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Testing a large fiber optic strain-rosette, embedded in a landslide area

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1 Introduction

Landslides are unavoidable natural processes in alpine regions, often associated with economic and social disasters. Therefore, large efforts have been made to investigate the causes and mechanisms of landslides using accurate monitoring techniques. The prediction of an individual landslide (site, time and velocity) is still unresolved.

Since a few years we investigate the application of precise monitoring techniques for landslides. The deep-seated mass movement Gradenbach was chosen as the experimental site (Brückl et al., 2011). We have developed a GPS monitoring system for landslides (Brunner et al., 2003) which is suited for continuous measurements. Since 1999 the GPS measurements showed a constant block-shaped movement, with two superimposed strongly accelerated motions, each with a sudden halt a few months later. Since the beginning of the GPS measurements, this phenomenon occurred twice in the years 2001 and 2009. So far the cause of the acceleration and deceleration is unknown. We assume local and spontaneous processes inside the landslide material which accumulate and, at any time, cause deformations that can be measured at the landslide's surface using GPS. However, the accurate and early detection of the slowing-down of the sudden motion would allow the de-warning of the population in the affected area. For this purpose we have developed a new measurement system, i.e. an embedded strain-rosette. The strain-rosette consists of three long gauge fiber optic sensors of the SOFO type. Its basic design, set-up and first test results were described in Woschitz and Brunner (2008). In the present paper we describe functional tests of the embedded strain-rosette at the test site Gradenbach. For the tests two different SOFO reading units were used to measure the local deformations. Long term deformations as well as rapid deformations caused by hammer impacts were investigated and the results are presented here.

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 located at the bottom of the landslide is threatened by this landslide. Its active deformation zone involves the entire slope with a width of 800 m, a length of 1800 m, and an extension in height over approximately 1000 m. The moving mass was estimated with $115 \cdot 10^6$ m^3. The clearly developed main head scarp is situated slightly below the mountain ridge (height 2268 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).

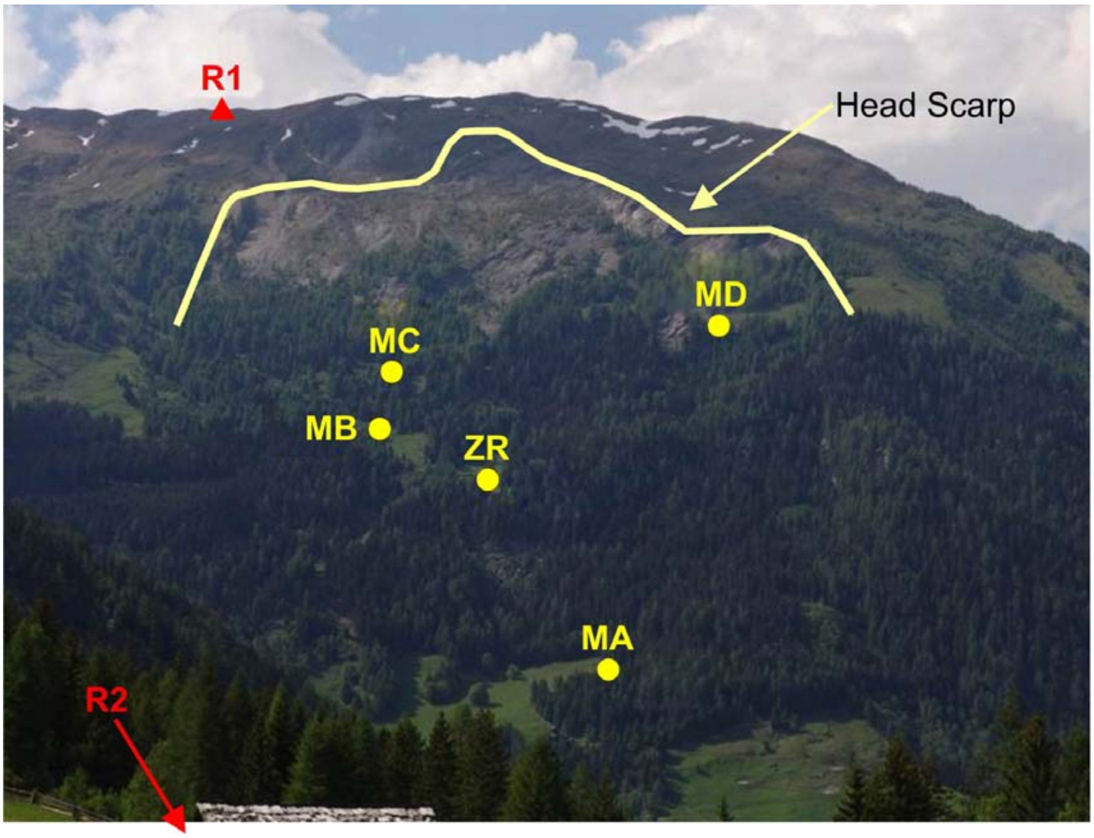

Figure 1: Gradenbach landslide, head scarp, GPS stations R1, MA, MB, MC, MD and ZR.

The current realization of the GPS monitoring system consists of seven GPS stations. Two reference stations (R1 can be seen in Figure 1 and R2 is situated at the opposite slope) were placed in stable bedrock area in order to provide control of the measured deformations. The four monitoring points (MA to MD) are situated in the active part of the slope. The fifth monitoring point (ZR) was established in 2007 and is the centre point of the embedded strain-rosette. For a summary of the latest GPS results of the landslide Gradenbach see Müller et al. (2011).

3 Strain-Rosette

3.1 Design of the Strain-Rosette

The principles of a strain-rosette are well known. Three single sensors are arranged in three directions but in one plane and measure the deformations. Assuming that the captured deformation is linear, then the major and minor principal strains ($\varepsilon_{1,2}$) as well as the orientation (φ) of the major principal strain can be calculated. The equations for the principal strain values depend on the orientation of the three sensors. Often their separation is 60° or 120°, but also rosettes with 45° separation are used. Usually resistance strain gauges are used as the sensing elements. Most strain gauges are rather small with sizes smaller than a few centimeters and they are mounted on a thin film which is fixed to the structure to be monitored. Considering landslide material, longer sensors are required to measure representative strain values of a landslide. Fiber optic extensometers can be manufactured several meters long, and were therefore proposed for landslide monitoring (Brunner et al., 2007).

Figure 2 shows the scheme of the embedded strain-rosette at the experimental site Gradenbach. Long gauge fiber optic sensors of the SOFO type (Inaudi, 1997) were used as extensometers.

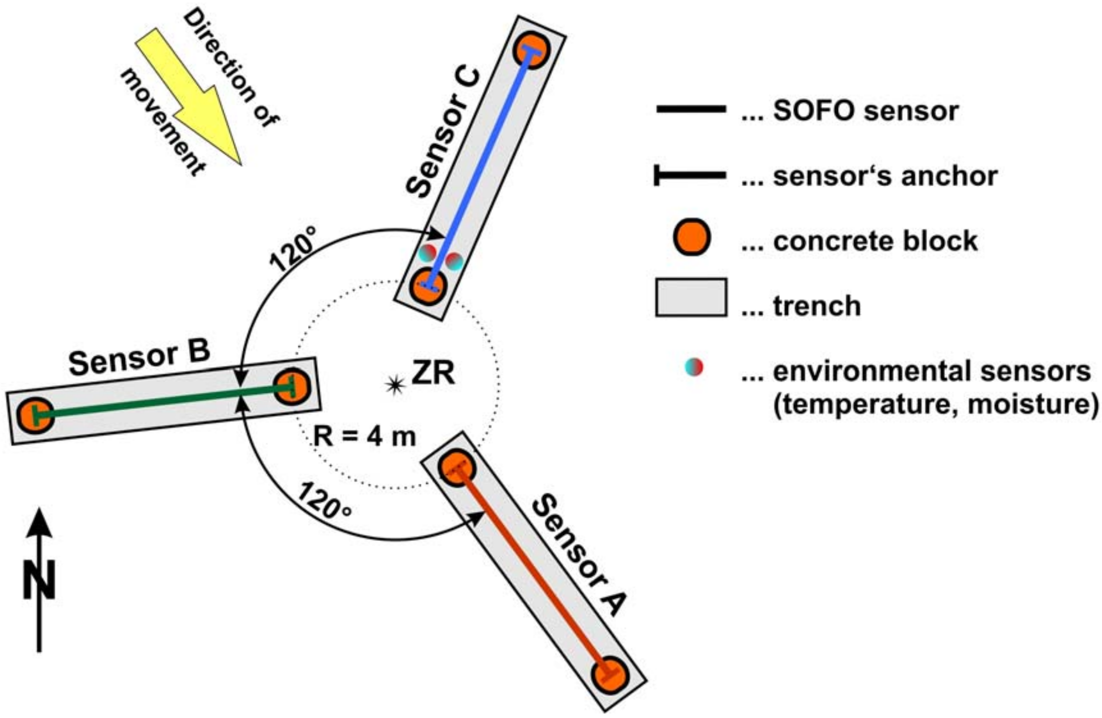

Figure 2: Scheme of the strain-rosette Gradenbach.

The strain-rosette consists of three 5 m long extensometers at a separation of 120° in orientation. Therefore, the parameters of a strain ellipse (ε_1 and ε_2) can be calculated by the formulas (1) and (2) where ε_A, ε_B and ε_C are the measured strain values of the corresponding sensor. The orientation angle φ is related to sensor A and counted counter-clockwise.

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

$$\varepsilon_{1,2} = \frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{3} \pm \sqrt{\frac{(2\varepsilon_A - \varepsilon_C - \varepsilon_B)^2}{9} + \frac{(\varepsilon_C - \varepsilon_B)^2}{3}} \tag{2}$$

3.2 Installation of the Strain-Rosette

When embedding the SOFO sensors the proper connection to the rock material is the main challenge. First experiences with a test strain-rosette were gained in a horizontal soil section. The description of this test strain-rosette and the results of the measurements are shown in Woschitz et al. (2011). For the Gradenbach site the concept of the test installation was modified. A separate trench was dug for each sensor. Separate for each anchor, concrete blocks (approx. 0.3 m in diameter and 0.5 m in height) were poured at the bottom of each trench. The holes for the concrete blocks were dug manually in order to disturb the rock material as little as possible. The concrete blocks were anchored to the rock using 1.5 m long reinforcement bars (see Figure 3a). Each anchor of a sensor is connected to an adapter which is mounted on the concrete block. The adapters are made of stainless-steel and constructed to allow adjusting to the length of the sensors (see Figure 3b). The coupler and mirror zones of each sensor were protected against external effects using metal pipes. The trenches were filled with sand close to the SOFO sensors in order to protect them against damage. A temperature sensor and a soil moisture sensor were placed near the coupler zone of sensor C (see Figure 2). The sensor set-up is completed by an air temperature sensor which is mounted near the embedded strain-rosette at an instrumental cabin.

The strain-rosette was setup in May 2007 between the GPS monitoring points MB and MA (Figure 1), and a new GPS monitoring point (ZR) was established in the centre of the strain-rosette. The orientation of the strain-rosette was chosen in a way that sensor A is parallel to the motion of monitoring point MB. The SOFO sensors were embedded parallel to the surface in a depth of about 2 m which is below the local depth of frost penetration.

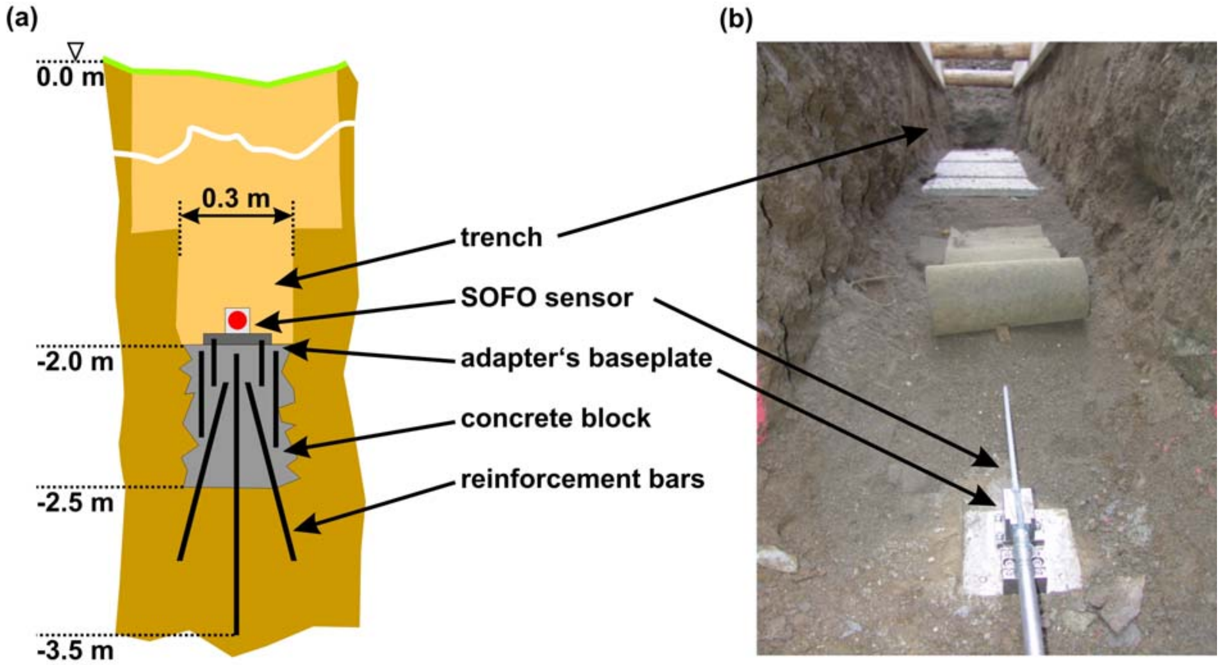

Figure 3: (a) Scheme of SOFO sensor installation and (b) photograph of a trench with a SOFO sensor being embedded.

3.3 Reading Units

A significant advantage of using the SOFO system is that the same embedded sensors can be used for the measurement of static (absolute) or dynamic (relative) length changes. However, two different reading units (RU) are needed, i.e. the SOFO-Static RU and the SOFO-Dynamic RU. The SOFO-Static RU is used for long term measurements and yields a precision of 2 µm, independent of the length of the SOFO sensors (Inaudi, 1997). It is based on low-coherence interferometry and its tandem interferometer design allows the measurement of absolute length changes. A single measurement takes about 6-10 s. It is possible to measure serially up to 20 SOFO sensors with a multiplexer connected to the SOFO-Static RU. The SOFO-Dynamic RU (LLoret and Inaudi, 1999) is designed to measure relative length changes with a precision of 10 nm and a measurement frequency up to 10 kHz (Inaudi et al., 2004). 8 sensors can be measured simultaneously. However, reference is lost if the RU is disconnected from the sensors.

4 Static Measurements

4.1 Selected Results of the Strain-Rosette

Starting from July 2007, continuous measurements with the SOFO-Static RU of one sensor were carried out. All three sensors were measured sporadically; however, the use of a multiplexer allowed measuring all sensors continuously since June 2009. During long term monitoring 12 single measurements of one sensor were started every 6 hours (noise reduction). After this first experience in the field and after the acquisition of the multiplexer every sensor of the strain-rosette and a reference sensor were measured twice every 3 hours. Using this measurement scheme the internal power supply of the RU is sufficient for about 50 days. After that period the battery has to be recharged, as a continuous charging by e.g. a solar panel is not established for the SOFO-Static RU yet. During winter the experimental site cannot be reached and therefore, the collection of measurements is only possible during a few months of the year, generally from June to October.

The measurement values are influenced by small temperature dependences of the SOFO sensor and the RU. Inaudi (2004) notes a temperature dependence of about 0.5 ppm/K. Lienhart (2005) showed that the length of the spindle built in the RU is temperature sensitive (about 10 ppm/K). Figure 4 shows the collected data of the strain-rosette from 2007 until 2010, which were corrected for temperature changes. The sum of the thermal corrections is less than 12 μm for an internal RU temperature difference of about 30°C and a difference of about 7°C of soil temperature.

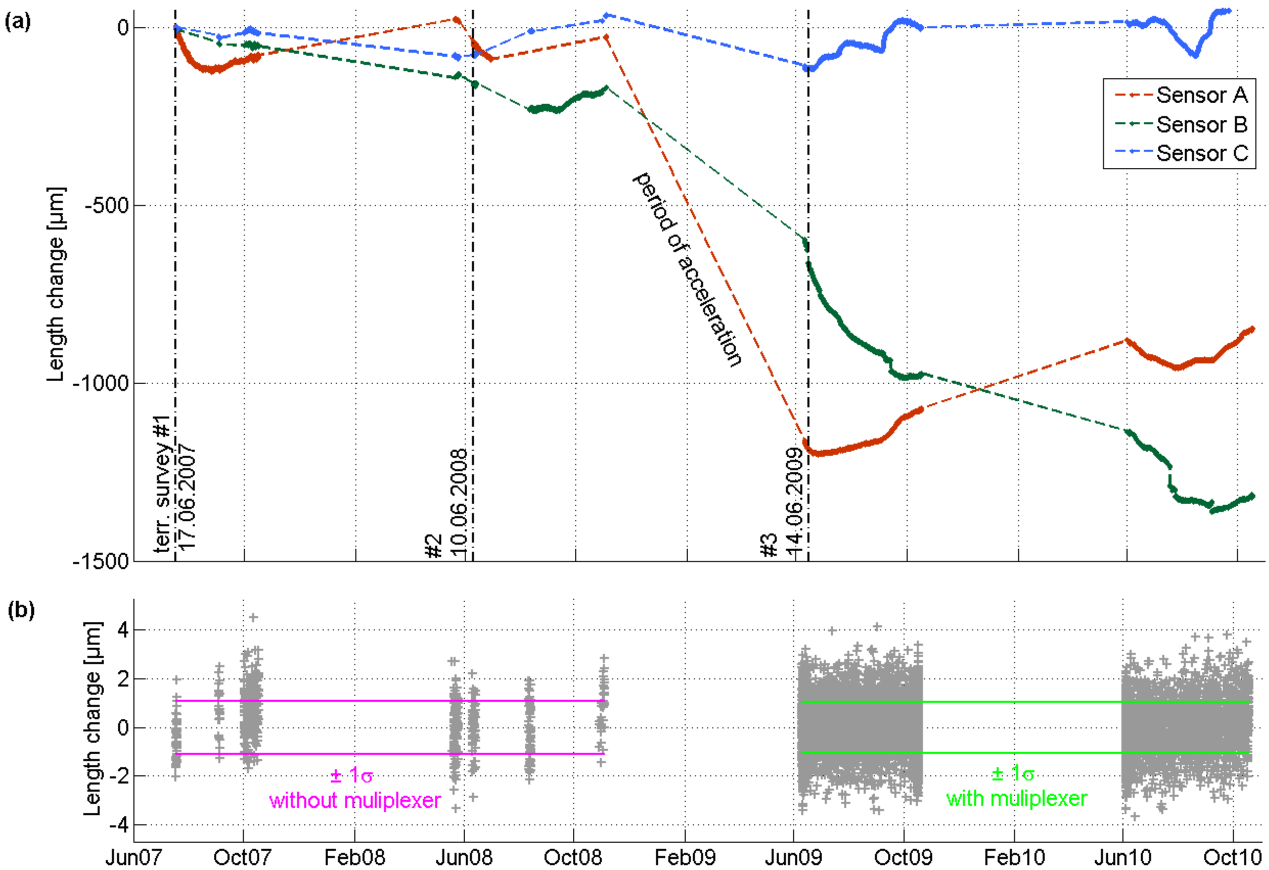

Figure 4: (a) Length change measurements with the three sensors of the strain-rosette and the measurement time of the terrestrial surveys (vertical lines).
(b) Length change measurements of the reference sensor.

Since the embedding of the strain-rosette several measurements were taken with all three sensors. Additionally, sensor A was measured continuously (about 7000 measurements) in 2007 and sensor B (about 6000 measurements) in 2008. Since 2009 each sensor was connected to the multiplexer and measured about 9200 times. Assuming that the movement of the landslide does not change during one day, measurements were averaged and the standard deviation was computed. The SOFO system has a specified standard deviation of 2 μm which has been confirmed by all our measurements, see also Woschitz (2010) for example. It is nearly impossible to check such a precise instrument with an independent method at the rough experimental site. Thus, proper working of the SOFO-Static RU is regularly controlled in the field by measuring a reference sensor with known and constant length, see Figure 4b. These measurements have shown proper functionality of the RU all the time. However, this does not provide control of the signals of the embedded sensors, if for example they are improperly anchored to the rock material. Thus another experiment was carried out, which will be described later.

Strain values are calculated with respect to the reference epoch July 17th, 2007. Simultaneously measured length differences of all three sensors are necessary to compute the parameters of a strain ellipse. Figure 5 exemplarily shows the strain ellipses for the epochs of the surveys of the terrestrial geodetic network.

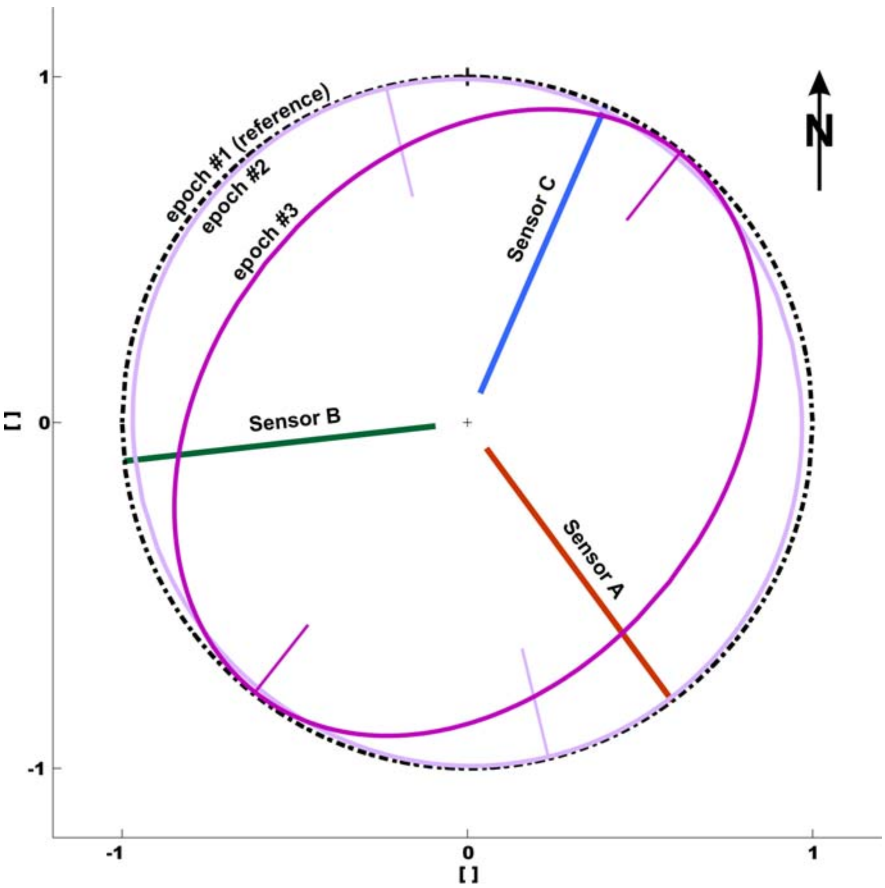

Figure 5: Strain ellipses calculated with data of the strain-rosette; ellipses are inflated (1000 times) and the orientation of their semi-major axes are indicated by short lines (epoch #1: June 2007, epoch #2: July 2008, epoch #3: July 2009)

Error propagation was used to derive the precision of the strain ellipse parameters. The precision depends inversely on the magnitude of the strain, i.e. the larger the strain the better gets the precision of the parameters. Using the strain of the third epoch (ε_1= -261 ppm) the calculated precision (1-σ-level) of the principal strain is about 0.6 ppm and the σ of its direction is about 0.1 gon. The computed orientation of the strain ellipse is related to the direction of the slope's motion which of course was expected.

4.2 Terrestrial Geodetic Network

The control of the embedded SOFO sensors in the field (about 2 m below the surface) is not possible. A geodetic terrestrial network could provide some information requiring, however, two assumptions to be fulfilled: The deformations at the depth of the strain-rosette are identical to those at the slope's surface, and the local deformations of the strain-rosette are homogeneous for the extent of the geodetic network. Even then the geodetic network will be at least ten times less precise than the measurements using the strain-rosette. Nevertheless, a precise geodetic terrestrial network was built up (Woschitz, 2010) surrounding the strain-rosette (dimension: 250 m x 200 m). The network consists of 10 control points (N1 – N8, MB, ZR; see Figure 6) with distances between the points ranging from 30 m to 150 m and a maximum height difference of about 75 m.

In the period shown in Figure 4, the terrestrial network was measured three times (July 2007, June 2008 and June 2009, see vertical lines in Figure 4a). The data of each epoch was adjusted as a free network using the two GPS monitoring points MB and ZR for the datum. The result of each geodetic terrestrial network is, in general, a maximum point error of 0.5 mm in position and 0.6 mm in height for all control points.

The absolute movements of the control points are shown in Figure 6a in respect to the first epoch. Additionally, in Figure 6 contour lines are plotted for a better understanding of the terrain. All control points move almost in the same direction, i.e. the direction of the slope which is about 160 gon. The total movements vary between 0.43 m and 0.54 m. In Figure 6b the relative movements in respect to the centre of the strain-rosette ZR are shown, as we are interested in the local deformations for a later comparison with the strain-rosette values. In this figure the different moving behavior of the control points in the area of the geodetic network can be seen more clearly. The maximum of the relative movements is about 9 cm in the upper area of the network, and consequently the area around the strain-rosette is compressed.

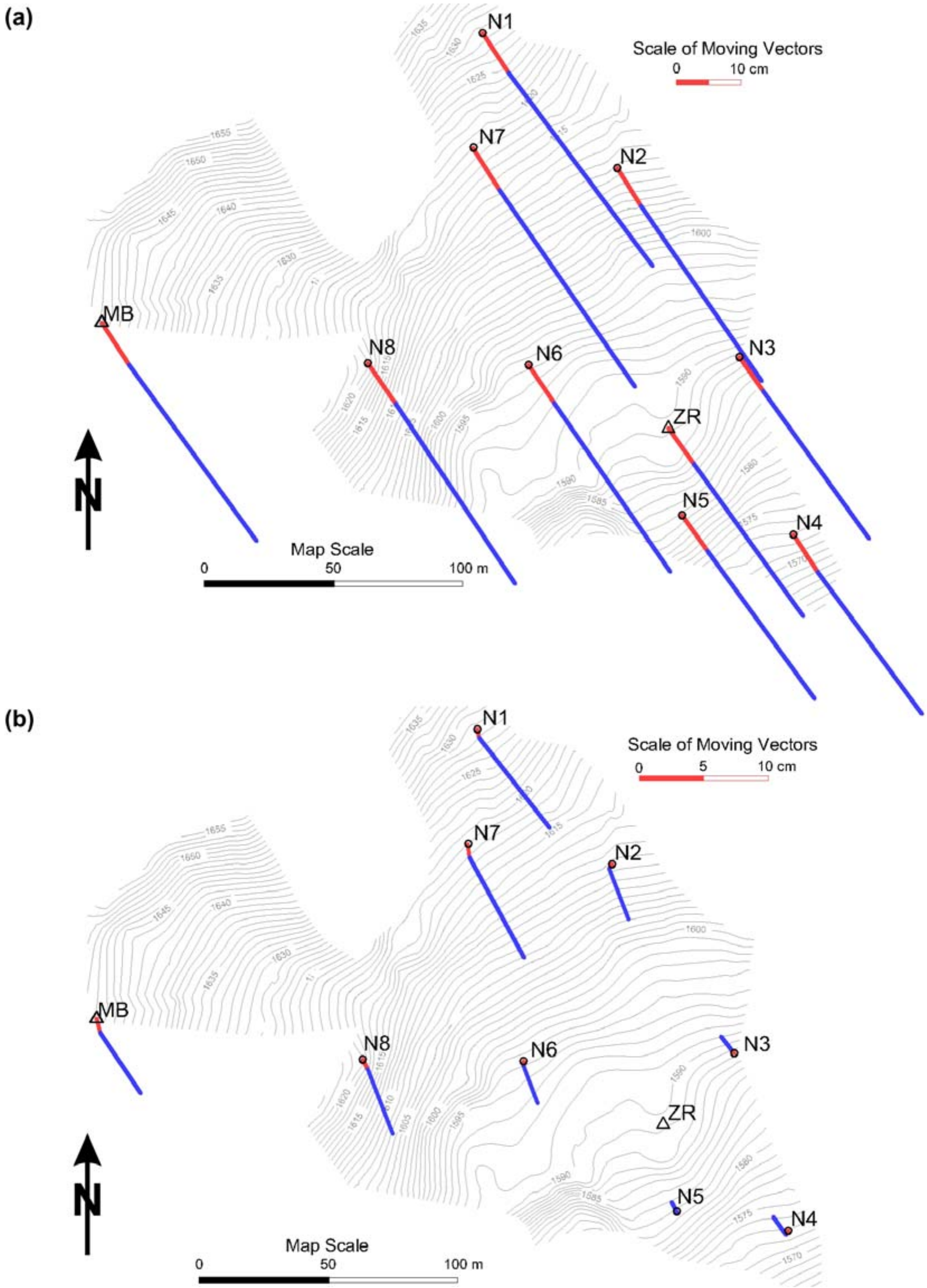

Figure 6: Control points of the precise geodetic terrestrial network with (a) their absolute movements (July 2007 - June 2008: red lines, June 2008 - June 2009: blue lines) and (b) their relative movements in respect to the central point of the strain-rosette (ZR).

For the comparison of the data of the geodetic network and the strain-rosette, the movements determined by the terrestrial measurements were interpolated to the end points of the strain-rosette, see Figure 7.

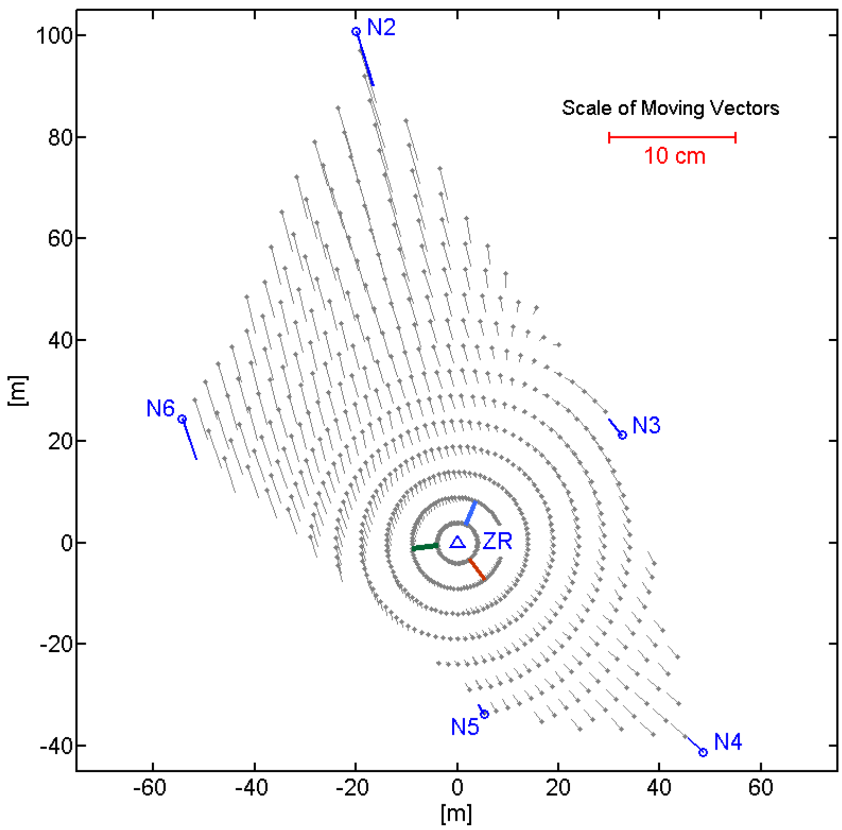

Figure 7: Movements of the control points of the geodetic network (blue) between epochs #1 and #3 (July 2007 - June 2009) and interpolated movements in the surrounding of the strain-rosette (grey).

Using the interpolated movements, the length changes between the end points of the strain-rosette were computed and subsequently the strain values were derived.

4.3 Comparison

In the winter 2008/2009 an acceleration of the landslide movement occurred. The acceleration can be seen clearly in the GPS data (Müller et al., 2011) and the data of the strain-rosette (Figure 4). Thus, the comparison of geodetic network and strain-rosette data is done for this period (epoch #1 - #3).

The strain-rosette data show a shortening of about 1.18 mm for sensor A and a shortening of about 0.66 mm for sensor B, whilst sensor C shows the smallest shortening (0.11 mm). The precision of the SOFO-Static measurement is 2 μm and thus the precision of the derived strain values is 0.6 ppm. Using the interpolated movements of the geodetic network, a shortening of 1.17 mm was derived for sensor A, 0.60 mm for sensor B and 0.32 mm for sensor C. The precision of the principal strain achieved with the terrestrial network is about 6 - 25 ppm and depends on the distance between the control points used. The largest difference is about 0.2 mm (sensor C) between the measurement of the strain-rosette and the interpolated values based on the geodetic network.

For further comparison, the strain ellipses were computed assuming that the deformation in the region of the sensor arms is linear. The resulting parameters are given in Table 1.

Table 1: Parameters of strain ellipses with 1-σ-level (epoch #3)

	ε_1 [ppm]	ε_2 [ppm]	φ [gon]
terrestrial network	-245 $\pm$ 28.2	-40 $\pm$ 32.2	49.3 $\pm$ 6.7
strain-rosette	-261 $\pm$ 0.6	-6 $\pm$ 0.6	42.8 $\pm$ 0.1

The parameters of the strain ellipse fit quite well and the differences are explainable using the standard deviations. Although the geodetic measurements are not as precise as the SOFO measurements and were intended only for a plausibility check, they have shown to be a valuable complement of the GPS and strain-rosette measurements.

5 SOFO-Dynamic Results

Dynamic measurements were planned to study the mechanism of the sequence of accelerations and decelerations of the Gradenbach landslide. For example micro earth-quakes (duration < 1 s) were assumed to be one candidate for trigging the motions and thus should be investigated. These micro earth-quakes are very rare and cannot be predicted yet. We carried out two measurement activities (in 2008 and 2010, each with the duration of 14 days) during which we could not detect an event like a micro earth-quake. However, until now it is not known if these seismic events, which can be detected clearly by e.g. vertically aligned geophones, also generate signals that can be measured with the strain-rosette which is aligned parallel to the slope. It can be assumed that changes in the motion pattern of the landslide are associated with strain waves in the moving mass. We decided to investigate the capability of the strain-rosette to detect strain waves using artificially generated hammer impacts. The same data are used to investigate the proper anchoring of the sensors to the rock material. A first experiment was carried out in June 2008 (Brunner and Woschitz, 2009) and further experiments were done in 2011 which will be described here.

Several hammer impact points were positioned around the strain-rosette with a maximum distance to the sensors of about 50 m. For the impacts a hammer with 5 kg weight was used. At every position 16 single consecutive impacts were performed with a temporal interruption of about 4 s. The sampling interval used for data acquisition was 1 kHz. During the sequence of 16 impacts (duration of about 90 s), the SOFO-Dynamic RU showed drifts up to 35 nm which is rather usual for this instrument. Thus, the data was high-pass filtered before further processing. By averaging the signals of the individual hammer impacts the noise of the entire signal was reduced to about 0.4 nm. Figure 8a shows exemplarily the data of sensor A for a 50 m separation of the hammer impact position. The overlaid signals of 15 single impacts and their mean value are shown. In general, the signal of the first impact at each position was detected as an outlier and thus eliminated. The most likely explanation for the significant deviation of the first signal from the consecutive signals is the compression of the rock material. The differences of each individual signal to the mean signal are plotted in Figure 8b. The maximum differences of all experiments are less than 1.5 nm which is quite close to the noise level of the instrument. The standard deviations are independent of the distance from the hammer impact to the sensor and are less than 0.5 nm for this sensor. Thus, the experiment has shown that the strain-rosette (whole measurement system, i.e. the SOFO sensor and the SOFO-Dynamic RU) is capable to detect very small movements.

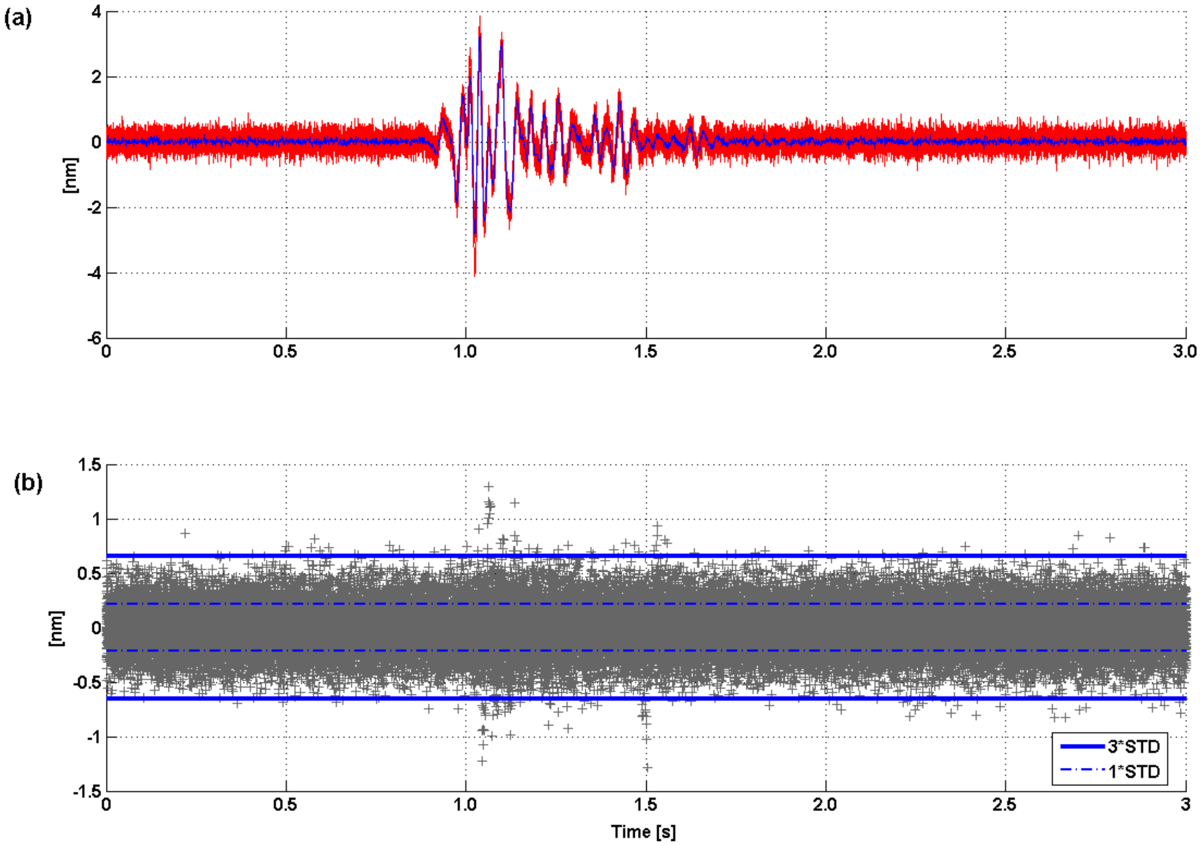

Figure 8: (a) Overlaid signals of 15 hammer impacts (red) 50 m away of ZR measured with sensor A and their mean signal (blue).
(b) Differences of the individual signals to the mean value.

The essential prerequisite of the strain-rosette is the tight connection of its anchors to the rock material which is difficult to investigate. However, if at least one of the anchors would have a loose connection, then offsets between the signals of consecutive hammer impacts might occur. These offsets might be caused by another resting position of the anchor compared to the one before the arrival of the strain wave. Investigation of the data has shown no offsets and the same response time for each of the anchors and thus it can be concluded that the anchors are connected properly to the rock material.

At several impact positions a second sequence of 16 impacts was made to investigate the reproducibility of the signals. Figure 9a shows the mean signal of two independent sequences for the 50 m distance with a time difference of 25 min in between. As the positions of the hammer impacts were different for some centimeters, the maximum amplitudes of the two signals were slightly different (about 0.3 nm). Thus, for comparison, the second signal was scaled to match the maximum amplitude of the first signal. Synchronization of the two time series was achieved using the cross-correlation function. The difference between the two sequences is shown in Figure 9b which highlights the excellent reproducibility of the signals. Thus we conclude that the sensors are still tightly connected to the rock material of the landslide mass, even 4 years after their installation and after the large movements of the landslide that occurred in this period.

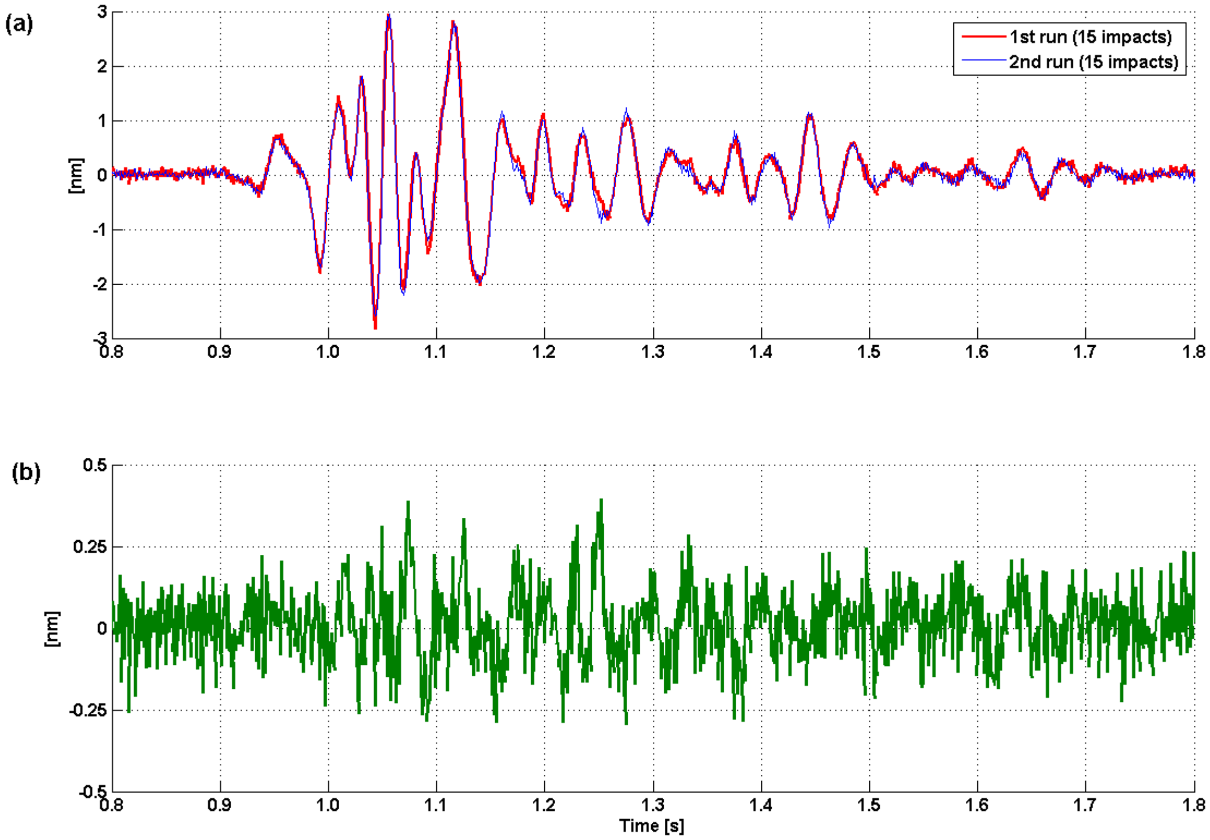

Figure 9: Signals of the repeated experiment at a distance of 50 m. (a) Mean value of two sequences. (b) Differences between the two sequences.

6 Conclusion

For a better understanding of the prediction of landslide motions we have developed a large embedded strain-rosette based on long gauge fiber optic sensors. The embedded sensors are of the SOFO type which can be used for long-term measurements (SOFO-Static, absolute measurements with a precision of 2 μm) and for the investigation of dynamic processes (SOFO-Dynamic, relative measurements with a precision of 1 nm at 1 kHz). To our knowledge, this is the first time that this fiber optic sensor type was embedded into a landslide. The Gradenbach landslide is used as the test site (Brückl et al., 2006). A critical issue is the anchoring of the sensors to the rock material. Therefore, hammer impacts were carried out at positions that are in line of the sensors and at several distances to the sensor. It was shown that a sequence of about 15 impacts is very precise and a very high reproducibility of the sequences could be shown. The tests and results have shown that the anchors of the strain-rosette are tightly connected to the rock material.

Since 2007 continuous measurements were carried out during the summer time. For a period of acceleration of the landslides motion a maximum strain of about 260 ppm was measured.

It is nearly impossible to evaluate the strain-rosette's performance, thus for verification of the local deformations a precision terrestrial geodetic network was set-up. This network was measured so far 3 times (July 2007, June 2008 and June 2009). The strain ellipses derived from the network are in good agreement, i.e. within one standard deviation of the terrestrial results, with the one derived from the strain-rosette data.

The embedded strain-rosette can be used to measure the principal strain values in a static as well as in a dynamic set-up. We plan to continue investigating the Gradenbach landslide using the fiber optic strain-rosette.

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References

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

Brückl E, Brunner FK, Lang E, Mertl S, Müller M, Stary U (2011) The Gradenbach Observatory - monitoring un-stationary deep-seated gravitational creep by geodetic, hydrological and seismological methods. Poster Presentation at EGU, General Assembly, Vienna, Austria, 03-08 April 2011. Geophysical Research Abstracts Vol. 13, EGU2011-3412, 2011 (online: http://info.tuwien.ac.at/geophysik/bibliography/EGU2011-3412.pdf)

Brunner FK, Woschitz H (2009) Langarmige eingebettete Strain-Rosette zum Monitoring eines Rutschhanges. Mitt. Gruppe Geotechnik TU Graz, 35: 263-278

Brunner FK, Woschitz H, Macheiner K (2007) Monitoring of Deep-Seated Mass Movement. CD-Proc. 3rd Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3), Nov: 13-16, 2007, Vancouver; 10 p.

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

Inaudi D (1997) Fiber optic sensor network for the monitoring of civil engineering structures. PhD Thesis, EPFL Lausanne, Switzerland, 262 p.

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, June, 9-11 2004, 4 p.

Inaudi D, Glišić B, Posenato D (2004) High-speed demodulation of long-gauge fibre optic strain sensors for dynamic structural monitoring. Proc. 2nd European Workshop Structural health monitoring 2004, Munich, July 7-9, 2004, Lancaster, Pa.: DEStech Publ.: 8 p.

Lienhart W (2005) Experimental Investigation of the Performance of the SOFO Measurement System. In Fu-Kuo Chang (ed.) *Structural health monitoring 2005*, Proc. 5th Int. Workshop on Structural Health Monitoring. Stanford, USA, DEStech Publ.: 1131–1138

LLoret S, Inaudi D (1999) Amplitude modulation of a low-coherence source, applications to distance and dynamic displacement sensing. Optics and Lasers in Engeneering, 32(4): 325–337

Müller M, Brunner FK, Lang E (2011) Long term measurement and analysis of a deep mass movement. CD-Proc. 8th Int. Symp. on Field Measurements in GeoMechanics, Sept.12-16, 2011, Berlin, 18 p.

Woschitz H (2010) Entwicklung einer langarmigen faseroptischen Strain-Rosette zum Monitoring eines Rutschhanges. Österr. Z. f. Vermessung und Geoinformation 98: 29-39

Woschitz H, Brunner FK (2008) Monitoring a deep-seated mass movement using a large strain rosette. CD-Proc. 13th Int. Symp. on Deformation Measurements and Analysis, May 12 15, 2008, Lisbon, Portugal, 10 p.

Woschitz H, Macheiner K, Brunner FK (2011) In-situ Strainmessungen mit langarmigen faseroptischen Sensoren. Allg. Vermessungs-Nachrichten 118: 242-251

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