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MONITORING OF DEEP-SEATED MASS MOVEMENTS

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Abstract

A GPS monitoring system has been developed for the investigation of landslides. The applicability of this system is demonstrated by monitoring the deep-seated mass movement Gradenbach, Austria. 17 GPS surveys of at least 48 hours duration each were carried out during the last seven years. The motions can be determined with an accuracy of 4 mm in horizontal direction and 8 mm in vertical direction. The accurate GPS results suggest that the velocity pattern of the deep-seated mass movement at Gradenbach 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 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. The concept, design and first test results will be presented.

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 10^8 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 [1]. We have developed such a GPS monitoring system [2], and used it for the monitoring of the landslide Gradenbach, Austria. In this paper we briefly describe the deep-seated mass movement Gradenbach, review the development of the GPS monitoring system, and discuss the results of the 17 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. Apparently such a pattern is more frequently observed than originally thought, however, the prediction of such a sudden halt seems to be poorly understood. For the detailed investigation of the mechanism of this pattern we are developing a large strain rosette which will be embedded in the landslide mass. The strain rosette uses fibre optic sensors. Its design, set-up and the first test results are described in this paper.

THE GRADENBACH LANDSLIDE

The landslide Gradenbach 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 reference is made to [3]. During the years 1965 and 1966 a very high acceleration of the movements was observed. However, the catastrophic mass movement came to a halt. This pattern occurred again during the summer months of the years 1972, 1975, 1977, 1980, 1991 and 1992, however, with motions which were not as large as those of 1966, [4].

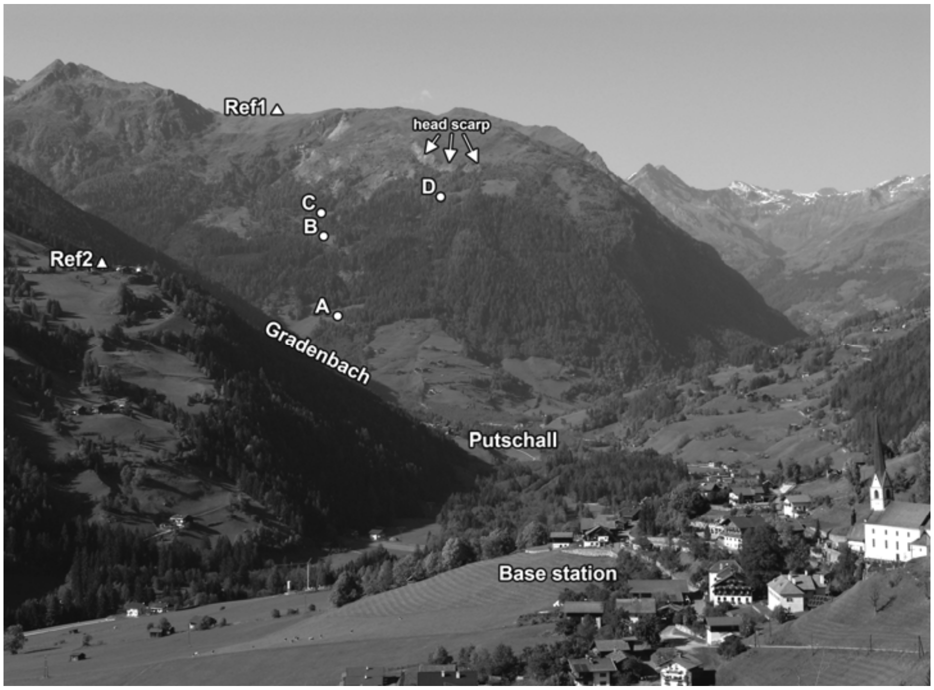

Figure 1. Gradenbach landslide, head scarp, GPS stations Ref 1, Ref 2, A, B, C and D

GPS MONITORING

Monitoring System

An autonomous GPS monitoring system has been developed for the investigation of landslides [2]. In its current realisation, the monitoring system consists of six GPS stations; at least two of them are used as reference for the remaining monitoring stations. The system could easily be extended to more than six stations. The GPS hardware at a station basically consists of a choke-ring antenna with a radome protection and a GPS receiver. The GPS data are transmitted by radio to a central computer, where the data are stored and immediately processed. Power supply and lightning protection units were developed for the autonomous operation.

The GPS results shown in the following were obtained using the GPS post-processing software BERNESE 5.0. The 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. If the coordinates of one station (reference) are assumed to be known, then the coordinates of the second station (monitoring) can be computed with high accuracy.

Currently we are investigating the continuously observed GPS data during the summer months of all years since the year 2000. For these investigations we have developed several improved models for the atmospheric propagation effects, the variances and the correlations of the GPS signals. First results using these models were discussed in [2], and final results will be presented elsewhere.

GPS Results

For the Gradenbach GPS network, two reference stations were selected in the stable bedrock area, see Figure 1. The four monitoring points (A to D) situated in the active part of the slope were selected to provide best satellite visibility and to form approximately a straight line between the two reference stations. The first GPS survey (zero-measurement) took place in August 1999. The results of all following campaigns refer to this zero-measurement.
So far 17 GPS surveys of the Gradenbach network were carried out. All GPS measurements lasted for at least 48 hours in order to reduce periodic (most likely diurnal) effects in the GPS phase data. The GPS post-processing software BERNESE 5.0 was used to calculate station coordinates for the 17 epochs. For this purpose the coordinates of the reference station Ref 2 (see Figure 1) were held fixed.

All coordinate results (obtained since the zero-measurements in August 1999) have been used to investigate the landslide motion during the following years. The azimuths of the observed displacements coincide approximately with the dip direction of the slope. The size of the motions depends on the inclination of the slope at the monitoring station which in turn depends on the height of the station. Obviously this pattern is derived from the very small sample of four stations only; however, it is in agreement with the general model of creep mechanism of a deep-seated mass movement [5]. In addition, the photogrammetric analysis of the whole landslide area (based on aerial photographs from 1962 and 1996) confirmed the spatial homogeneity of the landslide's motions, [3].

Figure 2 shows the computed height variations of the four monitoring stations and of the second reference station, Ref 1. Both reference stations were established in stable terrain in order to provide a control on the capability of GPS to determine accurate deformation values. The expected lack of significant height variations for the baseline Ref 2 – Ref 1, as shown in Figure 2, has been used to calculate the standard deviation of height difference results, i.e. 8 mm.

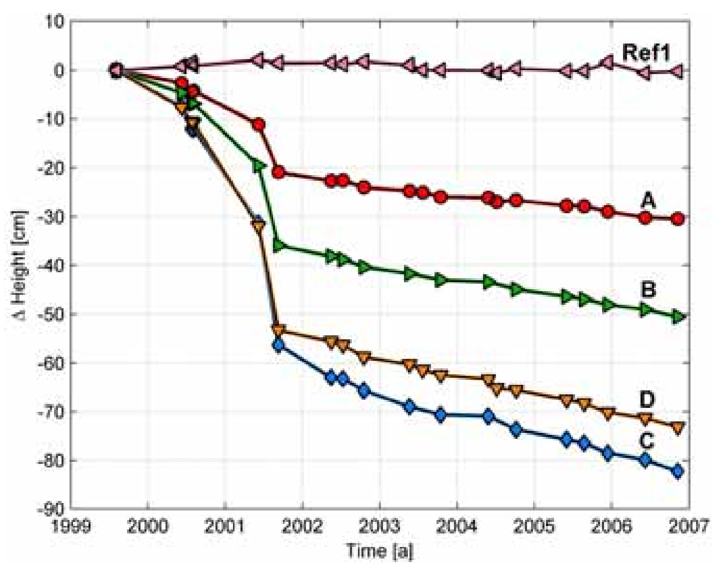

Figure 2. Time series of GPS results for station heights

STRAIN ROSETTE

Concept

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, based on the movements during the summer months of the year 2001. This pattern of accelerated motions is not unlike that of known landslide disasters. However, the motions drastically slowed down at the end of the summer period of 2001. Considering the history of the Gadenbach landslide [4] it appears that such periods of accelerated motions with a sudden halt have occurred several times during the past 40 years.

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]. Prolonged heavy rainfall is often considered to be the cause for the initiation of a landslide’s accelerated motion. However, the duration of this period of accelerated motions and in particular the reason and the timing of the sudden halt of the motions seem to be rather unknown.

A clear understanding of the mechanism of the accelerated motion phase of a landslide obviously would have an enormous value, especially as it is the foundation for the prediction of a halt or a further acceleration of the movements. For this purpose we started a detailed investigation of the periods of accelerated motions with continuous GPS observations. For continuous GPS surveys the GPS phase data were observed every three seconds. We expect that this analysis will reveal whether the landslide mass moves as a block or where the motion is being triggered. In a related research project – under the leadership of Prof. E. Brückl, Vienna University of Technology – the microseismicity of the deep mass movement is being measured and analysed.

The pattern of acceleration and deceleration of the landslide mass on the whole – as measured by GPS monitoring – ought to have related phenomena on a small scale. Very precise measurements of the local strain situation could yield an insight into the geomechanics of this behaviour of a landslide. In addition, it could close the frequency gap between the microseismic and the GPS measurements. For this purpose we are developing a large strain rosette which shall be embedded in the landslide mass. The strain rosette consists of three extensometers at a separation of 120° in orientation. The extensometers are long gauge fibre optical sensors of the SOFO type [6, 7] yielding a precision of 2 µm. In addition, the same embedded sensors can be used by another system to measure relative length changes with a precision of 0.01 µm up to 10 kHz over short periods.

In the following, the test set-up for this novel strain rosette is described and the first test results are reported. Currently a similar strain rosette is embedded in the Gradenbach landslide area near the station B (see Figure 1).

SOFO System

The SOFO system developed by D. Inaudi [7] and distributed by SMARTEC SA (now part of ROCTEST Ltd.) consists of two Michelson interferometers in tandem operation. One interferometer is embedded in the sensor, the other one is part of the reading unit (Figure 3). A detailed description of the SOFO measurement principle may be found in [7].

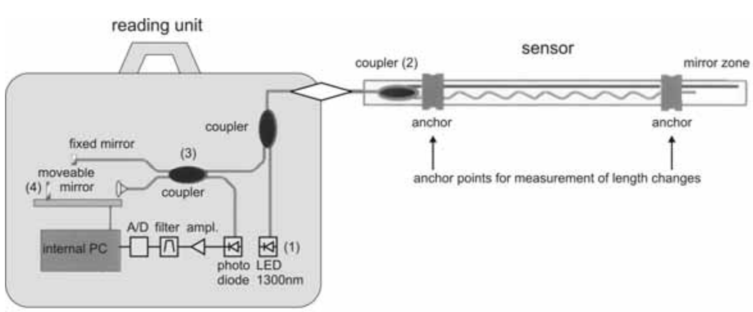

Figure 3. Components of the SOFO-Static system, after [8]

The advantage of the SOFO-Static system is that the reading unit may be disconnected from the sensor without losing information about the distance differences measured so far [7]. Thus, one reading unit may be used to measure various sensors. The SOFO-Static system is able to measure distance changes between the two anchor points of the sensor with a precision of 2 µm [9] using a measurement fiber and a reference fiber. In case of a deformation, the length of the measurement fiber is changed whereas the length of the reference fiber is not affected by the deformation.

In order to increase the sampling rate of the SOFO system, the so called SOFO-Dynamic has been developed [10]. High-frequency distance changes of SOFO sensors may be observed with a sampling rate of up to 10 kHz and a precision of 0.01 µm. However, as the SOFO-Dynamic reading unit loses its reference value after disconnecting a sensor and because of drifts (< 0.5 µm/d), this system cannot easily be used for long term measurements.

Both systems, SOFO-Static and SOFO-Dynamic, have been used for measuring the distance changes of the sensors within the presented strain rosette.

Test Installation

It is one of the main challenges to properly connect the SOFO sensors with the soil. The basic idea was to drill vertical holes, insert steel tubes and fill the remaining hollow spaces with concrete. Then, the SOFO sensors may be attached at a specific depth to these tubes.

In November 2005, three 5 m long steel tubes with a diameter of 89 mm and a wall thickness of 10 mm were vertically installed by Keller Grundbau GmbH at a planar test site near the Center for Construction Engineering (Bautechnikzentrum – BTZ) of the Graz University of Technology. The tubes were stabilized in the soil using a procedure similar to the Soilfrac® method. These tubes situated in a star-shaped manner represent the end points of the strain rosette (Figure 4).

In July 2006, three 5 m long SOFO sensors were placed in the horizontal trenches between the tubes. Adjustable adapters made of stainless steel were used to attach the sensors to the tubes, to compensate small misalignments of the tubes and to pretension the sensors by 10 mm. At their final positions, the adapters were fixed by welding them to the tubes. Due to fixing of the sensors to the central tube (Figure 5) and due to the dimension of the adapters, the sensors had to be situated at different depths. All sensors were placed below the local depth of frost penetration (65 cm to 85 cm below the surface). The coupler zones as well as the mirror zones of the SOFO sensors were protected against buckling using metallic pipes. When filling the trenches, sand was used close to the SOFO sensors in order to protect them. The sensor cables were embedded inside cable conduits for protection purposes.

A temperature sensor in a steel housing and a soil moisture sensor were placed near the central tube (65 cm below the surface). An ambient temperature sensor outside the BTZ building completes the sensor setup. For geotechnical monitoring purposes, inclinometer tubes were inserted inside the vertical tubes.

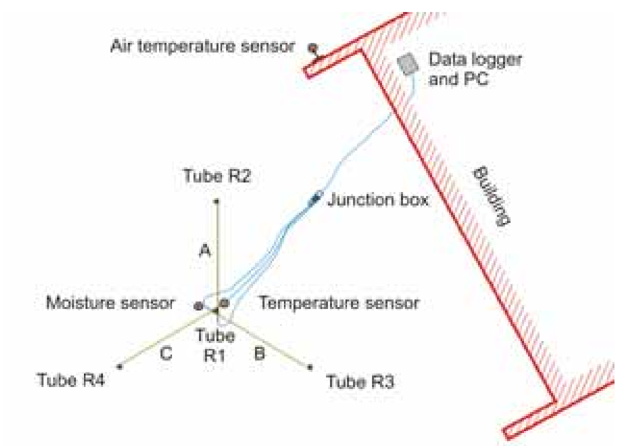

Figure 4. Site plan

A data logger for the temperature and moisture measurements and the SOFO-Static reading unit controlled by a PC were placed within the BTZ building (Figure 4). Starting from the end of July, continuous (one SOFO sensor) and discrete (all sensors) measurements were collected.

Figure 5. Central tube of the strain rosette during installation

STRAIN ROSETTE TEST RESULTS

Static Measurements

The goal of installing the strain rosette near the university was to test the process of embedding the sensors. The connection of the SOFO sensors to the soil and their protection against loose material were the most critical parts in this process. Furthermore, the whole system should be operated and tested under real conditions. It is one of the major advantages of the test site that it is located in a very stable region, and hence, only little deformations should appear. However, it ought to be mentioned that control measurements for the highly precise SOFO data are nearly impossible using an independent technique.

Immediately after sensor installation (see above), the sensors were measured with the SOFO-Static reading unit. As the available SOFO-Static reading unit is a single channel instrument, only one sensor can be measured continuously (twice an hour). The two other sensors are measured sporadically, usually once a day, as manual switching is needed for that. Aside the SOFO sensor values, the internal temperatures of the reading unit are stored in the database. Using a separate data logger, the temperature and moisture of the soil as well as the air temperature are measured every 5 minutes. For those additional sensors, the calibration parameters were determined prior to their installation and those values are applied to the raw data.

The measured SOFO values ΔL_{raw} are corrected for (a) the thermal expansion of the steel adapters (effective lengths 130 mm to 200 mm), (b) the remaining temperature sensitivity of the SOFO sensors, and (c) for the temperature sensitivity of the spindle of the SOFO-Static reading unit, giving a value ΔL. For the temperature sensitivity of the SOFO sensor see [11], and for the temperature sensitivity of the spindle of the SOFO-Static reading unit see [9]. The magnitude of the overall correction is about 18 μm for a change of the soil temperature of -15°C and a change of the SOFO-Static reading unit's temperature of -7°C with respect to the used reference temperature.

Figure 6 shows the movements ΔL between the tubes, determined by the three SOFO sensors A, B and C from July 28, 2006 till January 10, 2007. The ΔL values of all three sensors are close to 10 mm due to the pre-stressing of the

SOFO sensors. Initial movements (see gray shaded area in Figure 6) are caused by cooling down of the soil (used for filling the trenches) which previously was heated up by the sun when stored outside the trenches.

The initial phase ends on August 3 (see vertical, dashed line in Figure 6), after completely filling up the trenches on August 2. Afterwards, the movements are in between 0.2 mm (sensor B) and 0.5 mm (sensor C).

Since August 3, the soil temperature decreased from 23°C to 5°C and the soil moisture increased from 10 % to 15 %, see Figure 7. The influence of soil moisture on the measured length changes is still being investigated.

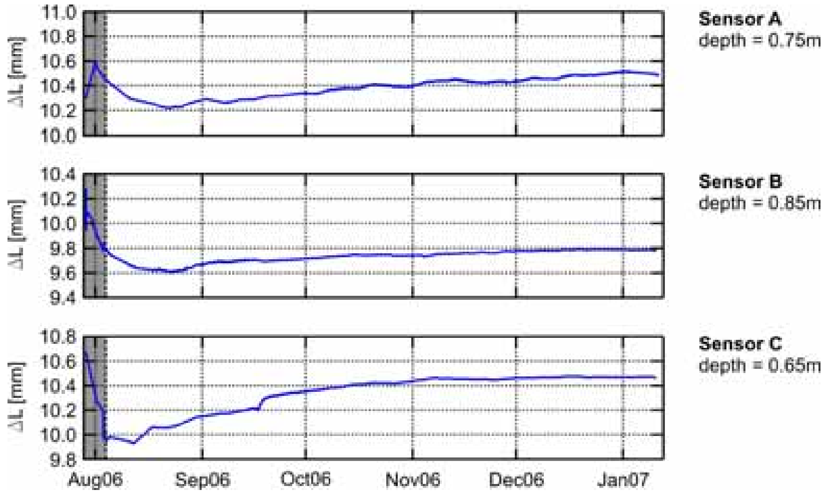

Figure 6. Relative movements of the tubes, determined by the three sensors A, B and C of the strain rosette

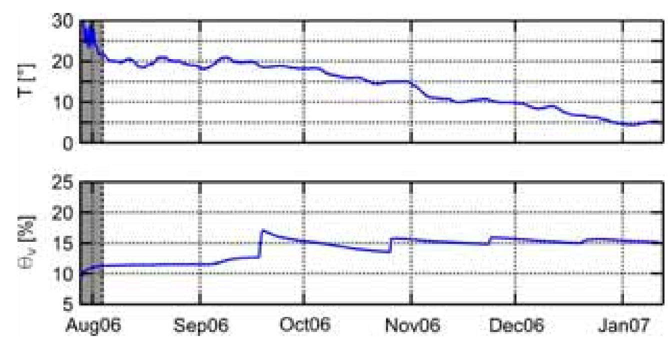

Figure 7. Soil temperature T and volumetric soil moisture content θ_V

With the known distances L_i between the vertical tubes, the measured movements ΔL_i can easily be converted to strain values ε_i, which are denoted ε_A, ε_B and ε_C for the three sensors. The measured strain values of August 3 were used as the initial strain values in order eliminate the influence of the initial motions and the pretensioning of the sensors. The principal strain values ε_1, ε_2 and the orientation φ were computed using the standard eqs. (1) and (2).

$$\tan 2\varphi = \frac{\sqrt{3}\cdot(\varepsilon_B - \varepsilon_C)}{2\cdot\varepsilon_A - \varepsilon_B - \varepsilon_C} \qquad (1)$$

$$\varepsilon_{1,2} = \frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{3} \pm \frac{\sqrt{2}}{3}\cdot\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2} \qquad (2)$$

Note, that these equations are valid for a 120° rosette only and that φ is the angle with respect to the direction of sensor A (mathematically positive).

The principal strains and angle are shown in Figure 8. The orientation φ varies between -64° and -56°, which is almost orthogonal to the wall of the adjacent building (BTZ). The precision s_{φ} is about 0.2°. The principal strain ε_1 (in the direction of φ) increases from 0 to 100 µm/m, where it stays almost constant since the beginning of November. ε_2 varies in between 0 and -60 µm/m. The increasing principal strain values indicate that the distance between the adjacent BTZ building and the strain rosette gets larger. We assume that this is caused by a thermally induced shrinkage of the building (BTZ), which is also corroborated by geodetic measurements (not shown here).

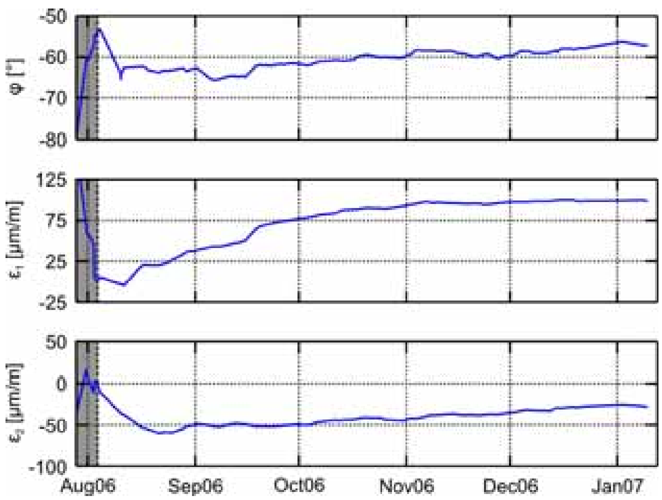

Figure 8. Principal strains ε_1, ε_2 and orientation φ

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]. However, the stable test site is free of micro-earthquakes. Therefore, artificial agitations were used to investigate whether strain waves can be measured with the strain rosette at this special test site. Several experiments were carried out and the results of one are shown here. We used hammer impacts to the ground to generate strain variations. Data were acquired with the SOFO-Dynamic reading unit with a sampling frequency of 1 kHz. Figure 9 shows the relative movements of the anchor tubes of the strain rosette caused by the impact of a 5 kg hammer, 30 m apart from the strain rosette's central tube.

The time of the first maximum is also plotted in Figure 9. The strain wave arrives almost simultaneously at the sensors B and C, but 7 to 10 ms later at sensor A. This is caused by the fact that the position of the impact was chosen to be almost symmetric with respect to sensors B and C. Using the time delay and the geometric relations of this experiment, the velocity of propagation can be computed as 185 m/s. Alternatively, the velocity was determined with accelerometers (190 m/s) showing acceptable agreement.

The period of the signal is 0.6 s (degradation of the amplitude to 5 % of its maximum value), which is about 5 times longer than the expected value. However, the longer period might be caused by the tubes, which may start to oscillate after being activated by the strain wave.

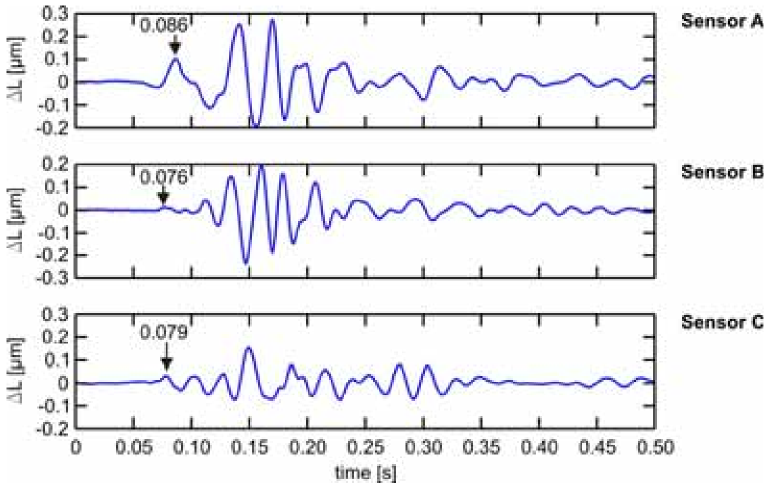

Figure 9. Relative movements of the tubes caused by a hammer impact

The maximum strain amplitudes for the three sensors are in the range of 0.15 to 0.23 µm, which can only be measured due to the very high resolution (< 0.01 µm) of the SOFO-Dynamic system. The amplitudes vary with the distance between the hammer impact and the strain rosette due to energy propagation and absorption within the soil. For example, experiments with the hammer impact only 5 m away from the strain rosette gave larger amplitudes, e.g. 1.0 µm.

The rather low energy hammer impacts have experimentally verified the high sensitivity of the SOFO-Dynamic system in amplitude and frequency, see Figure 9. Thus a similar strain rosette shall be established at the Gradenbach landslide. It is planned to embed the strain rosette near the GPS station B, see Figure 1. The purpose of this strain rosette is to detect possible strain waves associated with the deep-seated mass movements of the Gradenbach landslide.

CONCLUSION

Landslides are a serious concern of the International Strategy for Desaster 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.

For our field investigations, we have selected the deep-seated mass movement Gradenbach. Using the GPS monitoring system, we have carried out 17 GPS surveys during the past seven years. The results showed 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 0.01 µm for frequencies below 10 kHz. These values could be confirmed in a test set-up. A serious problem is the proper connection of the moving ground with the fibre optical sensors. In the test set-up this was achieved by attaching the fibre optical sensors to vertical steel pipes driven into the ground to a depth of 5 m.

The next challenge is to embed such a strain rosette in the landslide area. A site near the GPS station B has been selected for this purpose. A different design for the connection of the sensors to the ground is being developed. 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.

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