13th FIG Symposium on Deformation Measurements and Analysis
4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering
LNEC, Lisbon 2008 May 12-15

MONITORING A DEEP-SEATED MASS MOVEMENT USING A LARGE STRAIN ROSETTE

Helmut WOSCHITZ and Fritz K. BRUNNER

Engineering Geodesy and Measurement Systems, Graz University of Technology, Austria

Abstract: The monitoring results of the landslide Gradenbach, Austria, by GPS suggest that the motion of the deep-seated mass movement is not uniform but rather intermittent, i.e., periods of accelerated motions are followed by quiescent periods. However, GPS surveys are not sufficiently precise to allow for a detailed study of this pattern of motions. Therefore, we have developed an embedded strain rosette for in-situ measurements of local distance changes. It consists of three embedded extensometers with a separation in orientation of 120°. The sensors are long gauge (5 m) fibre optical interferometers of SOFO type (low coherence interferometer) yielding a precision of 2 µm for length changes. The same sensors can be used for dynamic measurements with a precision of better than 10 nm with sampling rates of 1 kHz. The concept and design of the strain rosette is discussed and its set-up is described. First results of the strain rosette embedded in the landslide mass are presented. They confirm the capability of this new measurement system under field conditions.

1. INTRODUCTION

Landslides are unavoidable natural processes in alpine regions, often associated with economical and social disasters. Therefore, large efforts have been made to investigate the causes and mechanisms of landslides using accurate monitoring techniques.

On alpine slopes, deep-seated gravitational creep is a frequently observed phenomenon. The rock material is best described as brittle rock. The volume of the creeping rock mass is usually about 10^7 m^3 or larger. The surface velocities vary from millimetres to metres per year and may significantly change with time. Precipitation and groundwater level variations are frequently considered responsible for the variations of the deformation rates, however, a general model describing these relationships is still lacking.

Geodetic techniques can be used to determine the deformation of a slope's topography at discrete points as a function of time using repeated surveys. GPS measurements have been found very useful either in sporadic campaigns or by continuous operation (Dzurisin, 2007). We have developed such a GPS monitoring system (Brunner et al., 2003), and used it for monitoring the landslide Gradenbach, Austria. In this paper we briefly describe the deep-seated mass movement Gradenbach and show the results of the 19 GPS campaigns carried out since August 1999.

The GPS results revealed the surprising phenomenon of a strongly accelerated motion with a sudden halt in autumn of 2001. Knowledge about the mechanism of this pattern is crucial for its accurate prediction. Thus microseismic data is recorded and analysed by a research group (Prof. E. Brückl) from the Vienna University of Technology, whilst we have developed a large strain rosette using fibre optic sensors. Its basic design, set-up and first test results were described in Brunner et al. (2007). We have now embedded the strain rosette in the landslide mass. First results using the Gradenbach installation are described in this paper.

2. THE GRADENBACH LANDSLIDE

The Gradenbach landslide is situated at the junction of the Graden-Valley and the Möll-Valley in Carinthia (Austria). The hamlet Putschall (see figure 1) is threatened by this landslide. Its active deformation zone involves the entire slope with widths ranging between 600 m and 1.000 m, and extends over approximately 1.000 m in height below the head scarp. The moving mass was estimated with $15 \cdot 10^7$ m^3. The clearly developed main head scarp lies slightly lower than the mountain ridge (2.270 m), see figure 1.

For the past 30 years, the landslide Gradenbach has been investigated using geodetic, geotechnical and seismic surveys. For a summary of these investigations and an interpretation of the kinematics of this landslide see Brückl et al. (2006).

Figure 1: Gradenbach landslide, head scarp, GPS stations Ref 1, Ref 2, A, B, C and D

An autonomous GPS monitoring system has been developed for the investigation of the Gradenbach landslide (Brunner et al., 2003). In its current realisation, the monitoring system consists of six GPS stations. Two reference stations (Ref1 and Ref2, see figure 1) were selected in the stable bedrock area in order to provide a control on the capability of GPS to determine accurate deformation values. The four monitoring points (A to D) situated in the active part of the slope were selected to provide best satellite visibility. The first GPS survey (zero-measurement) took place in August 1999 and the results of all following campaigns refer to this zero-measurement.

So far 19 GPS surveys of the Gradenbach network were carried out and a review of these results is provided in Brückl et al. (2006) and Brunner et al. (2007). Figure 2 shows the computed height variations, relative to the first GPS survey and Ref2, of the four monitoring stations and of the second reference station. Due to a receiver problem in 2007, the reference station was changed from Ref1 to Ref2. The expected lack of significant height variations for the baseline Ref2 – Ref1 (stable bedrock), as shown in figure 2 can be used to calculate the standard deviation of height difference results, i.e. 8 mm.

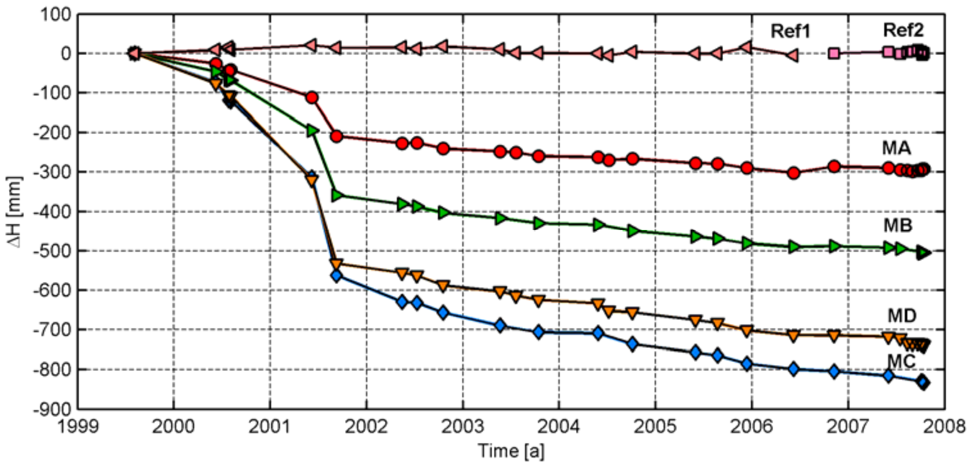

Figure 2: Time series of GPS results for station heights

The results show an acceleration of the slope in the year 2000, with a sudden deceleration in 2001. Within this accelerated period height changes of up to 50 cm were observed.

3. STRAIN ROSETTE

3.1. Initial Work

Figure 2 shows that we were quite lucky in picking up the accelerated motion of the landslide during the first two years of operating the GPS monitoring system. This data indicated a catastrophic collapse of the mountain slope with a pattern of accelerated motions which is not unlike that of known landslide disasters. The accelerated motion persisted also during the winter months. However, the motions drastically slowed down at the end of the summer period of 2001. Similar patterns like that depicted in figure 2 for the Gradenbach landslide have been observed at several other landslide locations and more frequently than originally thought (Brückl, personal communication).

For the detailed investigation of the mechanism of this pattern, the concept of using an embedded large strain rosette was argued in Brunner et al. (2007). Very precise measurements of the local strain situation could yield an insight into the geomechanics of this behaviour of a landslide.

The strain rosette consists of three 5 m long extensometers at a separation of 120° in orientation. The extensometers are long gauge fibre optical sensors of the SOFO type (Inaudi et al., 1994 or Inaudi, 1997). A significant advantage of using the SOFO system is that the same embedded sensors are used for the measurement of the static (absolute) and the dynamic (relative) length changes. Two different reading units (RU) have been used for measuring the distance changes of the three legs of the strain rosette: (a) SOFO-Static RU and (b) SOFO-Dynamic RU. The SOFO-Static RU is used for long term monitoring and yields a precision of 2 µm, independently of the length of the SOFO sensor (Inaudi, 1997). It is based on a low coherence interferometer and allows to measure absolute length changes of the sensors. A little drawback is the measuring time of a few seconds. The SOFO-Dynamic RU (LLoret and Inaudi, 1999) is intended to measure relative length changes over short periods with a precision of 10 nm up to 10 kHz. Reference is lost if this instrument is disconnected from the sensor.

When installing the large strain rosette and embedding the sensors, the main challenges are the proper connection of the SOFO sensors with the soil and their protection against other disturbances. In order to gather experience with this new application, a test rosette with 5 m long measuring arms was established in a horizontal soil section prior to the installation in the landslide area. The set-up of this test installation and results of its investigation are shown in Brunner et al. (2007).

3.2. Installation at the Gradenbach Landslide

The concept of sensor installation used at the test installation had to be modified slightly for the Gradenbach site, because of lacking infrastructure in the alpine region (1600 m elevation). The basic idea was to attach the sensors to small concrete blocks (approx. 30 cm in diameter, 40 cm in height) at the bottom of a trench with concrete-casted adapters. Those adapters were made of stainless steel and constructed to allow adjusting the lengths of the sensors. The holes for the concrete blocks were dug manually in order to disturb the soil as little as possible. Additionally, the concrete blocks were anchored to the soil using 1.5 m long reinforcement bars, see figure 3 left.

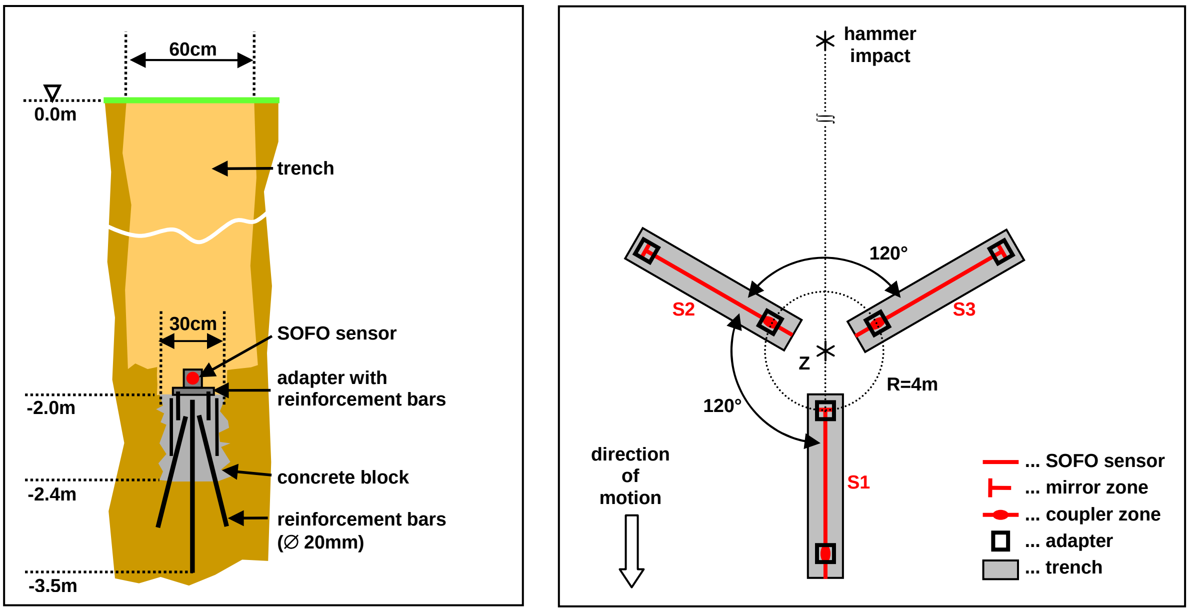

Figure 3: Schemes of SOFO sensor installation (left) and of the strain rosette (right)

The rosette was built in May 2007 between the GPS stations A and B in the Gradenbach landslide area (see figure 1). Each sensor was embedded in a separate trench as depicted in figure 3 right. The orientation of the rosette was chosen in a way that sensor S1 is parallel to the direction of motion of GPS station B. The SOFO sensors were installed parallel to the surface in a depth of about 2 m (i.e., below the local depth of frost penetration). Their coupler and mirror zones were protected against external effects using metallic pipes, which were attached to the concrete anchor, see figure 4. When filling the trenches, sand was used close to the SOFO sensors in order to protect them against damage.

Figure 4: Sensor S2 whilst embedding

A temperature sensor and a soil moisture sensor were placed near the coupler zone of sensor S3 for monitoring soil moisture and soil temperature. The sensor setup is completed by an air temperature sensor. It is mounted near the strain rosette at a cabin that houses and protects the instruments.

4. FIRST RESULTS OF THE STRAIN ROSETTE MEASUREMENTS

4.1. Static Measurements

Starting from the middle of July, continuous measurements were collected for sensor S1, i.e. 12 single measurements every 6 hours. Sensors S2 and S3 were measured sporadically, as the available SOFO-Static RU is a single channel instrument only, which needs manual switching between different sensors.

The SOFO-Static RU contains a data logger and an internal battery for the autonomous operation without a computer. The unit can be configured to go to the power saving sleep mode between the measurement epochs. Thus several thousand single measurements can be acquired without recharging the battery. After about 50 days, we recharged the batteries and took this opportunity to carry out measurements with sensors S2 and S3 (middle of July and in the beginning of September). Additional measurements with all tree sensors were carried out in October 2007, during a two week long measurement campaign with the SOFO-Dynamic RU.

In addition to the SOFO sensor values, the internal temperatures of the reading unit were stored in the database. Using a separate data logger, the temperature and moisture of the soil as well as the air temperature were measured every 10 minutes.

Using the temperatures of the soil and of the SOFO-Static RU, the measured SOFO values ΔL^{raw} were corrected for (a) the remaining temperature sensitivity of the SOFO sensors, and (b) for the temperature sensitivity of the spindle of the SOFO-Static RU, giving a value ΔL. For the temperature sensitivity of the SOFO sensor see Inaudi (2004), and for the one of the spindle of the SOFO-Static RU see Lienhart (2005). The magnitude of the overall correction is about 6 µm for a change of the soil temperature of 3°C and a change of the SOFO-Static reading unit's temperature of 30°C within the shown time span.

Figure 5 shows the SOFO-Static measurements of the three SOFO sensors S1, S2 and S3 from May till October 2007. The ΔL values show the length difference of the sensor's measurement fibre in respect to the reference fibre. If the distance between the concrete anchors gets smaller, the ΔL values also decrease. Sensor installation, especially when pre-stressing a SOFO sensor, must be within the working range of the SOFO-Dynamic RU (i.e., ΔL is within 38 mm ± 5 mm). Pre-stressing is important in order to make shortening of the sensors measureable, also in the rather loose soil material. Thus, we have pre-stressed the sensors by approx. 3 mm in the Gradenbach strain rosette.

Continuous monitoring of sensor S1 was first started in the middle of July, i.e. two months after installation of the strain rosette, as we have expected initial movements after the construction work. For each of the 450 measurement epochs the standard deviation (*std*) was computed for the 12 single measurements. Most of the *std* values are below the 2 µm that are specified by the manufacturer, only 30 values are larger (up to 4 µm), which proves the specification, but also shows, that more than one measurement per epoch is necessary.

From middle of July till the end of October the length changes are in between -0.14 mm (sensor S1) and -0.04 mm (sensor S2). The GPS results of the same period also show a shortening of the distance between GPS stations A and B. Of course, this apparent agreement of the two results will be further investigated using additional measurements.

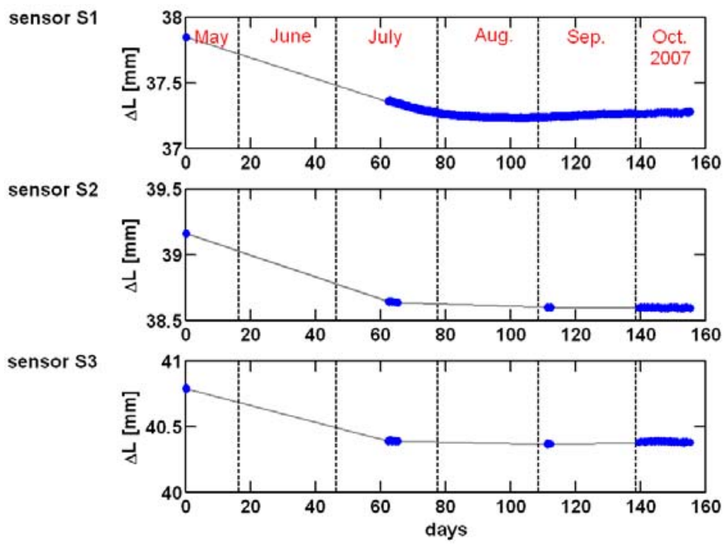

Figure 5: Relative movements of the concrete anchors, determined by the three sensors S1, S2 and S3 of the strain rosette

It ought to be mentioned that control measurements for the highly precise SOFO data are nearly impossible using an independent technique at the landslide area. Thus, the precision of the SOFO-Static RU is regularly controlled in the field by measuring a reference sensor of known length. Additionally, check measurements of another sensor, which is permanently mounted in our laboratory and thus kept under constant thermal conditions, are carried out.

4.2. Dynamic Measurements

At the landslide area, mass movements cause micro-earthquakes, which occur approximately once a week and have duration of less than 0.1 s (Brückl, personal communication). The exact relationship between these micro-earthquakes and the mass movement is rather unknown. One of the purposes of our strain rosette to detect possible strain waves associated with the Gradenbach deep-seated mass movement.

Immediately after installation of the strain rosette, artificial excitations were used to investigate its capability to measure strain waves. We used hammer impacts to the ground to generate strain variations. Data were acquired with the SOFO-Dynamic RU with a sampling frequency of 1 kHz.

The position of the hammer impact was in the line of sensor S1, 28 m apart from Z (see figure 3). Figure 6 shows the relative movements ΔL of the concrete anchors of the strain rosette caused by the impact of a 5 kg hammer. The time of the first maximum appearing in the signals is also plotted. The strain wave arrives almost simultaneously at the sensors S2 and S3. About 25 ms later, the strain wave activates sensor S1, and thus the velocity of propagation can be computed as 290 m/s.

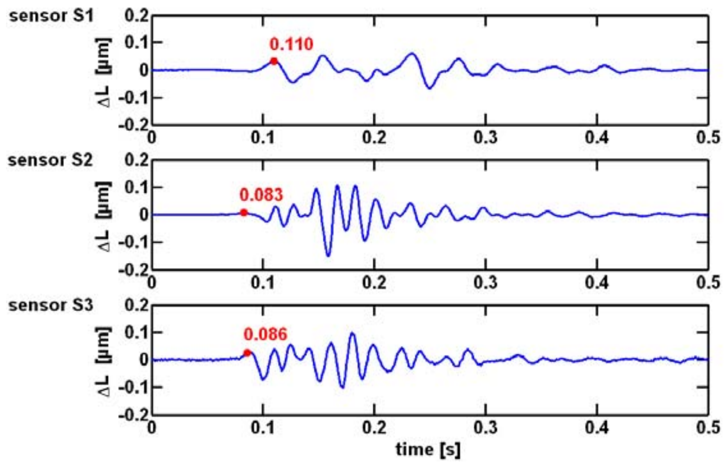

Figure 6: Relative movements of the concrete anchors caused by a hammer impact

For the shown hammer impact, the maximum strain amplitudes of the three sensors are in the range of 0.07 to 0.15 µm. Due to energy propagation and absorption within the soil, the amplitudes vary with the distance between the hammer impact and the strain rosette, e.g. they decrease to the 10 nm level at a distance of 100 m. However, the hammer impacts rather low energy has experimentally verified the high sensitivity of the SOFO-Dynamic system in amplitude and frequency.

Middle of July 2007, we carried out a first measurement campaign (3 days) to test the SOFO-Dynamic RU under field conditions and perhaps to detect a first seismic event. This test was necessary, as data should be collected at least over night without user interaction and during this period the power supply had to be realised by batteries and a 230V power inverter, which is a rather unusual operation of the system.

Figure 7 shows a 15 minutes long data set acquired with the SOFO-Dynamic RU. The shown data are high-pass filtered in order to reduce remaining drifts (up to 30 µm in 10 hours). The detected “signals” have maximum amplitudes of 15 nm and are plotted red in figure 7.

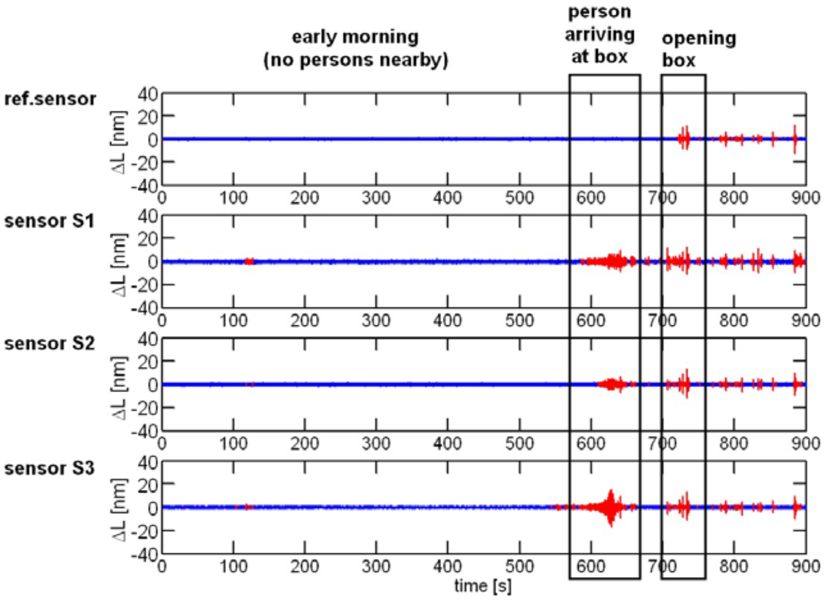

Figure 7: Example of high-pass filtered signal of SOFO-Dynamic RU

Nearly 10 minutes after the beginning of the data set, a person arrived at the instrument cabin which can be seen clearly by the signals of all three sensors. However, the reference sensor (ref.sensor in figure 7), which has been used for drift compensation, was located inside the cabin and protected against vibrations. This is the reason why it does not show the same vibrations as the embedded sensors. Afterwards, when the cabin was opened to replace the batteries, the reference sensor also shows a signal. This demonstrates the capability of our strain rosette to detect signals of very low amplitude (about 10 nm).

This example shows the very high sensitivity of the SOFO-Dynamic RU and it becomes obvious that additional information is necessary to locate seismic events in a noisy data set, especially in the current state of the investigation, where only little is known about the signal pattern of a micro-earthquake. Data of a seismometer array (operated at the Gradenbach landslide by the team of Prof. Brückl, TU Vienna) are used for this purpose and for the identification of seismic events.

Unfortunately, we could not detect a micro-earthquake induced by the landslide within this measurement campaign. However, the signal of an earthquake is shown in figure 8, which was classified as a regional earthquake with the epicentre in Yugoslavia using the seismometer array. In order to detect the very low signal generated by such an earthquake, the data of the SOFO-Dynamic RU had to be low-pass filtered. In the raw data set the maximum amplitudes are about 1.5 nm, which is close to the noise level of the SOFO-Dynamic RU. Again, the enormous potential of the SOFO-Dynamic system is clearly demonstrated.

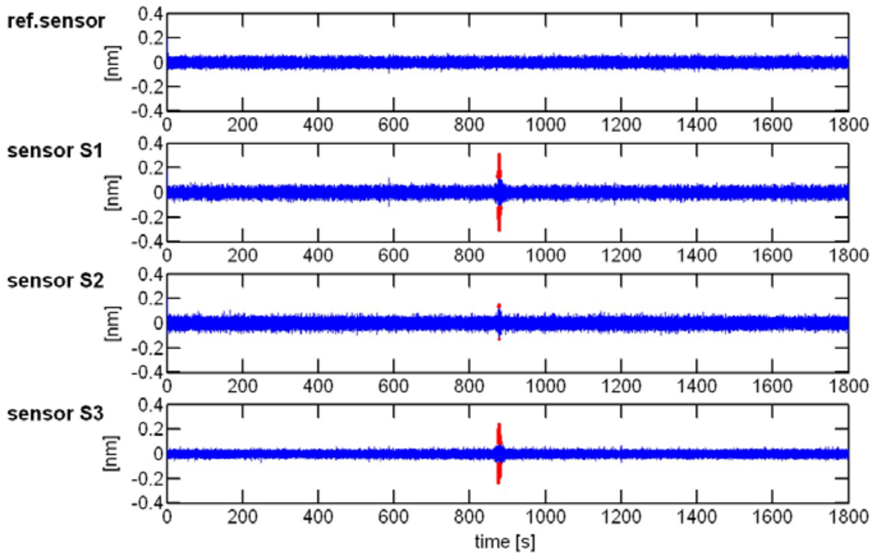

Figure 8: Low-pass filtered data showing a regional earthquake measured with the SOFO-Dynamic RU

5. RESUME

Landslides are a serious concern of the International Strategy for Disaster Reduction (ISDR), and the investigations described in this paper are an Austrian contribution (Austrian Academy of Sciences Project) to ISDR. We have developed an autonomous GPS measurement system to monitor landslide motions. This includes the development of several data processing models to increase the attainable accuracy.

Our investigations of the deep-seated mass movement Gradenbach using the GPS monitoring system have shown a period of accelerated motions with the potential of leading to a catastrophic landslide. However, the movements came to a sudden halt. Apparently such a pattern of intermittent landslide motions occurs more frequently than originally thought, but the reasons for this pattern and thus its predictability are hardly understood.

Therefore our investigations concentrate on this phenomenon. For this purpose, we have developed a large strain rosette. Basically the strain rosette consists of three 5 m long fibre optical sensors of the SOFO type which are embedded in the ground. Length changes can be measured statically with a precision of 2 µm, and dynamically with a precision better than 10 nm for frequencies at 1 kHz. Two different reading units are required, however, both use the same embedded SOFO sensors. These values could be confirmed in a test set-up. A serious problem is the proper connection of the fibre optical sensors with the moving ground, which was achieved by attaching the sensors to vertical concrete anchors, poured into the ground to a depth of 2 m.

The presented results show the high potential of the fibre-optic systems. In October 2007, a two week long measurement campaign was carried out in order to detect at least one micro-earthquake induced by the landslide. These data are currently analysed. It is expected that the strain rosette measurements will yield new information to better understand the propagation of strain waves in the deep-seated mass movement Gradenbach.

Acknowledgments

This paper is part of research projects funded by the Austrian Academy of Sciences within the Austrian contribution to IDNDR and ISDR. The cooperation with Prof. Dr. E. Brückl of Vienna University of Technology is very much appreciated. We would like to thank all colleagues who participated in the many strenuous GPS field campaigns and who contributed to the set-up of the strain rosette.

References

Brunner, F.K., Woschitz, H., Macheiner, K. (2007) *Monitoring of deep-seated mass movements*. 3rd Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3), Nov.13-16, 2007, Vancouver, Canada

Brunner, F.K., Zobl, F., Gassner, G. (2003) *On the Capability of GPS for Landslide Monitoring*. Felsbau 21: 51-54

Brückl, E., Brunner, F.K., Kraus, K. (2006) *Kinematics of a deep-seated landslide derived from photogrammetric, GPS and geophysical data*. Engineering Geology 88: 149-159

Dzurisin, D. (2007) *Volcano Deformation: Geodetic Monitoring Techniques*. Springer, 441 p.

Inaudi, D. (1997) *Fiber optic sensor network for the monitoring of civil engineering structures.* PhD Thesis, EPFL Lausanne, Switzerland

Inaudi, D. (2004) *Testing performance and reliability of fiber optic sensing system for long-term monitoring.* Proc. 2nd European Workshop on Optical Fibre sensors, Santander, Spain, 9-11 June 2004

Inaudi, D., Elamari, A., Pflug, L., Gisin, N., Breguet, J. and Vurpillot, S. (1994) *Low-coherence deformation sensors for the monitoring of civil-engineering structures.* Sensors and Actuators A 44: 125-130

Lienhart, W. (2005) *Experimental Investigation of the Performance of the SOFO Measurement System.* In Fu-Kuo Chang (Ed.) '*Structural Health Montoring 2005, Proc. 5th Int. Workshop on Structural Health Monitoring*', Stanford, USA: 1131-1138

LLoret, S. and Inaudi, D. (1999) *Amplitude Modulation of a Low-Coherence Source, Applications to Distance and Dynamic Displacement Sensing.* Optics & Lasers in Engineering Vol. 32, No. 4: 325-337

Corresponding author contacts
Helmut WOSCHITZ
helmut.woschitz@tugraz.at
Engineering Geodesy and Measurement Systems
Graz University of Technology
Steyrergasse 30
A-8010 Graz
AUSTRIA