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Case studies of high-sensitivity monitoring of natural and engineered slopes

Werner Lienhart*

Graz University of Technology, Graz, Austria

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ABSTRACT

High-sensitivity monitoring solutions are crucial for early warning systems of earth structures. In this paper, we discuss the design and implementation of such systems for natural and engineered slopes using two case studies. At the Gradenbach Observatory, one key element of the monitoring system is a large fiber optic strain rosette embedded in the slope. We demonstrate that the strain rosette can depict landslide deformations much earlier than geodetic sensors like GPS or total stations and is therefore well suitable for an early warning system. In a second application we report the construction of a reinforced earth structure using geogrids. A distributed fiber optic measurement system was installed to measure the current operating grade of the geogrids within the earth structure. About 2 km of Brillouin sensing cables were installed in the project area. It is demonstrated that the developed monitoring system is well suited for assessing the current state of health of reinforced earth structures.

1. Introduction

Alpine countries like Austria are especially vulnerable to natural phenomena like landslides which can cause severe damages (Fig. 1). Today, the understanding of the sequence of accelerations and decelerations of natural slope movements is limited and reliable prediction models do not exist. Therefore, high-sensitivity early warning systems are required which detect changes in the deformation behavior at an early stage. Sufficient warning time allows counter actions or at least can reduce the number of lost human lives.

Another challenge in alpine areas is the construction of roads or railway tracks in steep terrain. Today, reinforced earth structures are more and more used instead of conventional retaining walls. However, failures of such structures are known (Fig. 2). One key element of an early warning system for reinforced earth structures is the high-sensitivity monitoring of the internal strain distribution of the embedded geogrids.

In this paper, we report the development and implementation of monitoring systems for both applications using internal fiber optic measurements.

* Tel.: +43 3168736321.
E-mail address: werner.lienhart@tugraz.at.

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2. High-sensitivity landslide monitoring

2.1. The Gradenbach Observatory

The Gradenbach landslide (Fig. 3) is a deep-seated mass movement in the south of Austria. Its active deformation zone covers an area of approximately 800 m × 1800 m. The main scarp is located slightly below the mountain ridge with a height of 2268 m above sea level. The Gradenbach landslide has been monitored using epoch-wise measurements for more than 50 years. The landslide is constantly moving with a typical velocity of about 12 cm/year. The steady movement is interrupted by sudden acceleration and deceleration phases (Brückl et al., 2006).

Since 1999, monitoring activities increased within the IDNDR (International Decade for Natural Disaster Reduction) and ISDR (International Strategy for Disaster Reduction) research programs of the Austrian Academy of Sciences (OeAW). As a result, the Gradenbach Observatory was installed (Brückl et al., 2013).

This observatory consists of a geodetic component, a hydrometrological component (precipitation, temperature, snow cover) and a seismic component. An overview of all sensors installed at the Gradenbach Observatory is given in Fig. 4. The Institute of Engineering Geodesy and Measurement Systems (IGMS) of Graz University of Technology is responsible for the GPS measurements, the terrestrial surveys and the local strain measurements. The measurements are carried out epoch-wise or continuously and the results are accessible on the homepage of the Gradenbach Observatory (http://gbonline.tugraz.at).

Fig. 1. Damages in the village Doellach in Austria as a consequence of the Gradenbach landslide.

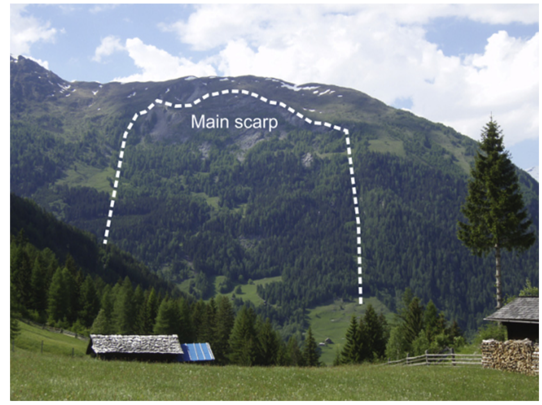

Fig. 3. Deep-seated mass movement in Gradenbach landslide.

2.2. Fiber optic strain rosette

2.2.1. Development and installation

Absolute displacements of the landslide can be determined with the continuous GPS monitoring system and the implemented height correction models with an accuracy of less than 1 cm (Gassner et al., 2002). This accuracy is well suited to determining the long-term behavior. For the determination of local deformations, measurement systems with higher precisions and higher resolutions are required. Fiber optic sensors fulfill these requirements and are robust enough to be embedded in landslides. One successful application of fiber optic measurements for the determination of the location of the boundary between stable and sliding areas of a landslide in Switzerland was reported in Iten et al. (2009). In case of the Gradenbach Observatory, the focus was placed on the early detection of an acceleration of the landslide. Therefore, a large fiber optic strain (LFOS) rosette was embedded in the central landslide area to detect local compression and decompression.

The LFOS rosette is composed of three SOFO sensors with a length of 5 m. Alternatively fiber Bragg grating (FBG) sensors can also be used. The SOFO sensors are based on an interferometric measurement principle. Each SOFO sensor consists of a stretched fiber and a loose fiber. A length change between the two anchor points of the sensor only affects the strained fiber. On the contrary, a temperature change has an influence on both fibers. Since the measurement result is the length difference of both fibers, the temperature influence is eliminated. In our application, the sensors were separated to each other by an angle of about 120° to form a rosette in analogy to strain rosettes used in classic mechanical stress analysis (Fig. 5).

Fig. 2. Failure of reinforced earth structure at the road B320, Austria (Liezen Online, 2011).

The sensors were installed in 2007, parallel to the surface below the frost penetration depth at a depth of about 2 m (Fig. 6). One sensor (sensor A) was oriented in the direction of movement of the landslide. More details about the development of the fiber optic strain rosette can be found in Wöllner et al. (2011) and Woschitz and Brunner (2008).

2.2.2. Results

Long-term strain measurements with the static SOFO reading unit can be performed with a precision of 2 μm according to the specifications of the manufacturer (Inaudi, 2004). This was also confirmed by our own investigations (Lienhart, 2005). This corresponds to a precision of strain measurements of 0.4 μm/m taking into account the length of the sensors (5 m). The principal strain values ε_1 and ε_2 as well as their orientation φ can be derived from the strain measurements ε_A, ε_B and ε_C of the individual sensor using the following equations:

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

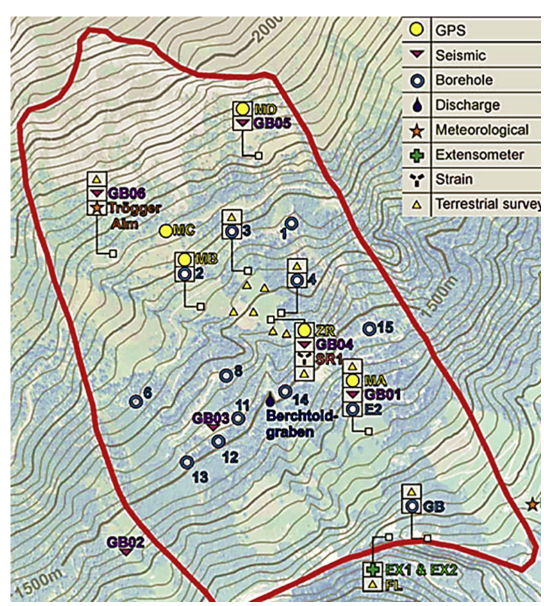

Fig. 4. Monitoring installations of the Gradenbach Observatory.