

High Resolution Monitoring of Retaining Walls using Sensors

Shaikh Mohd Salem¹, Sayyed Nadeem², Shaikh Mohd Ilyas³, Shaikh Adil⁴, Payal Agrawal⁵
^{1,2,3,4}UG Student Department of Civil Engineering, Rizvi College of Engineering, Mumbai, India
⁵M.E (Structures), Assistant Professor, Rizvi College of Engineering, Mumbai, India

Abstract - Retaining walls are important structures to stabilize slopes in the vicinity of infrastructure objects like buildings, highways, and tunnel portals. In Austria, conventional monitoring of these walls is based on visual inspection and on deformation measurements of a few distinctive points on or within the structure. However, these approaches leave large areas of retaining walls unobserved and thus relevant structural deficiencies may be missed.

We present a new approach consisting of remote surface-based measurements with mobile mapping systems and internal deformation measurements with high resolution distributed fibre optic sensors.

For the remote sensing, a measurement platform consisting of two laser scanners, an inertial measurement unit (IMU), a differential GNSS sensor and several cameras was used. Whilst a standard car with the attached multi sensor system platform travels with up to 100 km/h along the highway, data is continuously recorded with high frequency. As a result, georeferenced high resolution point clouds of all retaining walls along the highway can be obtained. We further analyse the point clouds to derive safety relevant parameters like tilt changes of the retaining walls.

Large retaining walls are often stabilized by fully or partly grouted anchors. We demonstrate that the utilization grade of these anchors can be measured reliably with distributed fibre optic sensors (DFOS). From the DFOS measurements, the longitudinal strain and also bending properties of anchors can be depicted.

Index Terms - Retaining walls, Fibre optic sensors, Mobile mapping systems, Laser scanning.

1.INTRODUCTION

Retaining walls stabilize slopes in the vicinity of infrastructure objects like buildings, highways and tunnel portals. Failure of these structures can lead to death of highway users and the repair works can cause massive delays due to closures of highway lanes. In a recent incident a truck driver was killed on the

Austrian Highway Brennerautobahn (A13) because of a collapse of a retaining wall [1]. Consequently, retaining walls have to be monitored during their construction and their lifetime to assess construction quality, to assure the safety of people and to enable condition-based maintenance.

Conventional monitoring approaches are based on deformation measurements of a few distinctive points on the surface of the structure and within the structure. Typically used sensors are total stations (TS) measuring angles (Hz, V) and distances (D) to reflective targets (P), tilt sensors (T), borehole inclinometers, extensometers or electric strain gauges (ESG), see Figure 1.

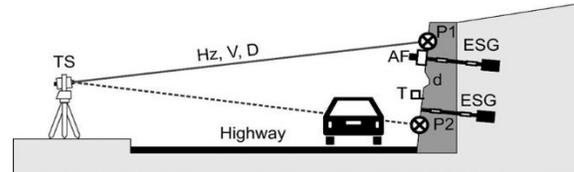


Figure 1. Conventional monitoring setup of an anchored retaining wall

Figure 2 shows a retaining wall within the Austrian highway network. Reflective targets (P1 to P4) are measured in regular intervals with a total station. Two targets are always placed in the same vertical profile in order to derive tilt changes from the 3D positions of the targets.

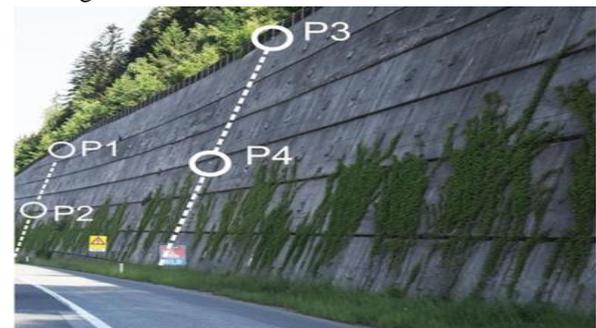


Figure 2. Prism positions for the geodetic monitoring of a retaining wall

Despite the immense effort of such a measurement installation, large areas of a structure remain unobserved and local damages cannot be detected. Moreover, in many cases, it is financially not feasible to monitor all existing objects, e.g., several thousand retaining walls, with such a measurement program.

2. NEW MONITORING APPROACHES

In order to obtain a complete picture of the deformation behaviour of a single structure and to observe all structures within a network, more efficient monitoring methods are needed. As will be shown in the following, mobile laser scanning is a valuable tool to analyse the surface behaviour of a structure in detail and distributed fibre optic sensors are well suited to assess the state of the internal supporting elements.

2.1 Laser Scanning with a Mobile Mapping System

Modern laser scanners are able to measure some million points per second. Conventionally, laser scanners are mounted on a static platform like a tripod or pillar. However, laser scanners can also be placed on mobile platforms like planes, drones, cars or trains. Sometimes data from static and mobile laser scanning are combined to deliver one large model. An example for this is given in [2], where airborne laser scanning (ALS) is used to measure the surface of the terrain and static terrestrial laser scanning (TLS) is used to measure underground. In order to monitor retaining walls along roads and railway tracks more efficiently, we investigated the use of a mobile mapping system (MMS), see Figure 3.



Figure 3. Mobile mapping system mounted on a car. The used MMS consists of a geodetic GNSS antenna with a receiver, an inertial measurement unit (IMU), two laser scanners, six cameras and an odometer. The entire measurement platform is mounted on a standard car. The position of the platform is calculated using differential GNSS and supported by the IMU and odometer data. The orientation is mainly determined with the IMU. The two laser scanners work in profile

mode and measure 1 million points per second each. Due to the high data acquisition rate, high resolution point clouds are obtained even at high driving speeds. Finally, the camera images are used to colour the point cloud and support the classification of the detected damages.

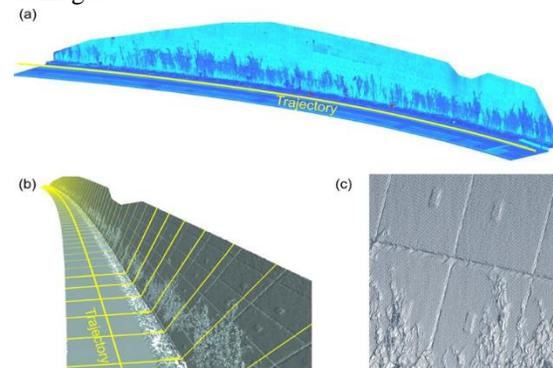


Figure 4. Point cloud (a) and TIN model (b) of the highway surface and retaining wall. The car trajectory and vertical profiles every 5 m are indicated as yellow lines. Detailed profiles (c) every 5 cm along the trajectory are used for further processing.

In the analysis [3], the point cloud (Figure 4a) is first converted into a surface model (Figure 4b), for instance into a triangulated irregular network (TIN). Next profiles orthogonal to the trajectory of the car are automatically generated every 5 cm (Figure 4c). The individual profiles are evaluated automatically using robust estimation methods to calculate the tilt, derived from a fitted robust regression line, of the retaining wall. In order to check the precision of the process, data of different walls were recorded multiple times at different driving speeds (60 km/h, 80 km/h, 100 km/h). A statistical analysis showed that the inclinations, depending on the type of retaining wall, can be determined with a standard deviation between $\pm 0.007^\circ$ (gravity wall with smooth concrete surface) and $\pm 0.074^\circ$ (dissolved anchored wall) [4].

By the robust tilt determination outliers are identified which may have multiple reasons. Outliers are categorized as significant deviations from the fitted regression line. Deviations are for instance caused by measurement errors but also by vegetation on the surface, construction elements on the wall or pop outs. An intelligent analysis of these outliers aims to identify and classify the outliers. We automatically group the outliers of different profiles and classify them. The recorded camera images are an essential data source for a reliable classification.

Figure 5-left depicts a typical result of the analysis of the mobile mapping data of a 40-year-old wall. Displayed are grouped and classified outliers. Group (a) belongs to vegetation, group (b) are the horizontal joints of the wall and group (c) are the concrete protections of the anchor heads. Remarkable is group (d) which is a potential deficiency of the wall. In order to verify this assumption, the recorded images are used. Figure 5-right shows that the outlier group (d) is in fact a pop out where concrete has fallen off the wall. Even the steel grid of the reinforced concrete is visible in the images. It has to be noted that this retaining wall is already monitored with conventional geodetic methods. Although the prism positions P1 and P2 may be measured with high accuracy, the damaged area in between the prisms remains undetected but can be found reliably using the mobile mapping data.

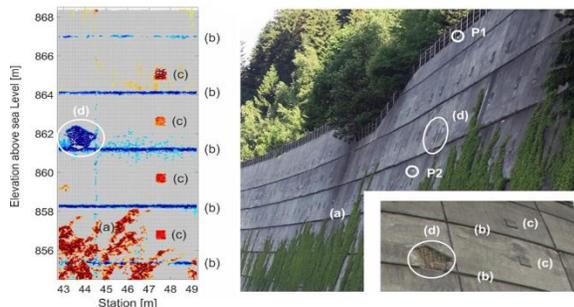


Figure 5. Automatically detected significant deviations from the linear regression lines (left), images of the retaining wall with prism positions P1 and P2 and local damage d (right)

2.2 Distributed Fibre Optic Sensing

Similar to surface-based measurements, internal measurements shall deliver reliable information and should be able to detect local damages like cracks. However, conventional electric sensors usually have limitations because either there is a gap between individual sensing elements where damages are not transferred to the sensors, or the connected sensors have such a long gauge length (e.g. in case of rod extensometers) that a local effect is averaged over a large distance and not clearly visible anymore.

Distributed fibre optic sensors (DFOS) overcome these drawbacks as the fibre itself acts as the sensor and therefore, measurements along the entire sensing cable are feasible. A good overview of the current status of various types of DFOS systems for applications in civil engineering is given in [5]. DFOS are already used for a long time to detect leakages of

pipelines or water dams. Leakages cause local temperature anomalies, which can be detected for instance by Raman backscattering. Strain monitoring over long distances is usually performed using Brillouin scattering techniques [6].

Here, we focus on high resolution distributed fibre optic sensing based on Rayleigh backscattering, which enables measurements over short distances of e.g., 70 m with a measurement precision of some $\mu\text{m/m}$ and a spatial resolution of about 10 millimeter. Therefore, up to 7000 measurement points can be realized along one single sensing cable. Comparable measurements with conventional, geotechnical sensors (e.g., electric strain gauges) are not practical due to their high installation effort as well as cabling issues. Nevertheless, it has to be considered that many manufactures of fibre optic sensors do not specify individual calibration parameters and refer to literature values instead, which might result in errors up to 10 % or more. For that reason, an individual calibration of the fibre optic system is essential to avoid systematic errors and to achieve the specified measurement precision within the harsh field environment. For details about sensor calibration and testing, see [7] or [8].

Within the last years, we developed reliable methods to monitor geotechnical structural elements like piles and anchors during load tests and in the long term [7], [9], [10], [11]. One of the retaining walls (Figure 7- left) was recently (July 2018) equipped with a fibre optic instrumented anchor.



Figure 7. Slope stabilization using ground anchors for retaining walls at highway (left) and at a refinery (right)

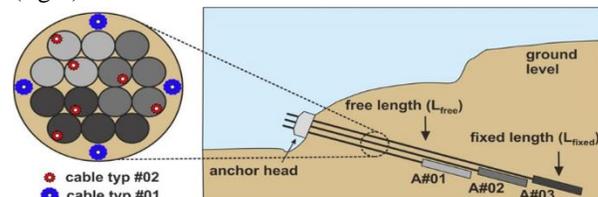


Figure 8. Schematic representation of single borehole multiple anchors with two sensing fibres along the

tendons of each individual anchor and two fibre loops in the grout material

Measurements of this anchor are currently ongoing, and the data analysis is in progress. We therefore report in this article about pull-out tests of single borehole multiple strand anchors (SBMA), which were installed in 2016 for the slope stabilization of a refinery (Figure 7-right). To assess the behaviour of the anchors under load, we installed two sensing fibres along the tendons of each individual anchor and two fibre loops in the grout material, as shown in Figure 8. Due to this redundant arrangement, measurements would have been feasible, even if one fibre had broken.

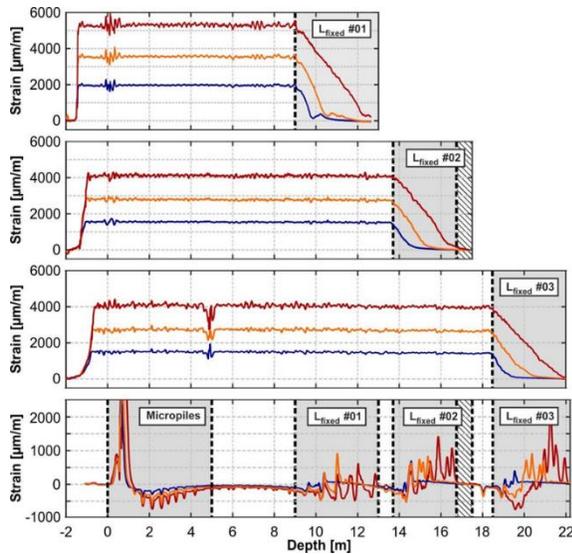


Figure 9. Measured strain profiles at load steps of 900, 1500 and 2100 kN along the anchor tendons of the short (#01), middle (#02) and long (#03) SBMA anchor and the grout material

During the load tests continuous fibre optic measurements were performed whilst the load was stepwise increased. As an example, the strain profiles along the anchor tendons and the grout material at three load steps 900 kN, 1500 kN and 2100 kN are displayed in Figure 9. The tendons show an almost uniform strain distribution along the free length of the anchor. Afterwards, the applied load is transferred from the anchor to the soil in the fixed length (L_{fixed}) and therefore, the strain values decrease with increasing depth. Thereby, the area of the fixed length that is utilized for the load transfer increases with higher loads, which demonstrates a progressive failure of the tendon/grout interface. This behaviour can also be depicted in the grout material along the fixed length

of each individual anchor, in which cracks (represented by local strain peaks) become visible. As it can also be seen, the last 0.5 m of the fixed length of the middle anchor (hatched area in Figure 9) is not influenced at the maximum testing load of 2100 kN. This might be an indicator that the final bearing capacity of this individual anchor is not achieved and thus the entire anchor works well at its designed lower operating load. More information on the installation and data evaluation of these tests can be found in [7].

In a different layout, slopes and construction pits are stabilized using fully grouted steel anchors combined with shotcrete layers at the surface. Contrary to the above-mentioned strand anchors, these so-called “soil nailing systems” do not have a free separated anchor length. In order to assess the bending behaviour of such an anchoring system, we glue a fibre optic strain sensing cable in grooves on the top and bottom of the steel nails (Figure 10-right). The feasibility of this approach was verified in laboratory investigations, where controlled bending was applied to instrumented nails. The true deformed shape of the nails was determined with laser and image-based methods and compared to the derived shape from the fibre optic measurements, see [10] and [11].

Three instrumented soil nails were also placed into a slope of a road construction site. For temperature compensation an additional temperature sensing cable was also installed along every nail. Continuous monitoring over several weeks started right after construction. Additionally, a pull-out test of one of the nails (nail #03) was performed after the monitoring campaign. Detailed information and results of the continuous monitoring as well as the pull-out test can be found in [10].

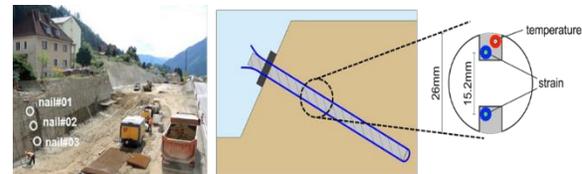


Figure 10. Fibre optic equipped soil nails at a construction site with three sensing nails (left) and their cable layout (right)

As already mentioned, strain changes were measured along the top and bottom of each nail. Knowing the lateral distance between the top and bottom fibre, curvature changes can be derived from the strain differences. Assuming that the position of the nail end does not change, the shape change can be derived by

double integration. Figure 11 shows the strain values of the top and bottom fibre of nail #1 and the calculated vertical displacements.

The bending of the nail resulted in a vertical displacement of about 7 mm at the front end of the nail within the observation period of more than one month. The construction sequence of the wall is supposed to be the reason of this bending. Nail #1 was installed when the level of the road lane was much higher. Following, the soil was removed until it reached the level shown in Figure 10-left.

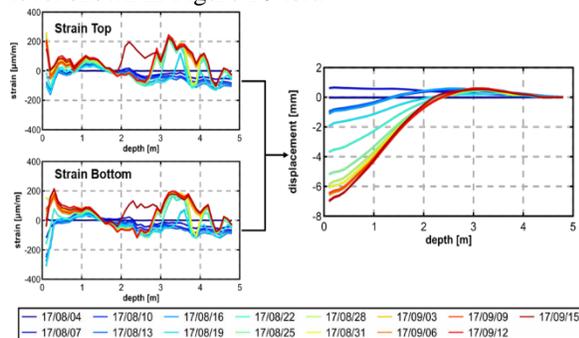


Figure 11. Strain profiles along the top and bottom of nail #1 and derived displacement curve

3.CONCLUSION

In this paper, we presented new, more efficient approaches to detect changes of the surface of large structures and to assess the internal behaviour of structural elements using laser scan, image, and distributed fibre optic data. The individual measurement points of the presented surface measurement methods may not have the same precision as conventional single-point measurements to prisms but have the big advantage that the entire structure is monitored, and local damages can also be detected. We showed that point clouds from a moveable laser scanner can be used to automatically derive relevant deformation parameters like tilt changes or to detect structural degradation effects like pop outs. In order to assess the structural behaviour internally, distributed fibre optic measurement methods are particularly promising because thousands of measurement points can be realized with a single cable and measurements with high accuracy are possible. We demonstrated that the internal deformations and the utilization grade of anchors of slope stabilizations can be reliably measured with distributed fibre optic sensors. If a new retaining wall

is being built, DFOS sensors could also be embedded along the wall.

All different monitoring methods together deliver a more complete picture of the deformation behaviour of a large structure and thus, a modern monitoring setup of retaining walls can look like depicted in Figure 12.

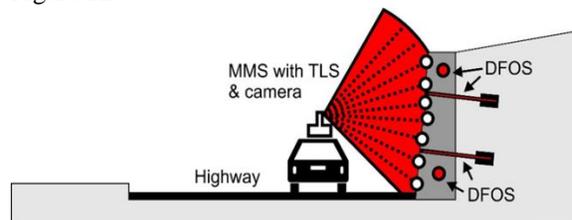


Figure 12. Example of a modern monitoring setup of an anchored retaining wall

Acknowledgement

We want to thank our project partners Keller Grundbau GmbH, Asian Institute of Technology AIT, Thailand, for giving us theoretical knowledge behind the Performance based design. We would also like to thank professor Payal Agrawal, (M.E Structures), for their encouragement to carry out this research work as a part of B.E project.

REFERENCES

- [1] Die Presse, “Brennerautobahn: Laster unter Betonmauer begraben”, newspaper article, 20.03.2012.
- [2] W Lienhart, “Geotechnical monitoring using total stations and laser scanners: critical aspects and solutions”, *Journal of Civil Structural Health Monitoring* 7(3), pp 315-324, 2017.
- [3] W Lienhart, S Kalenjuk, “Combined Laser Scanning and Image Based Monitoring of Large Infrastructure Objects”, *Proc. Int. Workshop on Structural Health Monitoring (IWSHM)*, Stanford, USA, pp 3147-3154, 2017.
- [4] W Lienhart, S Kalenjuk, C Ehrhart, “Efficient and Large-Scale Monitoring of Retaining Walls along Highways using a Mobile Mapping System”, *Proc. 8th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure – SHMII-8*, Brisbane, Australia, RS3-11, 8 p, 2017.

- [5] L Schenato, “A Review of Distributed Fibre Optic Sensors for Geo-Hydrological Applications”, *Appl. Sci.* 2017, 7, 896, 42 p, 2017.
- [6] W Lienhart, F Moser, H Schuller, T Schachinger, “Reinforced Earth Structures at Semmering Base Tunnel - Construction and Monitoring using Fiber Optic Strain Measurements”, *Proc. 10th Int. Conf. on Geosynthetics (ICG)*, 2014.
- [7] C Monsberger, H Woschitz, W Lienhart, V Racansky, M Hayden, “Performance assessment of geotechnical structural elements using distributed fiber optic sensing”, *Proc. SPIE 10168: Sensors and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems*, 2017.
- [8] H Woschitz, F Klug, W Lienhart W, “Design and calibration of a fiber-optic monitoring system for the determination of segment joint movements inside a hydro power dam”, *Journal of Lightwave Technology* 33(12), pp 2652-2657, 2016.
- [9] C Monsberger, H Woschitz, M Hayden, “Deformation measurement of a driven pile using distributed fibre-optic sensing”, *Journal of Applied Geodesy* 10(1), pp 61-69, 2016.
- [10] C Monsberger, W Lienhart, S Hirschmüller, R Marte, “Monitoring of soil nailed slope stabilizations using distributed fiber optic sensing”, *Proc. SPIE 10598, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2018*, 1059835, 2018.
- [11] C Monsberger, W Lienhart, P Caporossi, “Distributed Fiber Optic Sensing along Grouted Anchors to Assess Curvature and Bending Characteristics”, accepted for publication in *Proc. 26th International Conference on Optical Fibre Sensors (OFS)*, 2018.