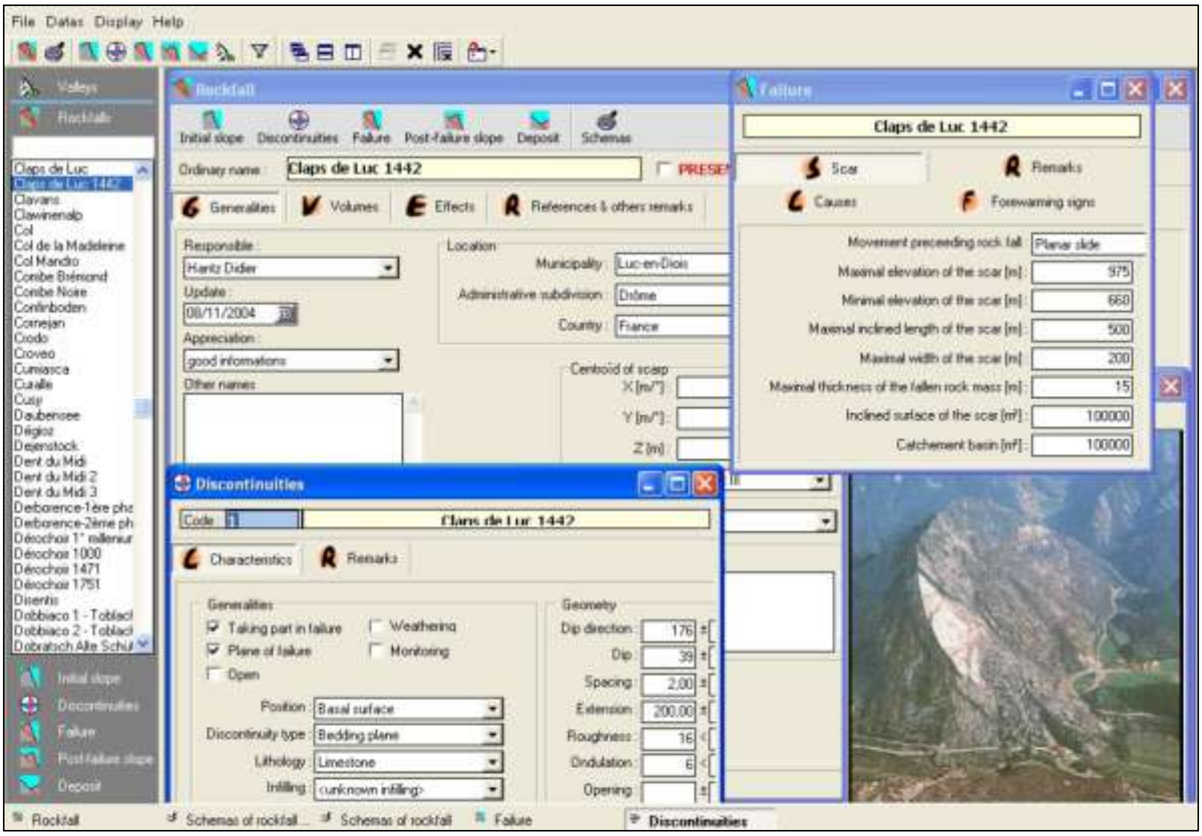

Fig. 80: User interface, illustrated with the Claps de Luc 1442 AD rockslide

The database has been developed on MS Access 2000, using MS JetEngine 4.0 and the object interface MS-DAO 3.6. The user interface has been developed with Delphi 7 (Fig. 80). The database can be used on any Windows computer without having Access installed. This version has been distributed to project partners only. A new, web interfaced version, is under development and will allow on-line access. The database will be available online in 2008 on the site http://www.crealp.ch.

The same database structure has been used both for the inventory and for the detailed cases. For the inventory, only the available fields are documented. The detailed database needed additional field work and document analysis, which has been done by the project partners from 2003 to 2006.

The inventory data

The inventory is mainly based on the compilation of existing published inventories (Montandon 1933, Strele 1936, Abele 1974, Eisbacher & Clague 1984) and other literature sources (Erisman & Abele 2001, Heim 1932, Oberholzer 1900, 1942, Schindler 2004, ...), as well as the Infoslide database of the Swiss geological survey. These inventories consider events of more than 1 to 3 106 m^3, as well as smaller events that caused numerous victims or significant damage. The inventories of Montandon (1933), Strele (1936) and Eisbacher & Clague (1984) are restricted to historical cases. Abele (1974) includes cases known from geological and geomorphological survey. Although there title announces inventories of “éboulements” or “Bergstürze”, most of them include also mass movement events of other types, like debris flows, slides or even glacial lake outbursts, as well as events where the main process is unknown or uncertain. Except Infoslide, none of these inventories was available in numeric form, and they had never been put together.

In order to harmonize the dataset and to allow the selection of true rock falls and rock avalanches, the following work has been done:

- extraction of text data and tables and conversion into tabular datasets;
- comparison of the inventories, identification of corresponding cases and elimination of duplicate records;
- separation of distinct events: some inventories agglomerate in a same case several successive events on the same location, or even different events in the same area. These have been considered as distinct events;
- identification of the main process for all events. Non-rockfall cases have been maintained in the database, in order to keep the integral original datasets, except for the Infoslide database, where only the rock fall/rock avalanche cases have been considered;
- determination of geographic coordinates for all cases (center point of scar or deposit), and conversion of the various national coordinates, if available, in universal WGS 84 geographic coordinates.

The following data fields could in most cases be filled:

- current name of event, and other corresponding names used by various authors;
- date of event for historical events, dating if available for dated events;
- WGS 84 geographic coordinates of centre point (scar or deposit), if available: national metric coordinates;
- administrative subdivision at country and canton/department/Land level, if available at community level;
- main propagation process;
- number of victims, level and type of damage;
- if available: surface of deposit, volume, and other tabular data (like height, length, H/L or Fahrböschung, mainly from Abele 1974 and Erisman & Abele 2001);
- triggering factor if known;

- identification number in the published inventories and literature sources. Published figures have been scanned and included, as well as in some cases map extracts for location and delimitation and, if the site could be visited, photographs. In addition to the published sources, several tens of new cases, resulting from personal surveys of the project partners have been added. This results in a total of 550 events (status September 2006), among them 357 are very rapid to extremely rapid rock movements, the others being either uncertain or of other types (Table 13 and Fig. 81). Several events involve process chains, like rock falls in catchment basins reworked by subsequent debris flows.

Table 13: Number of events recorded in published inventories

Source	# of entries	Effective # of events	# of rockfall events	# of events of uncertain type	# of non-rock-fall events
Montandon, 1933	160	164	103	1	60
Strele, 1936	35	35	2		33
Abele, 1974	279	285	220	53	12
Eisbacher & Clague, 1984	137	216	107		109
Total (excl. duplicates)		**500**	**306**	**54**	**40**

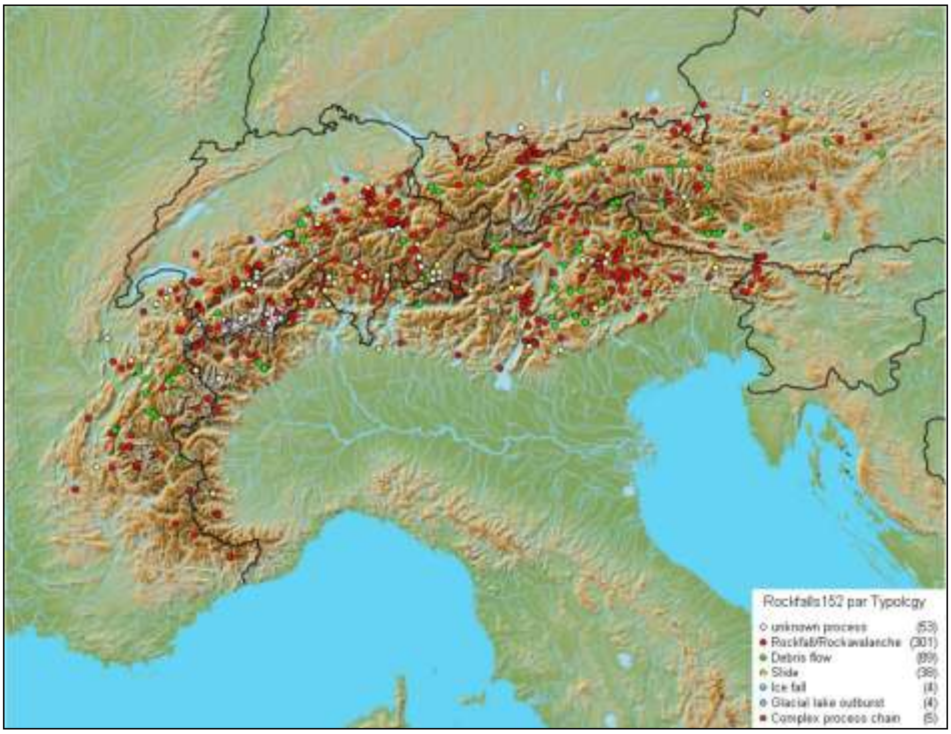

Fig. 81: Location map of the ca. 500 cases documented by published inventories

This inventory allows already some considerations on the spatial distribution of the cases, or on the temporal distribution of historical records. Fig. 81 shows the distribution of the around 500 events resulting from the compilation of the published inventories. It appears that the highest density is encountered in the Swiss Alps, followed by the Western Austrian Alps and Northern Italy, where the previous authors concentrated their work. The Southern Alps, both on the French and particularly the Italian side, as well as Eastern Austria and Eastern Slovenia show a very low density of recorded events. The circa 50 cases added by project partners concentrate in their working areas (Valais, Aosta valley and Rhone-Alpes region) and are not represented on the map.

Among the 357 certain rock falls or rock avalanches, 160 are dated: most are historical events, 15 are Holocene events dated by radiocarbon or radionuclides. A few Lateglacial events are indirectly dated by associated moraines. The distribution of historical events shows that their frequency is dependent on the quality of the historical record (Fig. 82). Four periods can be distinguished:

- the Antiquity and early Middle Ages, with isolated records only, almost restricted to cases that caused very numerous victims, and/or triggered by earthquakes;
- the end of Middle Ages (11th to 14th centuries) with 3 recorded cases/century;
- early modern time (15th to 18th centuries) marked by more systematic archives;
- the two last centuries, marked by the beginning of the scientific interest for natural processes, and later by systematic inventories.

Within each period, the frequency seems to be homogeneous, but the density of the record improves for younger periods. This expected result confirms that there are many missing cases, and that a statistical exploitation of the frequency with time would give no reliable results.

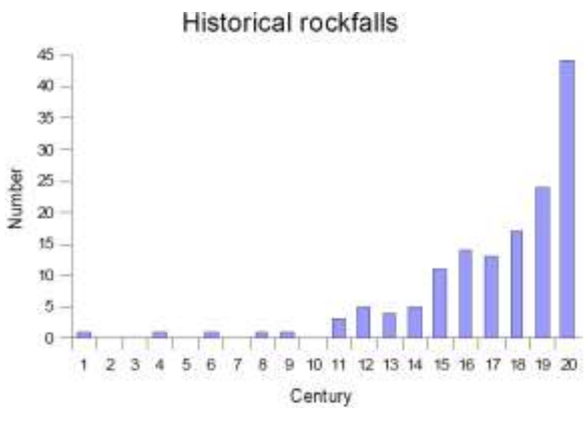

Fig. 82: Distribution of 145 recorded historical rock fall events (events/century)

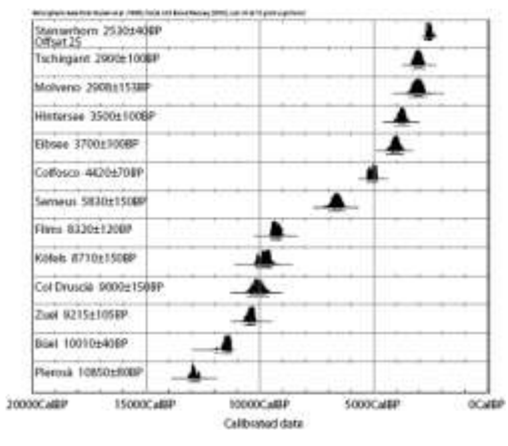

Fig. 83: Distribution of calibration ranges of 15 radiocarbon dated rock fall events

The few dated Holocene events are equally distributed over the Holocene, but their number is insufficient to allow any conclusions on a possible influence of climate changes (Fig. 83). One can notice however that several events, including the two largest known (Flims &Köfels), occurred at the beginning of the Holocene Climate Optimum, a period during which almost no slide event is dated

(Schoeneich & Dapples 2004). This could indicate that large rock falls/rock avalanches are less dependent on precipitation than other types of mass movements. Concerning triggering factors, the trigger by earthquake, often mentioned as possible or probable trigger, is actually confirmed for only 8 historical events. It must however be pointed out that the trigger is unknown in most cases.

The detailed cases

Several tens of events have been documented in detail, ranging in volume from 104 m^3 to several 106 m^3. Most cases are located in the working area of the project partners. They include cases known from the inventory, which have been revisited in order to acquire detailed data, and new cases studied by the project partners. Several cases of unstable zones representing potential hazards have been documented too.

The acquisition of detailed data needed intensive field work, including survey of the deposit and of the scar, measurements of the jointing in the scar area, as well as analysis of available documents like pre-failure topographical data.

This information level is not intended to cover exhaustively the entire Alps, but to focus on the most important, respectively the best documented events, and on some study areas. In some limited and geologically homogeneous areas, like the Ecrins massive or the Chartreuse range in France, a comprehensive inventory covering the whole size range will be achieved, in order to allow frequency/size analyses (Dussauge-Peisser et al., 2002).

In most cases, only part of the fields could be documented. The dataset is therefore very heterogeneous yet, making statistics difficult at the present state. As examples of good documented fields, volume estimations for the scar or the deposit are available in 156 cases (Fig. 84), the area of the deposit in 285 cases, values for the “Fahrböschung” for 216 cases. But initial slopes are documented in only 27 cases, geometric characteristics of the scar in 38 cases, discontinuities have been measured for only 30 cases.

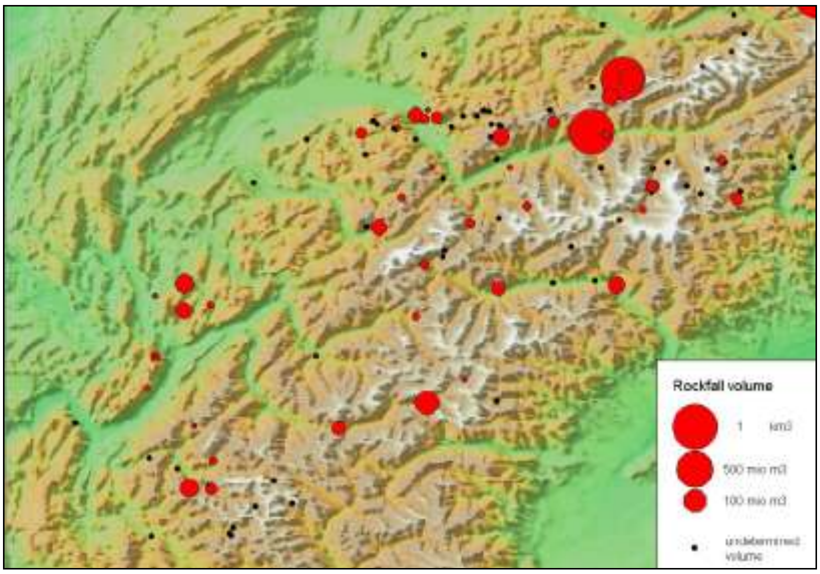

Fig. 84:Volume of rockfall events within the working area of the project partners

Outlook

The database structure is ready and tested, but the data collection is still in progress. It will be continued within the Interreg IIIB project ClimChAlp, in order both to complete and improve the inventory and to extend the detailed database to the entire Alps for the largest rock fall and rock avalanches, together with new partners from Germany, Austria, Italy and Slovenia.

As mentioned above, it should be made available on-line, for consultation and for on-line contribution. It should also be linked to a GIS, in order to allow mapping and spatial analysis.

The collected data will be used in future for:

- search for similar cases in hazard assessment;
- statistical analyses of susceptibility and triggering factors (Frayssines et al., 2006);
- frequency analyses, giving constraints to hazard assessment (Hantz et al., 2003);
- study of the influence of climate changes on the occurrence of rock avalanches during the-Holocene period (Schoeneich et Dapples 2004);
- analysis of propagation;
- ...

In the idea of the Rockslidetec project, the dataset should also serve as base and control data for the validation of propagation modelling. It appeared however that only a limited number of recent events, for which detailed topographic data of the pre-failure slope are available, are usable.

Acknowledgements

This work was funded by the EU within the cooperation program Interreg 3 ALCOTRA, of the Conseil général de la Haute-Savoie, the Conseil général de la Savoie, the Syndicat Mixte pour l'élaboration et le suivi du Schéma Directeur de la Région Grenobloise (SMSD), the Délégation Interministérielle à l'Aménagement du territoire (DIACT, ex DATAR), and the Federal Office for Water and Geology (FOWG) of the Italian State.

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A11. GPS observations at Mt. Hochstaufen

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Weblinks: http://www.erdbeben-in-bayern.de/
http://www.alps-gps.units.it/

Objectives

In this project the aim was to monitor long-term deformations due to swarm earthquakes on a mountaintop within millimetre accuracy for positional coordinates by means of relative, static and non-permanent GPS measurements. Due to the short project duration without the occurrence of meaningful earthquakes no significant deformations were expected, therefore the accomplished studies may indicate the benchmark for this monitoring method in Alpine Space. The measurements were realized by the Chair of Geodesy at the Technische Universität München and include two measurement campaigns in 2006 and 2007. A third campaign after an earthquake reaching 3.5 on the Richter scale in September is foreseen for May 2008.

Geology and Microseismics

Mt. Hochstaufen (1775 m) belongs to the Staufen Massif which is an east-west striking mountain chain in southeastern Germany, northwest of Bad Reichenhall in the Berchtesgadener Land.

Fig. 85: Mt. Hochstaufen

The summit region consists of limestone (Wettersteinkalk), which shows distinct signs of Karst formation. Haselgebirge[43], a leached and weathered breccia of evaporitic permo-triassic sediments, can be found in some outcrops on the northern flank of the Staufen Massif and in the Reichenhall Basin. Presumably, Haselgebirge also exists in the innermost fold cores of the Staufen Massif (Kraft et al., 2006). A detailed description of tectonic setting and the geology of the Staufen Massif can be found in e.g., Erhardt (1931), Henrich and Zankl (1981) and Weede (2002). Geologic evidence for mass movements at the southern flank of Mt. Hochstaufen was recently summarized by Weede (2002). Large east-west striking open fractures can be found near the summit of Mt. Hochstaufen. They reach a length of several hundred meters and openings of up to 3 m. Those fractures could be followed to a depth of nearly 100 m below the surface (Glaser, 2004). Gravitational collapse and/or subsidence due to leaching of the Haselgebirge are debated as causative processes.

[43] Typically the salt content of Haselgebirge is 50%

Mt. Hochstaufen is always vulnerable to earthquakes, so-called swarm earthquakes seem to be closely related to heavy rainfall. In July 2005, extreme rainfall led to flood damage in the region and swarm earthquakes up to a magnitude of 2.8 on the Richter scale were triggered. In September 2007 an earthquake reached 3.5 on the Richter scale. Fortunately earthquakes of this strength do not cause major damage but the area Mt. Hochstaufen is monitored by a scientific network consisting of seismometers and additional measuring devices (groundwater levels and meteorological observables).

Geophysicists at the Ludwig-Maximilians-University in Munich carried out a study of the spatio-temporal behaviour of earthquakes, fluid-related parameters and precipitation in the swarm earthquake area. The observations and first interpretations indicate that seismicity in the Staufen Massif is influenced and partially even triggered by meteorological events. Almost every rain event matches a corresponding event in the time-shifted (~ 10 days) seismicity record (Kraft et al., 2006).

Network Design

Geodetic monitoring solutions are described as a spatial network of observables (in the case of GPS these are vectorial baselines). The conceptual design of the monitoring network consists of a network with 4 control points (reference network) and 13 observation points on the summit of Mt. Hochstaufen. Additionally a fifth control point could be used thanks to the Interreg IIIB “Alps GPSQuakenet” project that runs the Geodetic Alpine Integrated Network[44] (GAIN) with one station settled in suitable distance to Mt. Hochstaufen.

The observation network is a local network which covers an area of only 4.7 hectares with a maximum baseline length of < 400 m and a maximum altitude difference of 106 m (1664 to 1770 m). The locations were installed in close consultation to geologists to describe possible movements of 5 separated blocks. The five control points were installed in the regional surrounding of the mountain within 4 and 11 km and a maximum baseline length of 17 km. The points were chosen to be located evenly distributed in all directions on about the same altitude level (1280 to 1702 m) in order to low tropospheric delay. For the present all these points were assumed to be stable. Since the massif is followed by a plane in the north-eastern part, the last control point is down in the valley at 470 m. Unfortunately this point had to be excluded from further investigations due to damaged point marking.

Network Installation

Since non-permanent GPS campaigns always are a logistical challenge as well, two main actions were implemented to reduce effort and to increase accuracy:

- **Monumentation:** the installation of the observation points was realized by threaded bolts with holes made by a drilling machine. This kind of marking is cost-effective and means only a small intervention into the environment. Besides, this allows a reliable forced centering of the GPS antennas.
- **Antenna mounting:** since no infrastructure leads to the mountain top, the equipment (GPS receivers, antennas, batteries for power supply) had to be carried up. To minimize weight, un-

[44] The Alpine Integrated GPS Network for Continental Deformation project, operative since May 2004. The aim of the project is to build up a high-performance space geodetic network of continuous GPS (CGPS) receivers in the Alps and a number of campaign sub-networks. GAIN consists of more than 35 CGPS stations and is the first ever installed transnational geodetic network across the Alps.

handy wooden tripods were replaced by self-constructed antenna mountings (Fig. 86, Fig. 87). This construction has proved its worth at several points: Low antenna heights enabled a set-up close to the marked points; additionally no antenna heights had to be measured in place but in laboratory which eliminated one typical error source (the antenna can be levelled with three tribrach screws; a metall ball forces a constant antenna heights in every epoch)

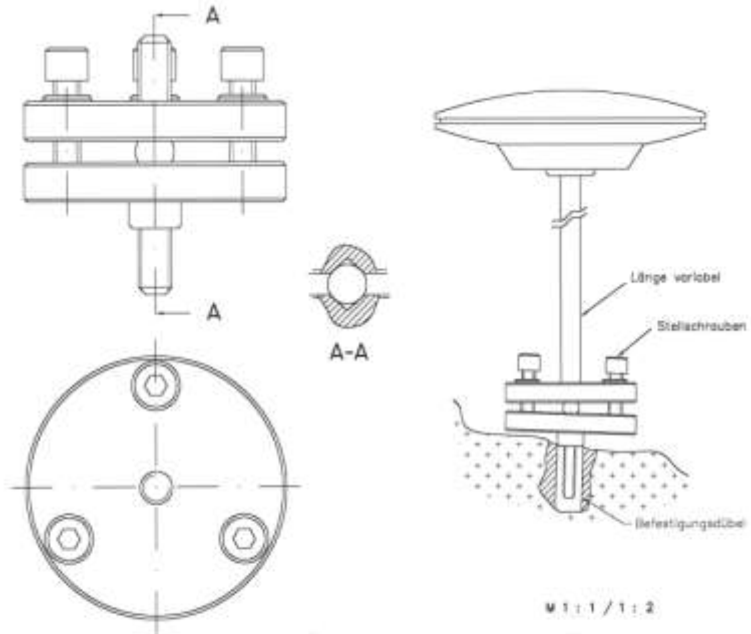

Fig. 86: Construction of antenna mounting

Fig. 87: Field setup

GPS Measurements

- **Time Table:** Epoch 0 in Aug. 2006 & Epoch 1 in May 2007 (Epoch 2 foreseen in May 2008)
- **Observations:** static, relative GPS (RGPS). This technique to achieve highly accurate GPS results is based on the use of so-called double differences of GPS phase data between two stations and two satellites. The receiver systems were run in static mode for ~60 hours consisting of 5 sessions with a data frequency of 15 seconds. This involves measuring points at least twice and creates safety checks against problems that would otherwise go undetected.
- **Equipment:** 9 dual-frequency GPS receivers (3 × Leica 1200, 6 × Leica 530). Specifications in observation mode as mentioned above: Accuracy of baseline 5 mm + 0.5 ppm (horizontal) and 10 mm + 0.5 ppm (vertical).

Data Processing and Deformation Analysis

The baselines were post-processed using standard software Leica Geo Office (LGO) V4.0 which is included in delivery of the system. Such commercial software packages use standard algorithms and are the state of the art in medium-sized surveying offices. In comparison with scientific GPS software LGO is expected to deliver good results for local and regional GPS networks. Due to long observation times and excellent satellite availability the baselines were estimated with a very high precision (internal accuracy).

Network adjustments and deformation analysis of both epochs was calculated in GeoTec Panda/Defana V1.3 (PANDA). The high redundancy of the network lead to very precise coordinates of about 1 mm (1σ) for the horizontal component which has to be seen sceptically. These values indicate the internal accuracy of the networks. This assumption was confirmed by a first comparison of the adjusted networks, which resulted in apparent horizontal point movements of 3 to 10 mm for the observation network and more than 15 mm for some points of the reference network. Based on high internal accuracies but low repeatability of the networks, deformation analysis is not possible because every point movement would be assumed to be highly significant.

To avoid this problem, an approach considering a global movement was used. The global movement allows you to accommodate the point accuracies to the measurement circumstances. Such a definition is useful if the precision of the comparative networks is very high due to a forced centering but the external accuracy still contains systematic errors which are not considered in the stochastic model. This can be prevented by magnifying the standard deviations of each point. In this example two factors were considered: the variations of the antenna's phase-centres as well as the limited precision for the set up of the antennas over the observation points.

The deformation analysis then was tested with a confidence interval of 95% (2σ) showing no significant movements on the mountaintop (Fig. 89). However, two stations in the reference network show significant movements in 3D. Neglecting the less accurate height component (a well known effect of GPS), these movements are close below significance as well (Fig. 88). But it is the subject of further investigations whether these points can be assumed to be stable or whether long baselines cause inaccurate results.

Conclusion

Static RGPS with long observation times is suitable to detect horizontal displacements of ~5 mm per epoch. Higher accuracies can only be achieved by using a permanent GPS network marked with stable pillars or by using a scientific GPS software and accurate modelling of phase-centre variations of GPS antennas.

Nevertheless, high precision (internal accuracy) can be achieved since the method allows putting redundancy into a network if many receivers are used at the same time. This is mainly because no direct line-of-sight between the receivers is necessary. At Mt. Hochstaufen 9 receivers were used leading to a redundancy of more than 400. Thus, the customer has to distinguish exactly between the terms of "precision" and "accuracy".

Our example combining two campaigns within a time span of seven months showed no significant displacements. To find realistic results, the stochastic model had to be influenced manually by allowing global movement resp. increasing standard deviations of systematic errors like phase-centre variations and limited precision for the stable set up of the antennas.

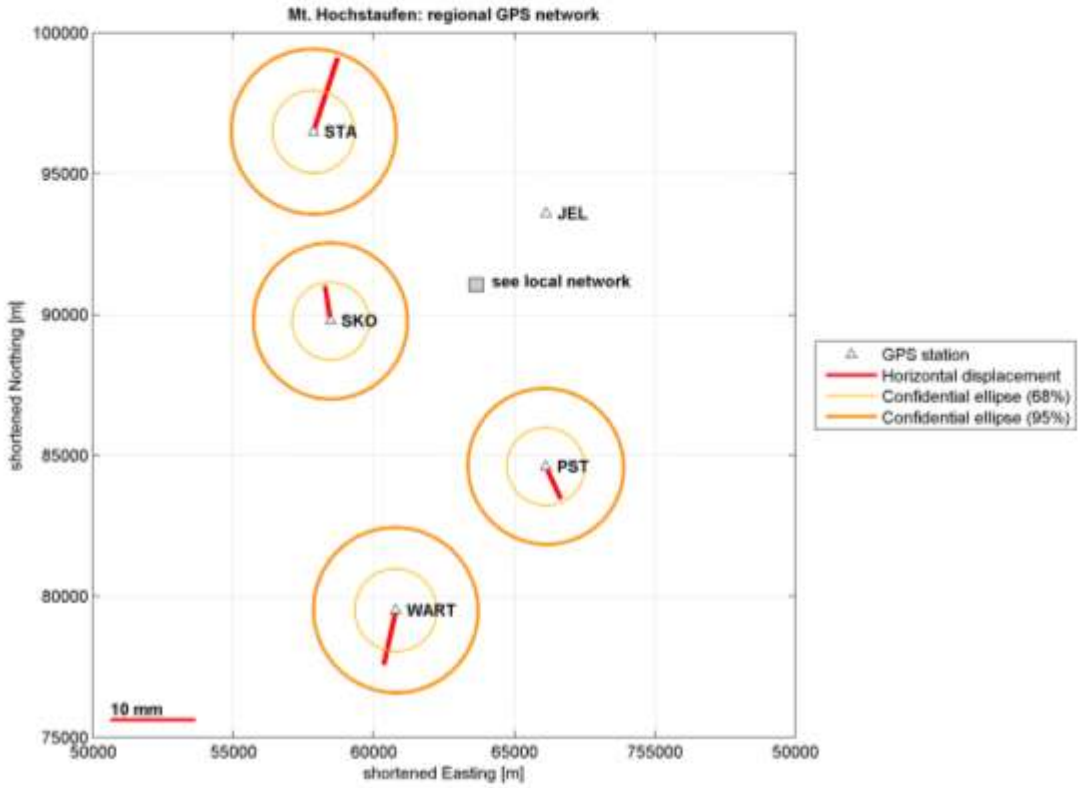

Fig. 88: Horizontal displacements in the regional GPS network around Mt. Hochstaufen

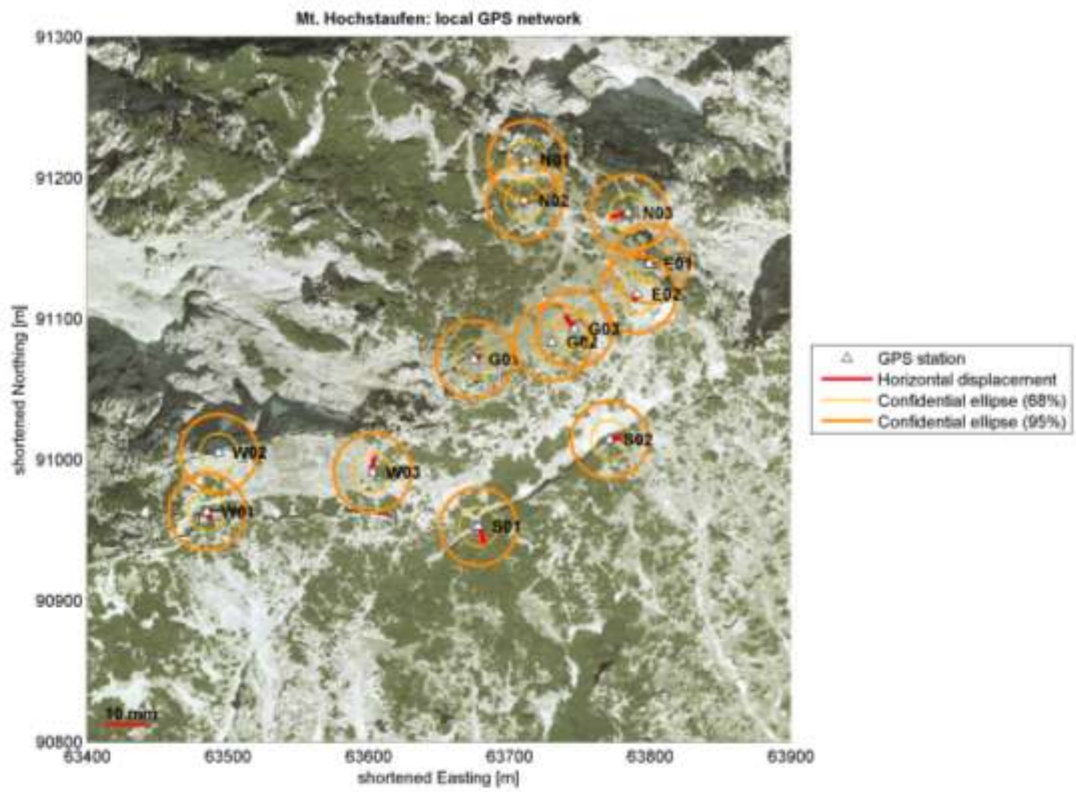

Fig. 89: Horizontal displacements in the local GPS network on the top of Mt. Hochstaufen

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A12. The Landslide of Triesenberg

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Weblinks: http://www.hydrogeologie.ch/

Introduction

The Triesenberg landslide affects an area of approximately 5 km^2 extending from an altitude of 460 m to 1350 m above sea level. The landslide represents an estimated volume of 460 mio m^3.

The moving mass is situated on the right bank of the Rhine valley, between Balzers and Vaduz. It affects the village of Triesenberg (approx. 2600 inhabitants), which is situated on the landslide, and parts of the village of Triesen, which lies at the foot of the landslide mass on the edge of the Rhine valley floor (Fig. 90). This is a very ancient feature, the origin of which dates back to earliest 12000 years BP, latest 8500 years BP (Carbon-14).

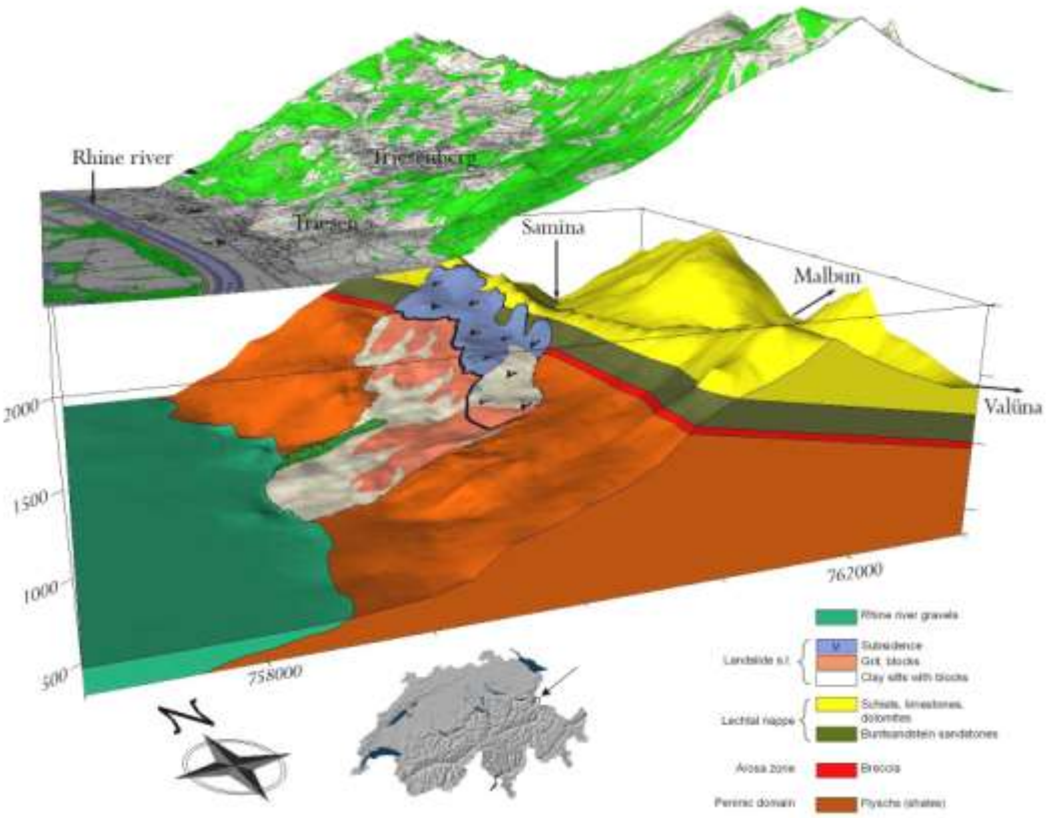

Fig. 90: Map and geological model of the Triesenberg slope with the boundaries of the active landslide and the area of subsidence (rock slide) in its upper part. The now stable mass of the ancient landslide does not crop out through the topographical surface. Behind the crest is the perched valley of the Samina river.

Since the end of the 1970's it has been the object of periodical surveys to measure its movement (geodesy and inclinometry). A large-scale project targeting the stabilisation of the moving mass, drawn up in 1991, was based on a drainage system totalling around 8 km in length to harvest the sub-surface waters. The Liechtenstein Office of Civil Engineering (TBA FL), by whom the work was commissioned, expressed reserve as to the long-term efficiency of the measures proposed, since these did not sufficiently take into account the hydrogeological aspect of the landslide. In 1998 the TBA instructed Dr. Riccardo Bernasconi Geological Consultancy to carry out a hydrogeological study in the sector that was considered to be particularly critical, situated just above the village of Triesenberg.

Characteristics of the landslide

- **Geology:** The complex structure of the sliding mass is divided into three main sections. The upper part corresponds to a subsidence of intact bedrock packages by sagging (rock slides), mainly affecting the hard Triassic rock formations (Buntsandstein and Muschelkalk). The subsided section has the appearance of stairs descending in a southerly direction from the north. The intermediate section of the landslide is characterised by block streams that originate in the rock face of the subsided masses and are supplied by the debris resulting from their disintegration. These debris flows, which are composed of stones and blocks of sandstone and dolomite, extend over several hundred metres downhill. They are generally separated laterally by soil with a high proportion of clay and silt resulting from the disintegration and weathering of the marl and flysch of the bedrock (Fig. 90). The lower part of the landslide consists mainly of a mixture of weathered marl and flysch, with some elements of Triassic sandstone and dolomite. The average thickness of the slide mass is approximately 80 m; in some places, in particular towards the foot of the slide, it is more than 100 m. At present only the top layer (10 to 15 m thick) is active.
- **Hydrogeology:** Due to the soil materials present, permeability is very heterogeneous. In fact the subsided upper sector of the slide, as well as the block streams in the central part are characterised by moderate to high permeability ($k \geq 5 \cdot 10^{-4}$ m/s), whereas the permeability of the clay-silt soils between the block streams and predominant in the lower sector is only low ($k \leq 1 \cdot 10^{-5}$ m/s). Whilst groundwater circulation in the upper part of the slide (subsidence and block streams) is phreatic (unconfined), we find that in the lower part groundwater circulation is often confined or semi-confined. A particularity of this slide is the occurrence in its central part of a number of springs with high discharge (Q average discharge ≥ 5 l/s); these are generally situated at the lower end of the block streams.
- **Dynamics of the slide:** the average speed of displacement varies between 2 and 5 cm per year in the central part of the slide, and between a few mm and 2 cm per year in the peripheral areas. In most of the boreholes there is only one identifiable sliding surface, which is situated at a depth between 10 and 15 m. In spite of the fact that none of the boreholes equipped with an inclinometric tube reached the bedrock, it can be presumed that there is no other active sliding surface at greater depth, given the coherence between the displacements measured at the sliding surface and geodesic observations on the surface. Taking into consideration the displacements measured in the past (periodic measurements every 3 to 6 months) it was assumed up till now that the landslide moved at a more or less constant speed.

Concept of the observation and instrumentation system

From 1978 to 1997 observation of the landslide was carried out in the classic manner, by means of geodesic survey and inclinometric measurement of displacements. In 1999 a different observation strategy was adopted, with the aim of discovering the factors that could have a decisive influence on the dynamics of the landslide. The site under study was equipped with instruments measuring various hydrogeological parameters:

- a pluviometer in the central area of the landslide,
- 5 piezometric devices in the piezometric tubes reaching the sliding surface,
- devices measuring discharge, electrical conductivity and temperature of the 5 most important springs and
- 2 in-place inclinometers.

All data were continuously and automatically gathered over a period of two years (1999-2001). Apart from the continuous monitoring, observations were supplemented by periodical measurements in 4 piezometric tubes, 11 springs and 4 inclinometers.

Results of data collection

The long-term movements of a few cm per year are known from the geodetic measurements and the inclinometer monitoring.

Fig. 91 shows an overview of the results obtained for some of the measuring stations in the period 2000-2001. As a result of the continuous monitoring programme it was discovered that the sliding mass does not move at a constant speed and that the variation in speed is not directly influenced by local precipitation. The speed of downslope movement appears clearly to be a function of the water pressures measured within the moving mass. The water pressures, and the discharge of the springs, are connected in a complex manner with meteorological conditions. Slight to moderate rainfall provokes an immediate but limited increase of the groundwater table. Heavy rain (such as on 6 Aug 2000) triggers, at first, a rapid rise of the groundwater table and, a few days later, a second rise of far greater importance than in the first instance. The conductivity measurements of the spring waters show the first rise to be accompanied by an increase in the mineralization of the water, whereas the second rise is characterised by a dilution of the spring waters (decrease of the electrical conductivity).

What is more, the graphs of the discharge of the springs (e.g. Q16) and the water pressure in the aquifer (B8) show an important increase of values in the period April-May 2000, in spite of the fact that there were no precipitations that justified such change within that period. The influence of snowmelt on the mountainside can be excluded since this had reached its completion one month before. A numerical simulation carried out for higher altitudes has shown that the snowmelt between 1600 and 1800 m above sea level would correspond to a marked increase of the recharge as observed in the groundwater level in springtime (Fig. 91).

These observations suggested that the variations in the groundwater level on the Triesenberg hillside were greatly influenced by a topographically external watershed situated at an average altitude of 1600 to 1800 m above sea level; they also corroborated the hypothesis that such an adjacent watershed could supply the slide with groundwater, which would influence the dynamics of the slide. In view of the topographical situation and the geological structures this could only be applicable to the Valüna watershed, situated behind the crest, in the SE, whose main effluent (Samina) flows towards the North (Fig. 90). Further investigations, in particular a tracer test, provided confirmation of this hypothesis.

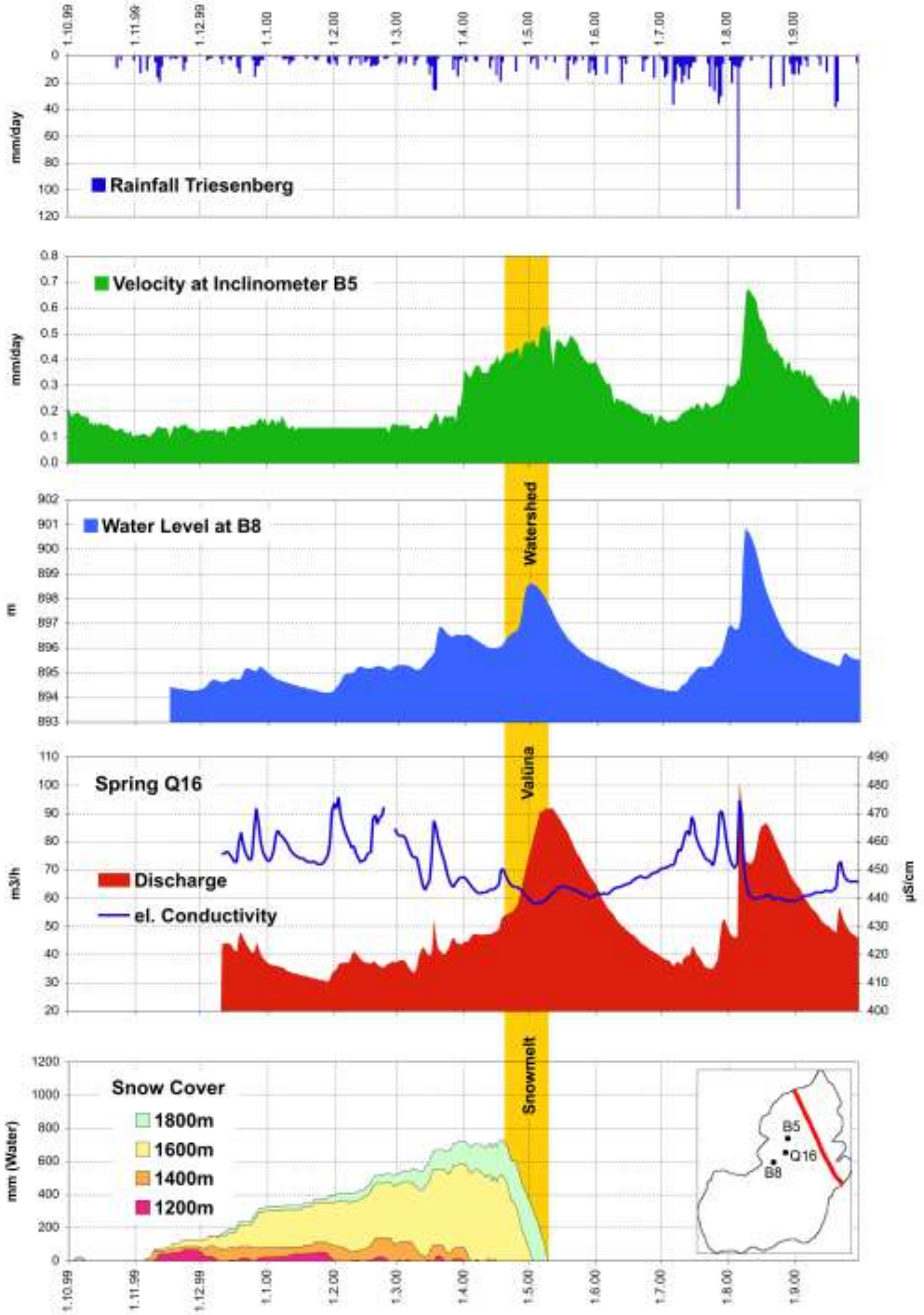

Fig. 91: Graph of the continuously collected data in the inclinometric tube B5, with the piezometric device B8, and of the discharge of spring Q16. The location of these observation points is depicted in the inset map.

Conclusions drawn from monitoring to date

The monitoring concept chosen has made it possible to understand in detail the relation between the groundwater dynamics and the displacements within the landslide. In particular the supply of the unstable landmass with water originating from two distinct watersheds has been brought to light and their respective contribution quantified by means of continuous monitoring of critical parameters, such as daily climatic data, which enabled the establishment of an efficient and well-documented chronology of infiltration.

Modelling of the landslide

The high quality of the continuous climatic and hydrogeological data, together with the inclinometer data, enabled the establishment of numerical hydrogeological and geo-mechanical models of the unstable mass; at the same time certain relatively precise constraints were intro-duced, which led to an accurate calibration of the model. These hydrogeological and geomechanical models implemented by EPFL/ GEOLEP (Fig. 92) yielded reliable results concerning the reaction of the system in case of extreme meteorological events, or as a result of a reduction of the hydraulic pressure due to drainage, or brought about by climatic changes (e.g. increase of precipitation). This latter scenario, simulated with an increase of 50% in hydraulic pressure did not lead to an important acceleration of the system. Conversely, the scenarios where water pressure was reduced, simulated by a general drainage, did not bring about any significant stabilisation.

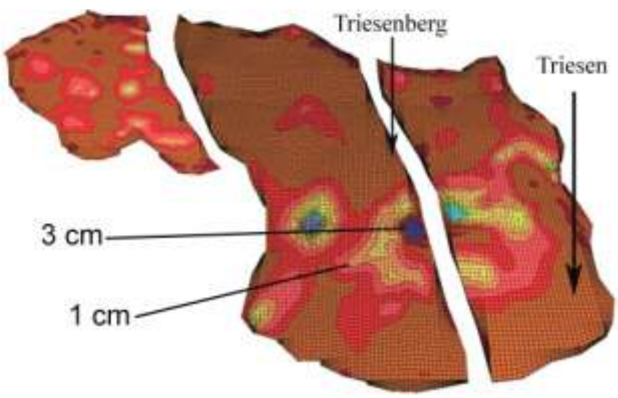

Fig. 92: Field of annual displacement in the active slab of Triesenberg landslide, calculated by numerical modelling with normal meteorological conditions. Calculated displacement rates match the observed value range and more active areas can be distinguished from areas with slower movement. Calculations were carried out for three distinct domains within the landslide, allowing enhanced numerical accuracy within each one.

Prospect

Based on current knowledge of the dynamic of the landslide it is certain that there is no large-scale acute threat to property or human life that would call for area-wide real time monitoring. Local monitoring networks can cover the need for the monitoring of sensitive or single objects worthy of protection. However, there is a need for a survey of the long-term development within the landslide area. The methods used up till now (geodesy and inclinometry) only offer a rough chronological solution (months in the case of inclinometer measurements, years for geodesic measurements) and do not sufficiently cover the unstable area. Furthermore, material, labour and financial costs for these methods are relatively high.

Recent technologies allow the spatially inclusive and comprehensive logging of landslide movement at little cost. Satellite-based radar imagery of earth movements of the size of those occurring in the Triesenberg landslide has already been used successfully in the past. Using ground-based radar interferometry it is possible to gather data of displacements within the whole area and within arbitrarily selected intervals of time (as small as minutes); initial pilot experiments concerning the Triesenberg landslide have delivered encouraging results (Fig. 93). The long-term dynamics of the sliding mass, as well as the temporary acceleration phases, could be observed and documented by means of land-based radar monitoring in conjunction with low-cost, individually placed automatic borehole extensometers, which have a considerably longer lifespan in comparison to the traditional inclinometers.

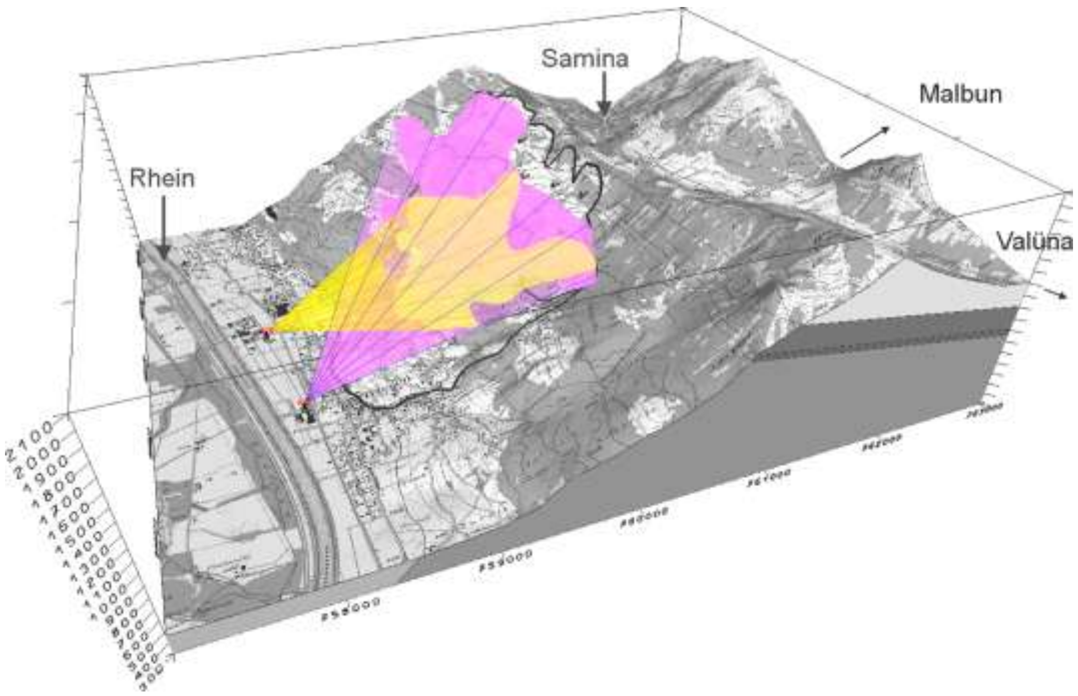

Fig. 93: Scheme for displacement observations by ground-based radar interferometry. With initial pilot measurements from two locations at the valley-bottom the major part of the area covered by the landslide were screened by the radar.

References

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Colesanti. C., Wasowsky, J. (2006): Investigating landslide with space-borne Synthetic Aperture Radar (SAR) interferometry; Engineering Geology Volume 88, Issues 3-4, Pages 173-199

ANNEX B METHODICAL SPECIFICATION SHEETS

The following annex presents several specification sheets of discussed slope monitoring methods. Besides the detailed description of the methodology in chapter 6 the specification sheets are supposed to give a detailed view of the achievement potential, limitations and capabilities in a more numerical matter. This shall provide the reader with the most relevant parameters, although the description will not go into details.

It has to be noted that the information provided in this annex does not describe concrete instruments but summarizes an overall evaluation.

B1. Tacheometry

General Information	
Category	Geodesy
Background	terrestrial
Basic Principle	
Technology	Horizontal & vertical angle measurements combined with electronic distance metres
Processing	Polar coordinates converted to Cartesian coordinates.
Particularly suitable for…	
Landslides with very small movement rates (few mm per epoch)	
Possible (Monitoring) Applications	
Installation of a network (pillars and monitoring points) always recommended. - Survey of a wide-spread area during several field campaigns - Permanent monitoring is possible with motorized total stations (e.g. fixed in a shelter), Automatic Target recognition allows to observe retro-reflective targets that are mounted on the slope/object	
Main Advantages	
- Link to national reference frame provides information on abso lute movement of the slope - High precision allows the detection of even small geometrical changes between two epochs - Easy combination with other geodetic methods (sensor fusion, data integration)	
Main Disadvantages / Problems	
- survey campaigns are time consuming and should be realized by small teams of 2-3 persons - Provides only surface information	
Main Results	
type	relative/absolute point movements
Dimensions	3D (ΔPosition)
typical product	geodetic network/vectorial displacement rates
Coverage	
single-point	Yes
area-wide	No
territorial expansion	small scale to medium scale (several km²)
range coverage	Typically ~300 m, possible: up to 10 km
spatial res./point density	~100 per km²
temporal resolution	on demand

Uncertainty in Measurement	
display resolution	distance: 0.1 mm, angle: 0.01 mgon
precision	distance: 0.5 mm, angle: 0.15 mgon
accuracy	distance: 1 mm, angle: 0.20 mgon
reliability/validation	adjustment theory (self validation)
Degree of Automation	
data acquisition	0% …. 100%
data processing	50%
Availability and Service Provider	
state of the technology	standard tool
service provider	Surveying offices
hardware	(mot.) total station & accesoires
software	standard surveying tools
data access	self-acquisition
historical data	no
Infrastructure	
energy consumption	rechargeable battery
shelter	No (Yes for permanent monitoring)
communication	No
extra data necessary	No
Degree of Difficulty	
installation	Experts only
processing	Experts only
interpretation	Easy to use
Cost Estimation	
equipment	€€
data collection/campaign	€€

B2. Terrestrial Laserscanning

General Information	
Category	Geodesy / Remote Sensing
Background	Terrestrial
Basic Principle	
Technology	The laser instrument emits a short pulse of light, usually near-infrared radiation. At the same instant, an electronic clock is started. The pulse propagates trough the atmosphere, bounces off the target's surface, propagates back, and is detected by a photodiode. Detection of the pulse stops the clock, so the two-way travel time to the surface can be determined. If the absolute position of the instrument is known, the absolute position of the reflecting point on the target's surface can therefore also be determined. The object is scanned in both horizontal and vertical directions, at the rates of several thousands points per second, depending on the ranging approach employed.
Processing	The output of the scanning process is a highly detailed 3D image of the object, typically consisting of millions of densely spaced points, called "point cloud". The point cloud is than filtered and following a surface hull is created by triangulating or interpolation between point data (geostatistical methods). The digital surface model (DSM) created can than be used for analysis.

Particularly suitable for…

Local landslides, approximately 500 m x 500 m, setting rates > 10 cm per epoch, spatial determination of mass movement (erosion and deposition of material)

Possible (Monitoring) Applications

Usually terrestrial laser scanning is done temporarily in several epochs

For continuous monitoring the following tasks are necessary: power supply; a protection against external forces and fixed mounting of the device; data transfer and management; automated data post processing.

Main Advantages

High spatial information

Very flexible

Main Disadvantages / Problems

Accuracy decreases with increasing distance to the object (measured slope)

Not automated data post processing (different steps of post processing are necessary)

Main Results	
type	Pointclouds (coordinates)
Dimensions	3D, RGB & intensity values
typical product	Digital Terrain Model (DTM) and Digital Surface Model (DSM) due to first-pulse/last-pulse technology

Coverage	
single-point	no
area-wide	yes
territorial expansion	small scale
range coverage	5 – 4000 m
spatial res./point density	depending on range (cm … dm)
temporal resolution	on demand
Uncertainty in Measurement	
display resolution	Variable
precision	
accuracy	2 cm (at 100 m range); 30 cm (at 1000 m range)
reliability/validation	Pointcloud Registration, Tacheometry
Degree of Automation	
data acquisition	up to 100%
data processing	A high degree of automation can be established for a single site
Availability and Service Provider	
state of the technology	Standard tool / ongoing research
service provider	Surveying offices, engineering consultants
hardware	Riegl, Optech, Leica, Faro, etc.
software	RiScanPro, Geomagic, GIS, etc.
data access	Self-acquisition
historical data	No
Infrastructure	
energy consumption	~ 90 W
shelter	Preferred
communication	Laptop
extra data necessary	For adding global coordinates GPS or tacheometry
Degree of Difficulty	
installation	Easy but experts needed
processing	Experts needed
interpretation	Easy
Cost Estimation	
equipment	€€
data collection/campaign	€€

B3. Precise Levelling

General Information	
Category	Geodesy
Background	Terrestrial
Basic Principle	
Technology	Main idea: The difference in elevation between two points is determined by measuring their vertical distance from a horizontal line of sight. Line levelling is used to bridge large distances (e. g. to geological stable areas)
Processing	accumulation of height differences network adjustment
Particularly suitable for…	
Local landslides & zones of subsidence with setting rates even < 1 mm per epoch	
Possible (Monitoring) Applications	
Usually Precise Levelling is done temporarily in several epochs For continuous monitoring, motorized levels can be used to observe fix mounted bar-coded staffs in a very limited surrounding (radius of 20 to 30 m) Vast settlement measurements cannot be automated. Automatic measuring systems can however be used for local settlement measurements	
Main Advantages	
very accurate height information cost-effective	
Main Disadvantages / Problems	
only surface information of height changes no horizontal component (position) available	
Main Results	
type	height information, changes in height
Dimensions	1D (height)
typical product	Profiles/intersections or maps of subsidence
Coverage	
single-point	Yes
area-wide	Yes
territorial expansion	small scale to medium scale (several km)
range coverage	distances of 20 - 30 m per set up
spatial res./point density	every 10 - 100 m
temporal resolution	on demand

Uncertainty in Measurement	
display resolution	0.01 mm
precision	~0.1 mm
accuracy	0.15 - 3.0 mm/km
reliability/validation	adjustment theory (self validation)
Degree of Automation	
data acquisition	0%
data processing	80%
Availability and Service Provider	
state of the technology	standard tool
service provider	Surveying offices
hardware	levelling instrument + 2 levelling staffs
software	standard surveying tools
data access	self-acquisition
historical data	no
Infrastructure	
energy consumption	rechargeable battery
shelter	no
communication	no
extra data necessary	no
Degree of Difficulty	
installation	easy to use
processing	easy to use
interpretation	easy to use
Cost Estimation	
equipment	€
data collection/campaign	€

B4. Global Positioning System

General Information	
Category	Geodesy
Background	terrestrial & space-born

Basic Principle	
Technology	Main idea: determination of a receiver's position by triangulating "pseudoranges" from at least 4 GPS satellites. Geodetic GPS receivers use the signal's phase to determine the precise range from the receiver to the satellite (in contrast to navigational purpose, where only a modulated code is used).
Processing	Difference between two reveivers is calculated (reference station – rover = baseline). Thus, identical meteorological influences can almost be eliminated. Therefore a simultaneously measurement under comparable conditions are necessary.

Particularly suitable for…

Local Landslides with displacement rates of about 1 cm per epoch. Higher accuracy hard to achieve, but possible.

Possible (Monitoring) Applications

Installation of a network (pillars and monitoring points) always recommended. Reference station and rover stations can be used for 3 strategies:

- Real-time Kinematic (RTK-GPS) for quick survey of control points (occupation time on each point: ~15 min)
- Static occupation with GPS-receivers (for ~12-24h) during several campaigns
- Permanent monitoring with GPS receivers is possible

Main Advantages

- Absolute and relative 3D-positioning
- No direct line-of-sight between monitoring points necessary
- Comfortable connection to stable points out of deformation area
- Cheapest technique for monitoring very large landslides and deep-seated-deformation: several control/object points, scattered over a wide area, may be effectively measured in one workday
- Installation of monitoring points is easy and cost-effektive: they can be simply bolted in place (with drilling machine-made holes.

Main Disadvantages / Problems

- Multipath effects
- Shadowing (view to the sky is indispensable)
- Lower accuracy of height component

Main Results	
type	baselines (vectorial slope distances)
Dimensions	3D (ΔPosition)
typical product	geodetic network/vectorial displacement rates

Coverage	
single-point	yes
area-wide	no
territorial expansion	0.1…~700 km² (small and medium scale)
range coverage	baselines <30 km recommended
spatial res./point density	~ 0.2... 2 points/km²
temporal resolution	on demand, also continoulsy

Uncertainty in Measurement	
display resolution	0.1 mm
precision	2 - 10 mm (position), 5 - 25 mm (height)
accuracy	3 - 30 mm (position), 7 - 50 mm (height)
reliability/validation	adjustment theory (self validation); classical tacheometry

Degree of Automation	
data acquisition	0%... 100% (manual measuring epochs… permanent stations)
data processing	80%

Availability and Service Provider	
state of the technology	standard tool
service provider	surveying offices, universities
hardware	Leica Geosystems, Trimble, Ashtech, …
software	variety of commercial products and few scientific products (e.g. Bernese Software)
data access	self-acquisition
historical data	no

Infrastructure	
energy consumption	rechargeable battery
shelter	no
communication	essential for RTK-GPS, not needed for static/permanent obs.
extra data necessary	DGPS: yes; RGPS: no

Degree of Difficulty	
installation	external experts needed
processing	easy…external experts needed
interpretation	easy

Cost Estimation	
equipment	€€ (per receiver), at least two receivers necessary, 3-5 recomm.
data collection/campaign	€

B5. Direct Current Geoelectric

General Information	
Category	Geophysics
Background	terrestrial
Basic Principle	
Technology	Main idea: repeated measurements of subsurface electric resistivity. A fix installed geoeletric profile is used for geoelectric monitoring. Repeated measurements to investigate the changes of electric resistivity. Distribution of resistivity changes indicates changes in landslide water regime
Processing	2D Inversion of geoelectric data;
	2D time lapse inversion of geoelectric data to evaluate the resistivity changes
Particularly suitable for…	
Local landslides	
Possible (Monitoring) Applications	
Installation of a geoelectric profie for 2D geoelelctric measurements	
Permanent monitoring system with a proprietary development of measuring device	
Main Advantages	
+ monitoring of resistivity changes as evidence for changes inside a landslide	
+ fast measurements	
+ high reliable data with substantial data processing/filtering	
Main Disadvantages / Problems	
- stand alone solutions for power supply	
- stroke of lightnings	
Main Results	
type	changes in electric resistivity of subsurface
Dimensions	2D (ΔPosition)
typical product	information of short/long lasting processes within landslides
Coverage	
single-point	yes
area-wide	yes
territorial expansion	small scale
range coverage	
spatial res./point density	
temporal resolution	2 – 3 hourly
Uncertainty in Measurement	
accuracy	
reliability/validation	Borehole instrumentation

Degree of Automation	
data acquisition	permanent possible
data processing	common
Availability and Service Provider	
output	
state of the technology	standard tool/ongoin research
service provider	surveying offices, universities
hardware	Geomon 4D
software	variety commercial products and scientific products
data access	self-acquisition
historical data	no
Infrastructure	
energy consumption	yes
shelter	no
communication	needed
extra data necessary	no
Degree of Difficulty	
installation	easy
processing	easy
interpretation	easy
Cost Estimation	
equipment	€€€ (per geoelelctric profile)
data collection/campaign	€€ (depends on accessibility of site)

B6. Fixed Camera Photogrammetry

General Information	
Category	Remote Sensing
Background	terrestrial
Basic Principle	
Technology	A block of overlapping images is acquired over the area of interest with calibrated digital cameras. Depending on hardware and processing facilities: 1) a set of ground control points (gcp) is available (i.e. by total station) or 2) image acquisition is synchronized to a GPS tied to the camera
Processing	Softwares for stereoscopic or monoscopic manual restitution (targets); digital image correlation (DEMs) Homologous image point coordinates are measured (manually or automatically) in every image. Bundle block adjustment provides image orientation. Object point coordinates are determined by tri-angulation or multiple intersections. Points on the object can be selected manually (targets) or automatically (DEMs).

Particularly suitable for…

Rock faces (stability analysis) and
small glaciers with displacement rates of min, 5 cm per epoch

Possible (Monitoring) Applications

- Installation of a network with signalised ground control points
- Direct image orientation with GPS
- Permanent monitoring possible with digital video-cameras

Main Advantages

- Absolute and relative 3D-positioning
- Points can be measured almost anywhere, if there is texture
- Images are a permanent record; new points can be measured at any time in old images
- Accuracy can be adjusted to project needs
- Productivity increases as accuracy decreases

Main Disadvantages / Problems

- Target and maintenance of ground control points
- Illumination (shadows);
- Inhomogeneous accuracy of coordinates
- Connection to stable points outside the deformation area or reliance on GPS

Main Results	
type	coordinates
Dimensions	2D or 3D (Δcoordinates)
typical product	terrain surface (DEM), vectorial displacements of targets, field deformation (DEM)

Coverage	
single-point	Yes
area-wide	Yes
territorial expansion	10 … 15.000 m² (small/med. scale)
range coverage	1 m … 200 m
spatial res./point density	100 points/m²
temporal resolution	monthly to yearly
Uncertainty in Measurement	
precision	1 - 3 cm, best results (targets, image scale 1:2000, gcp, multiple convergent images)
accuracy	2 - 5 cm, best results (targets, largest image scale, gcp, multiple convergent images)
reliability/validation	Adjustment theory (self validation): object point accuracy is estimated from covariance matrix or covariance propagation. Redundancy: image overlapping with multiple images
Degree of Automation	
data acquisition	manual
data processing	DEM generation automatically, targets/gcp only manually
Availability and Service Provider	
state of the technology	standard tool / ongoing research
service provider	surveying offices, universities
hardware	any calibrated high resolution digital camera with interchangeable optics
software	variety commercial products (PCI Geomatics, Inpho,....) and scientific products
data access	self-acquisition
historical data	possible but unlikely
Infrastructure	
energy consumption	reference GPS station
shelter	No
communication	Not essential (RTK)
extra data necessary	
Degree of Difficulty	
installation	External expert needed
processing	External expert needed
interpretation	easy
Cost Estimation	
equipment	camera: € - €€; software::€ - €€€
data collection/campaign	€

B7. Aerial Photogrammetry

General Information	
Category	Remote Seinsing
Background	airborne
Basic Principle	
Technology	A block of overlapping images is acquired over the area of interest with calibrated digital cameras from flying airborne platforms. 1) a set of ground control points (gcp) is available (i.e. by total station) or 2) image acquisition is syncronized to an integrated Inertial Navigation System (INS) & GPS
Processing	- Homologous image point coordinates are measured in every image - Bundle block adjust. provides image orientation - Object point coordinates are determined by triangulation/least squares multiple intersection - Points on object can be selected manually (targets) or automatically (DEMs) - Orthoimage generation from DEM - Orthoimage correlation - DEM difference

Particularly suitable for…

Landslides (from 100m² to few km²), glaciers with displacement rates of min 10 cm per epoch

Possible (Monitoring) Applications

- Installation of a network of signalised ground control points
- Direct image orientation (INS/GPS) and direct geo-referencing
- Permanent monitoring not possible

Main Advantages

- Absolute and relative 3D-positioning
- Points can be measured almost anywhere, if there is texture
- Images are a permanent record; points can be measured at any time in old images
- productivity increases as accuracy decreases
- 3D motion map by combining image corr. and DEM difference

Main Disadvantages / Problems

- Target and maintenance of ground control points
- Illumination (shadows);
- Inhomogeneous accuracy of coordinates
- Connection to stable points outside the deformation area
- Vegetation

Main Results	
type	Coordinates
Dimensions	3D (ΔPosition)
typical product	- Terrain surface (DEM), - Vectorial displacements of targets, - Field displacement/deformation - Ortho-image, - landslide cartography

Coverage	
single-point	Yes
area-wide	Yes
territorial expansion	0.2… 20 km² (medium/large scale)
range coverage	10 m… 10 km
spatial res./point density	20 points/m²
temporal resolution	monthly to yearly; 5 year cycle
Uncertainty in Measurement	
precision	Position: 4 - 5 cm, Height: 5 - 12 cm
accuracy	1/10 pixel for surface displacement Position: 7 - 10 cm, Height: 10 - 15 cm
reliability/validation	Adjustment theory (self validation) Redundancy: image overlapping with multiple images
Degree of Automation	
data acquisition	- obtained from national geographic institutes or land surveying offices - self-acquisition with unmanned aerial vehicle (UAV)
data processing	possible: Structure& Motion, Automatic Aerial Triangulation, DEM generation ; target/gcp only manuallly
Availability and Service Provider	
state of the technology	standard tool / ongoing research
service provider	surveying offices, universities
hardware	Leica Geosystems, Intergraph Z/I Imaging, Vexcel, Trimble, …
software	variety commercial products and scientific products
data access	surveying companies, mapping agencies, self-acquisition
historical data	available
Infrastructure	
energy consumption	GPS ground stations with GPS/INS
shelter	no
communication	not necessary
extra data necessary	GPS/INS
Degree of Difficulty	
installation	external experts needed
processing	external experts needed
interpretation	easy
Cost Estimation	
equipment	data acquisition by a service provider; processing software: € - €€€
data collection/campaign	€€

B8. Optical Satellite Imagery

General Information	
Category	Remote Sensing
Background	space-borne (different platforms), to lesser degree air-borne
Basic Principle	
Technology	Main idea: space-borne observation of surface changes (land-cover changes, vegetation, surface temporal alterations and surface displacements) with passive optical sensors working in visible or near IR spectrum. Data can be acquired from a catalogue of existing images or a specific campaign can be programmed. It is generally difficult to obtain 2 images of the same area with a time span less than 3 days.
Processing	- Raw or processed (geo-referenced, noise-reduced/removed) data is available. - Images are processed by classification methods - Multitemporal image correlation for calculation of surface map displacement - Raw data and very precise orbital parameter are required to correct geometrical distortions

Particularly suitable for…

Local and regional landslides (which size is les than a image length < 60km) with displacement rates of half to few pixel per epoch (depending of the quality of the geometrical information on images acquisitions). It is difficult to correlate images acquired by 2 different sensors because the geometry of acquisition if too different.

Possible (Monitoring) Applications

- Constant repetitive/periodic monitoring, governed by weather conditions and day/night conditions , orbital configuration
- Permanent monitoring system (with eventually low-cost for end-user) requires too many satellites on the same orbit cycle

Main Advantages

- Synoptic view of the landslides and their velocity fields
- Broad coverage, constant periodic monitoring (also in hardly accessible areas)
- Possible panchromatic/multispectral imagery
- Easy comparison of observed areas of slope mass movements with stable areas
- For surface displacement calculation by image correlation

Main Disadvantages / Problems

- Low accuracy of monitoring of displacements
- Horizontal changes detectable only/ no vertical component
- Shadowing, weather conditions, day/night conditions
- Images not always available on requirement

Main Results	
type	raster (coordinates, Digital Number of signal per pixel per image), grid
Dimensions	2D (ΔPosition)
typical product	typology, surface displacement

Coverage	
single-point	no (limited resolution)
area-wide	yes
territorial expansion	few km² to 60 × 60 km² (depending on satellite parameter)
range coverage	450 - ~ 700 km (satellite orbit)
spatial res./point density	~ 4500 to 3 mio.points/km² (pixel size from 0.6 m² to 15 m²)
temporal resolution	depends on groundtrack repetition period (3-dayly, weekly, monthly)
Uncertainty in Measurement	
display resolution	~ 0.6 - 15 m
precision	ideally less than a pixel size, 1/2 pixel for surface displacement
accuracy	depends on geo-referencing quality (several m to several tens of m)
reliability/validation	groundtruthing
Degree of Automation	
data acquisition	permanently (for the period of lifetime of platform)
data processing	yes, with various algorithms ~ 90%, still final expert decision is needed
Availability and Service Provider	
output	Digital Images
state of the technology	Standard tool / ongoin research
service provider	Space Agencies
hardware	Sensor systems on platforms
software	Variety commercial products and scientific products (e.g. Erdas Imagine)
data access	data centre (e.g. ESA)
historical data	Yes
Infrastructure	
energy consumption	Solar panels on space vehicle
shelter	No
communication	No
extra data necessary	groundtruthing/geo-referencing
Degree of Difficulty	
installation	external experts only
processing	experts needed, manageable
interpretation	experts needed, manageable
Cost Estimation	
equipment	€€€€€ - high-tech equipment, but cost on the service provider
data collection/campaign	€ - €€, depends on data resolution and territorial expansion

B9. Airborne Laserscanning

General Information	
Category	Remote Sensing
Background	airborne
Basic Principle	
Technology	- Time-of-flight distance measurement - Active sensors on airplane/helicopter
Processing	3D-point cloud (positioned and oriented by GPS/INS in real-time or post-processing) With each scan, measurements are taken of the slant range to the point of reflection and of the beam angle in the locator's coordinate system. The path of the aircraft is registered by an airborne GPS receiver and its orientation by INS data. Position data obtained together with measured slant distances and scan angles provide accurate 3D positions of each reflected laser point.
Particularly suitable for…	
Landslides with displacement rates of min. 1 m per epoch	
Possible (Monitoring) Applications	
Main Advantages	
Good results in areas covered with shrubs and trees	
Applicability in unaccessible or difficult accessible areas	
Good results under poor meteorological conditions	
Main Disadvantages / Problems	
Steep slopes	
lower accuracy of horizontal component	

Main Results	
type	coordinates, heights
Dimensions	3D (Position)
typical product	Digital Terrain Model (DTM) and Digital Surface Model (DSM) due to first-ulse/last-pulse technology
Coverage	
single-point	No
area-wide	Yes
territorial expansion	Medium and large scale
range coverage	200 m... 6000 m
spatial res./point density	depending on range (dm … m)
temporal resolution	
Uncertainty in Measurement	
Accuracy (height)	>11 cm (flying altitude < 1000 m) >15 cm (flying altitude > 1000 m)
Degree of Automation	
data acquisition	only by service-provider
data processing	high degree of automation

Availability and Service Provider	
state of the technology	standard tool / ongoing research
service provider	specialiced surveying offices, national land surveying offices
hardware	Leica Geosystems, Optech, Topo-Sys
data access	-
historical data	no
Infrastructure	
energy consumption	-
shelter	-
communication	-
extra data necessary	GPS/INS
Degree of Difficulty	
installation	external experts only
processing	external experts only
interpretation	easy
Cost Estimation	
equipment	-
data collection/campaign	€€€€

B10. PSInSAR

General Information	
Category	Remote Sensing
Background	space-borne, synthetic aperture radars

Basic Principle	
Technology	The PSInSAR™ analysis is based on the processing of long series of SAR data (min. 25-30) acquired in the same geometry over the same area in order to single out those pixels, referred to as Permanent Scatterers (PS), that have a "constant" electromagnetic behaviour in all the images. PS can be rock outcrops or large boulders, metal or concrete power poles, buildings, etc. For each PS identified it is possible to calculate the displacements occurred in the time span considered.
Processing	The PSInSAR™ overcomes the main limiting factors of conventional SAR techniques (i.e. DINSAR): the PS singled out allow to assess and remove the typical atmospheric artefacts and noise affecting the SAR image thanks to an image processing algorithm developed and patented by Politecnico di Milano (POLIMI) sensor will detect variation in the distance by comparing different acquisitions.

Particularly suitable for…

Local & regional landslides with displacement rates of 0.1-x mm/epoch; displacements with maximum velocity of 10 cm/a

Possible (Monitoring) Applications

- Since radar satellites pass over the same area once every 35 days it is possible to observe landslide with this frequency
- If no natural radar reflectors (PS) exit on the landslide artificial reflectors can be placed on the slope
- Constant repetitive/periodic large area monitoring

Main Advantages

- data available since 1992
- Cost-efficient monitoring of a large number of slow-moving landslides over a wide area
- Apart from the case in which artificial reflectors are used there is no need for any field device, benchmark, monument, etc.
- The monitored area can be inaccessible
- High PS density (up to 1 000 PS/km^2)
- all-time/weather monitoring possibility
- easy comparison of slope mass movements with stable areas

Main Disadvantages / Problems

- Only displacements along line-of-sight (LOS) between satellite and PS can be measured.
- The technique is not applicable in wooden/grass-covered areas
- Since satellite orbits are NS oriented; displacements along EW oriented slopes are difficult to detect.
- Since radar satellites pass over the same area once every 35 days (average); real-time monitoring is non possible.
- PSInSAR™ analysis is a patent of Politecnico di Milano and analyses are only made by a spin-off company.
- If the target is affected by LOS displacement values approaching 14 mm between two successive acquisitions, measurements can be “aliased” and the estimation of the displacement may no longer be correct (ambiguity of results).

Main Results	
type	Displacement velocity (mm/a)
Dimensions	1D, along LOS
typical product	Geographic dataset including PS location and related velocities
Coverage	
single-point	Yes
area-wide	Yes
territorial expansion	1… ∞ km² (medium & large scale)
range coverage	from satellite
spatial res./point density	~10 … ~1500 points/km²
temporal resolution	~35 days (groundtrack repetition)
Uncertainty in Measurement	
display resolution	0.01 mm/a
accuracy	0.5 mm/a average displacement rate
single displacement acc.	0.5 mm
reliability/validation	field comparison with GPS
Degree of Automation	
data acquisition	100%
data processing	80%
Availability and Service Provider	
state of the technology	ongoing research / standard tool
service provider	Telerilevamento Europa TRE, Milano, spin-off of Politecnico di Milano, many others…
hardware	satellite systems, SAR sensors
software	proprietary software
data access	data cenrtre (ESA, EURIMAGE)
historical data	yes (since 1992)
Infrastructure	
energy consumption	No
shelter	No
communication	essential, but for data provider
extra data necessary	optional / GPS, ground-truthing
Degree of Difficulty	
installation	external experts only
processing	external experts only
interpretation	Data interpretation can be made by a skilled geologist who has, however, to have a good knowledge of basics and limits of the PSInSAR™ method.

ANNEX C PARTNERS LIST

WP6 Lead Partner

	Institution	People involved
	LfU: Bayerisches Landesamt für Umwelt (Bavarian Agency for Environment)	Andreas von Poschinger Karl Mayer Thomas Gallemann

WP6 Project Partners

	Institution	People involved
	ARPA: Agenzia Regionale per la Protezione Ambientale del Piemonte (Piemonte Regional Agency for Environmental Protection)	Carlo Troisi Alessio Colombo
	AWNL: Amt für Wald, Natur und Landschaft (Ministry of Environmental Affaire, Land Use Planning, Agriculture and Forestry)	Emanuel Banzer
	BAFU: Bundesamt für Umwelt (Federal Office for Environment)	Hugo Raetzo
	BMLFUW: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (Ministry for Agriculture, Forestry, Environment and Water Economy)	Andreas Reiterer Margarete Wöhrer-Alge
	GeoZS: Geološki zavod Slovenije (Geological Survey of Slovenia)	Marko Komac, Mateja Jemec, Jasna Šinigoj Špela Kumelj, Katarina Hribernik, Matija Krivic, Mitja Janža
	RAVA: Région Autonome Vallée d'Aoste (Aosta Valley Autonomous Region)	Liliana Cazaban
	RhôneAlpes: Region Rhône Alpes, Direction de l´Environment et de l´Energie (RhôneAlp Region, Dept. of Environment and Energy)	Jean-Marc Vengeon
	UCBL: Université Claude Bernard Lyon 1 (Claude Bernard University of Lyon 1)	Pascal Allemand Philippe Grandjean
	WBV: Autonome Provinz Bozen: Abt. Wasserschutzbauten (Autonomous Province of Bolzano, Dept. 30)	Hanspeter Staffler Evelyn Scherer

WP6 External Experts

	Institution	People involved
	Abenis AG	Andreas Zischg
	BOKU: Universität für Bodenkultur Wien, Department für Bautechnik und Naturgefahren (University of Natural Resources and Applied Life Sciences, Dept. of Structural Engineering and Natural Hazards)	Alexander Prokop
	CETE: Centre d'études technique de l'équipement de Lyon	Jean-Paul Duranthon Johan Kasperski Pierre Potherat
	Dr. Riccardo Bernasconi: Beratender Geologe und Hydrogeologe	Riccardo Bernasconi
	ETH: Eidgenössische Technische Hochschule Zürich, Ingenieurgeologie (Swiss Federal Institute of Technology Zurich, Engineering Geology Group)	Andrew Kos Simon Loew Kerry Leith
	FondMS: Fondazione Montagna Sicura – Montagne sûre (Aosta Valley Autonomous Region)	Jean Pierre Fosson Marco Vagliasindi Iris H. Voyat
	GBA: Geologische Bundesanstalt	Alexander Römer Robert Supper
	TUM: Technische Universität München, Lehrstuhl für Geodäsie (Chair of Geodesy)	Wolf Barth, Thomas Schäfer Thomas Wunderlich
	UJF: Université Joseph Fourier – Grenoble 1, Laboratoire de Géophysique Interne et Tectono-physique, CNRS, Observatoire de Grenoble	Didier Hantz Denis Jongmans Stéphane Garambois
	UNIPR: Università degli Studi di Parma (University of Parma)	Anna Maria Ferrero Gianfranco Forlani Riccardo Roncella
	UBO: Univerité de Bretagne Occidentale	Christophe Delacourt