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FIBRE OPTIC SENSORS FOR LONG-TERM SHM IN CIVIL ENGINEERING APPLICATIONS

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Abstract

This paper shows different fibre optic sensors used for such monitoring tasks in civil and soil engineering for which other methods do not have capability. One example is the monitoring of anchors in difficult soil areas by using FBG sensor arrays. Another example presents fibre optic acoustic emission (AE) sensors embedded in concrete piles. They enable precise assessment of the pile's integrity and bearing capacity especially for dynamic loading. The potential of a fibre optic pH sensor to monitor the pH value of steel-reinforced concrete structures in the range from 9 to 13 with a resolution of about 0.5 pH unit is also shown. Concrete-embeddable pH sensors are installed in soil anchors to fix a sheet piling in the oil harbour of Rostock (North Germany). Finally, we report on development of distributed fibre optic sensors and their integration into geosynthetics as they are commonly used for reinforcement of dykes, dams and unstable or endangered slopes. Using the Brillouin frequency-domain analysis, the system is capable of monitoring the strain along the optical fibres and thereby detecting critical soil displacement in case of extreme flood events or slope slides. The system is designed to monitor soil deformation with a spatial resolution of 5 m over a length in the range of 10 km.

INTRODUCTION

Fibre optic sensor (FOS) technology has gained worldwide recognition into diverse fields of application due to their specific characteristics, mainly to monitor deformations and/or the overall integrity of structure components with high levels of risk, or to evaluate structures with high safety requirements. In contrast to mechanical measurements, fibre optic chemical sensors have the potential to provide early online information about danger of corrosion in steel-reinforced concrete structures. Such monitoring methods that enable non-destructive detection of corrosion-promoting conditions are therefore very welcome. FOS's replace electrical monitoring methods which can be destroyed by lightning strokes. In structural engineering and in geotechnique, rough installations as well as operational conditions are usual. New sensor systems have to survive this environment. For long-term use of sensors, high demands are put both for operational safety of the sensor system and for reliability of all components (stability of sensor characteristics itself and of related components, accuracy, repeatability of recorded data, long-term stability of used materials, definition of temperature influences, drifts onto sensors, …).

In detail, the following requirements have often to be considered:

- Reproducibility of static measurement results over 20 years, at least;
- Indication of zero-point drifts over time because recalibration of sensing elements is not possible after installation after test loading;
- Minimum of aging;
- Control of influences caused by leading cables or other components, and
- Watertightness (IP 68), safety against aggressive media in some cases.

SELECTED EXAMPLES

Monitoring of Bearing Behaviour of Large Steel Anchors and Micro Piles

The classical way to evaluate the bonding of fixed anchor length in difficult soil areas and/or to carry out suitability tests is the pulling-out of the fixed anchor length and the measuring of resulting forces at the anchor head. This test method delivers integral information on whether the introduced anchor forces will be transferred into the soil area. However, it does not provide any information on how the skin friction is distribution along the steel anchor, and finally to which amount the anchor length is involved in the load bearing.

Fibre Bragg grating sensor arrays attached to the surface of steel bars provide, in principle, the necessary information to evaluate the load transfer behaviour. This method was used, first, to probe micro piles (type GEWI® 63.5 mm Z-32.1-9/1/) that were used for fixing foundation plates of a sluice in the German river Weser against uplift. Second, these sensors can provide long-term monitoring of anchor bonding behaviour using heavy steel elements. In order to find an economic method to obtain the necessary information, a measuring concept was developed and realised in cooperation with the Neubauamt für den Ausbau des Mittellandkanals in Hannover, the German Federal Waterways Engineering and Research Institute (BAW), and the consulting office Dietz Geotechnik Consult Hilden/Germany. For the field tests the micro piles were extended and manufactured with a free length like an anchor. The quasi-distributed fibre optic strain sensors were installed in the complete length of the GEWI® steel bar (maximum length: 18 m) to measure strain distribution in the loaded anchors/micro piles. The gauge length for each sensor in the chain was 200 mm; the distance between the sensors was between 750 mm and 1500 mm. Each bar was equipped with two sensor arrays for redundancy reasons. Fig. 1a shows the attachment of one grating from the FBG array in the STUMP GmbH anchor factory, Fig. 1b shows the box where sensor fibre and leading cable are connected. Attention was paid to reliable fixing and protection of the sensors as well as to safe cabling at the head of the anchor because the sensor-equipped anchors had to be transported to the building site over a long distance. Fig. 1c shows the egress area for the fibre optic cable, Fig. 2 the introduction of one anchor into the borehole.

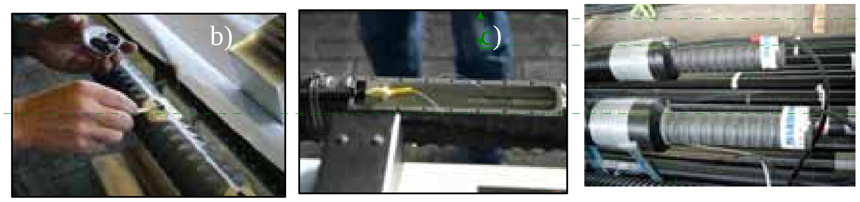

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Figure 1. Instrumentation of anchors with FBG sensors: a) attaching FBG; b) connecting box; c) cable protection at the head of the fixed length.

After the grout was cured, pull-out tests were carried out at the end of December 2006. The tensile force during the anchor tests was stepwise increased up to 1580 kN, and the strain distribution along the fixed anchor length was measured. Fig. 3 shows one preliminary result for one anchor pull-out test. The strain reaction during the time-limited loading and relieving can clearly be seen. Several strain levels represent the strain distribution along the fixed anchor length. It could be observed that the loaded anchor obviously slips a certain amount because it does not go back to the original fixing position when the load is relieved. At present, measuring results are evaluated in detail; findings will be presented at the conference and published soon in an appropriate Journal.

Figure 2. Installing the anchor.

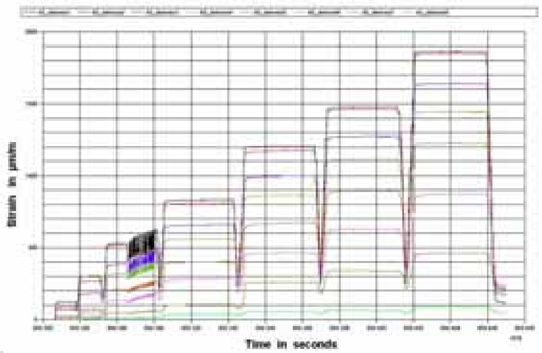

Figure 3. Strain distribution during stepwise anchor loading.

This measurement system not only helps optimizing the design of anchors but also enables evaluation of the long-term bonding behaviour in the fixed anchor area.

Concrete-Embeddable Fibre Optic AE Sensors for Analysis of Concrete Pile Integrity as well as Bearing Capacity

Assessment of the integrity and ultimate bearing capacity of large concrete sections and large concrete piles in existing or newly constructed (underground) foundations remains a difficult task. In order to get information about the performance of the hidden concrete structure, sensors are attached onto the reachable part of the concrete component such as at the pile head, and propagating waves are then excited by an impact at the pile head. The sensors record the acoustic emission signals from the concrete structure. The bearing capacity and the pile performance can be estimated using the one dimensional theory of wave propagation. Especially for difficult soil areas, one can only make vague assumptions about pile material and subsoil conditions. Often, the commonly used instrumentation at pile head does not provide sufficient information.

With the intention to improve the performance analysis of large concrete piles highly resolving fibre optic AE sensors based on Fabry-Perot technology for embedment into concrete piles at several levels have been developed. Fibre Fabry-Perot sensor elements enable recording of dynamic signals up to the range of several hundred kHz. This method promises to provide more precise information about the pile response over the whole length. However, because the introduced impact energies under high-strain pile testing or during the driving in procedure of prefabricated piles are quite high, a series of laboratory tests had to be performed to find out the proper application method for the selected AE-sensors.

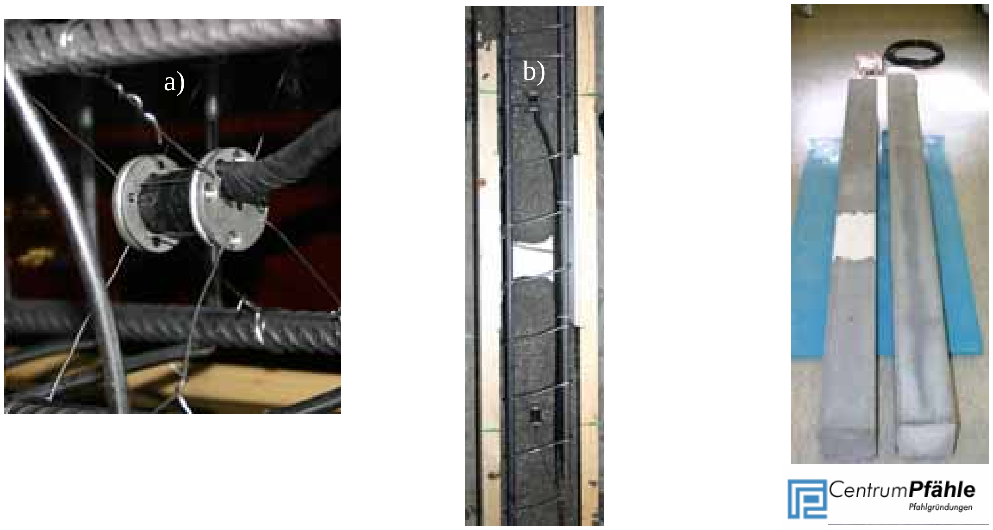

Figure 4. Sensor body with sensing elements fixed at reinforcing bows (One of the pre-casted piles an imperfection).

Fig. 4a shows the sensor body onto which the sensing elements are attached. The fibre optic AE sensors are attached to the inner surface of the sensor body by using a special tool. For comparison purposes, accelerometer sensors are installed inside of the sensor body; resistive strain gauges (RSG) are attached to the outer surface of the body. Fig. 4b shows two of the three sensors fixed in the model piles during concreting. One model pile has got an imperfection (see Fig. 4c).

Small scale model piles have been investigated in dynamic low-strain tests, high-strain and static load tests. All signal responses from integrated sensors have been recorded and compared to signals obtained from common methods of instrumentation. Fig. 5 compares strain responses of EFPI sensors from one pile without an imperfection (left) and one with an imperfection (right) during low-strain integrity testing. In the left picture (undamaged pile) it can be seen, that the introduced wave travels from the pile head passing the embedded sensors at measuring level (ML) 1, ML2 and ML3 to the pile toe and back to the pile head. The simulated geometric defect of 30 cm length in direction of pile axis at pile 2 is marked to dotted circles in the right picture of Fig. 5. The length of the defect could be calculated from the measured travel time differences from pile head to the secondary peaks at pile 2 to 31.7 cm. By applying the same procedure, however using the embedded sensors, a defect length of 29.6 cm follows from ML1, and 30.3 cm follows from ML3. These measured results from embedded sensors are more consistent with the real length of the defect of 30 cm. Only ML2 shows no significant secondary peaks caused by superposition of reflecting wave parts from the very closely located defect and the applied wavelength of impact. The developed application method of Fabry-Perot sensors on the inner surface of the steel cage could be well proven.

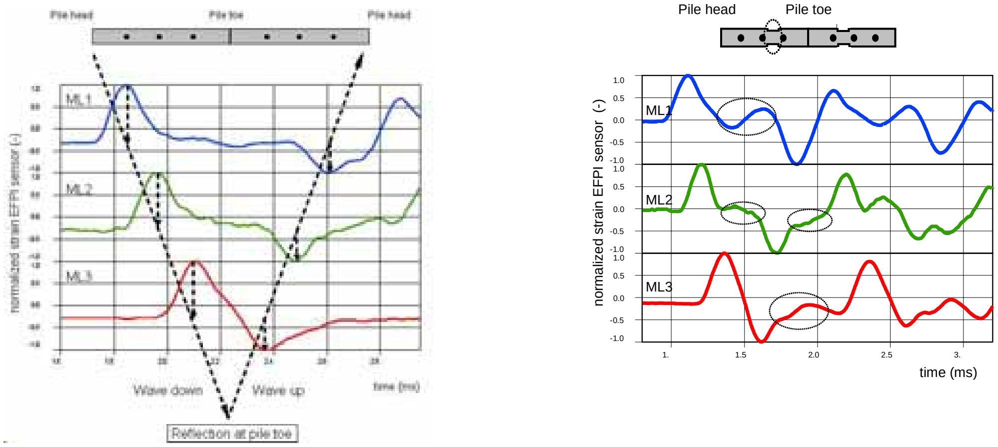

Figure 5. Strain responses over time of EFPI sensors from one pile without imperfection (left) and one with imperfection (right) during low-strain integrity testing (impact was generated by steel ball with diameter of 40 mm, and falling height of 60 cm).

Strain results from all applied strain gages (RSG and EFPI) for high-strain pile testing are shown in Fig. 6. It can clearly be seen that the reduction in EFPI strain intensity from one measuring level to the next one is caused by friction forces. This reduction in strain is also caused by radiation damping losses at the pile skin and toe. On the other hand, comparison of internal strain from embedded Fabry-Perot sensors (EFPI_ML1, 2, 3) with resistive strain gages (SG_ML1, 2, 3) at the same location at each measuring level reveals that both measuring systems vary in a range of about 5 %.

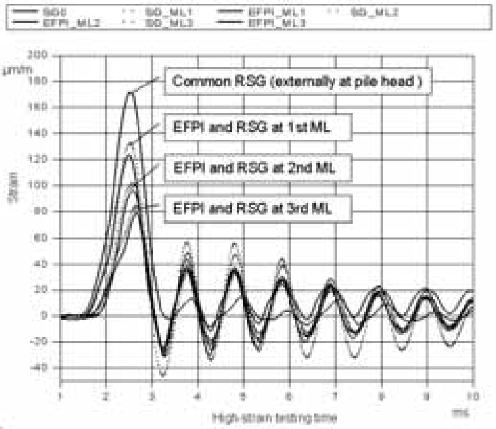

Figure 6. Comparison of measured strains during high-strain testing.

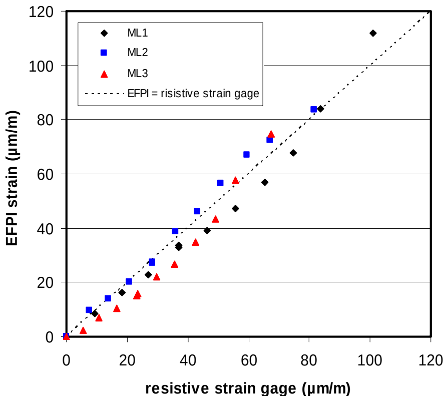

Fig.ure 7. Comparison of strains from fibre optic Fabry-Perot sensors with those from resistive strain gages.

Although the concrete embeddable strain sensor was developed for AE signal recording, static load tests were also carried out at both model piles. Loads were applied in three cycles. Fig. 7 shows the strain values from fibre optic Fabry-Perot sensors compared with that from resistive strain gages at each measuring level (ML). The maximum load was 110 kN which led to a permanent pile head settlement of 50 mm after the third loading cycle. Comparison of both sensor systems revealed good agreement; the measurement results achieved from EFPI sensors and resistive strain sensors differ in a range from 5 % to 10%. Comparing the shapes of the strain curves, it can be concluded that the pile concrete transfers the strain properly to the sensor cage. Detailed description is given in [2].
All measuring results show that EFPI sensors embedded as described above can be used for dynamic pile testing under low-strain as well as high-strain loading conditions, and also for static load tests. It is possible to calculate bearing capacity of the piles in the same way as with standard methods using additional embedded accelerometers. However, in contrast to this, calculations can be made with measurements at different locations which provide more precise information about the piles bearing behaviour. Therefore, the usually required assumptions for calculation of bearing capacity can strongly be reduced.

pH Sensor for Early Detection of Potential Danger of Corrosion in Concrete Structures

Steel-reinforced concrete structures such as sewer pipes, cooling towers or rock anchors are often exposed to a wide variety of damaging influences. Aside from mechanical stress, corrosion of steel due to chemical attacks is one of the most relevant damaging processes in concrete. It presents a safety risk to people and environment because failure can occur without prior indication. Besides moisture and chloride ions concentration, pH value is a chemical parameter of major importance in health monitoring of steel-reinforced concrete structures. The lifetime of steel-reinforced concrete structures depends strongly on their pH stage as embedded steel in concrete structures are only passivated at the pH values higher than 9. For this reason, monitoring of pH value in the range from 9 to 13 with a resolution of about 0.5 pH unit is relevant for early detection of corrosion condition.

In order to avoid time-consuming inspection, and in some cases destructive tests, cost-effective monitoring methods to detect beginning corrosion processes are requested. Commercially available sensors systems for early detection of steel corrosion in concrete structures do not always sufficiently match the in-situ requirements. Fibre optic based sensors are a promising technology for corrosion monitoring because they offer a large number of attractive features such as small size, flexibility, geometric versatility, resistance in corrosive and hazardous environments, no signal interference due to present moisture, in-situ and non-destructive measurement, and immunity against lightning strikes.

As a result of cooperation between German research institutes and SMEs, a concrete-embeddable long-term stable fibre optic pH sensor was developed. The most challenging requirements concern the long-term stability under strong alkaline conditions, since the sensor should record pH changes within the pH range between 13 and 9 over a period of at least 25 years. And, the sensor has to be integrated in harsh environments and inaccessible places. Moreover, it must be guaranteed that the sensing element has an intimate contact to the concrete matrix to see pH changes. And finally, the price of pH sensors has to be as low as possible to enable the fabrication of multiple-sensor structures.

The fibre optic pH sensor consists of a pH-sensitive layer made of a pH indicator that is immobilized in a solid substrate. In creating a long-term stable sensor for pH monitoring in concrete structures, several sensitive membranes have been prepared and investigated using both fluorescence lifetime and absorption measurement methods. It could be proved that only the absorption method provided reliable measurement results. In order to overcome instability problems resulting from a decrease of the indicator concentration due to photodegradation or leaching out, drifts of the light source intensity or bending of optical fibres, a so-called ratiometric method based on the use of the ratio between the intensity at two different wavelengths (e.g. at the intensity maximum points or at the isosbestic point) was applied because such a ratio of intensities is not altered by external factors. Some more details are described in /3/.

Fig. 8 shows the measurement principle for fibre optic pH measurement and the exploded view of the sensor head. Fig. 9 shows samples of the sensor head and a typical calibration curve. This curve resulted in a pH range between 9 and 12, a measurement resolution of 0.1 to 0.6 pH unit - dependent on the pH range. One particular condition of use is that the pH sensitive membrane must not dry out. This requirement is mostly fulfilled in hydraulic engineering and geotechnical applications. In order to prevent drying out before integration into concrete structures, the pH sensitive membrane is protected by a small watertight topcoat.

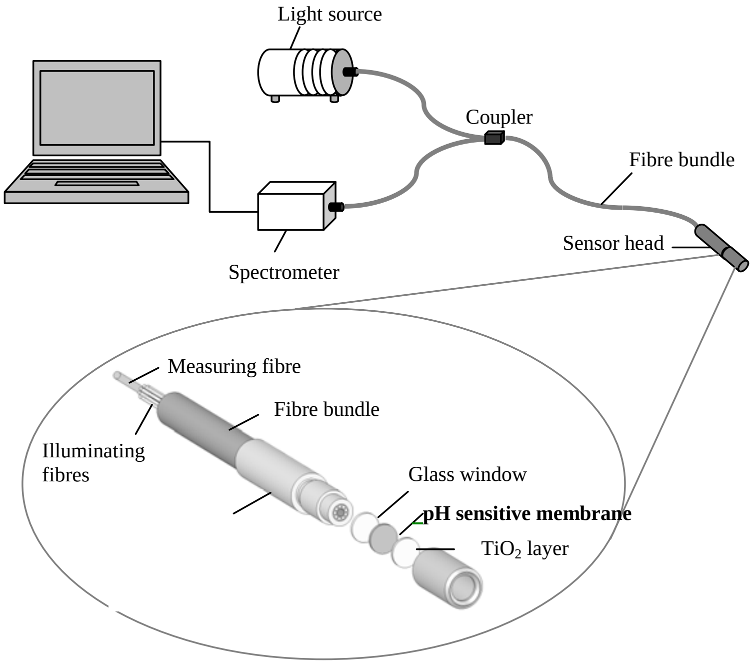

Figure 8. Measurement principle and enlarged view of the sensor head.

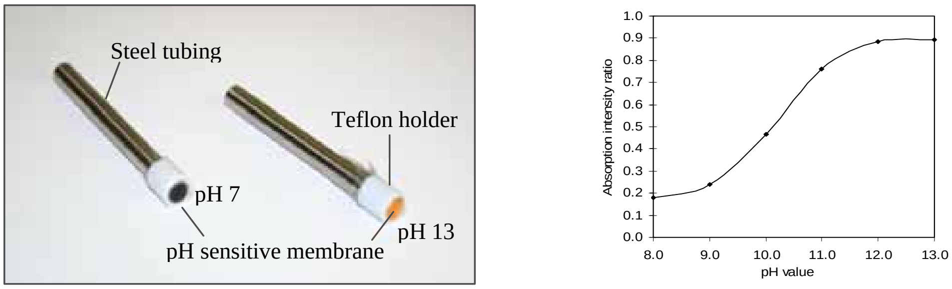

Figure 9. pH sensor heads (left); typical calibration curve for the pH range from 8 to 13.

Suitability of this sensor has been tested in steel anchors installed in the harbour of Rostock (North Germany). Fig. 10 shows two of 10 pH sensor prototypes that have been fixed on prefabricated anchor bodies before introducing them into the borehole. The topcoat (Fig. 10) was removed shortly before introducing the anchor into the borehole. This ensured that the membrane maintained its hydrophilic properties. Seven of 10 installed sensors have provided, for at least 1 year, useful information about the pH value of the grout. Two sensors were damaged during the installation of the anchors, one sensor failed after few months.

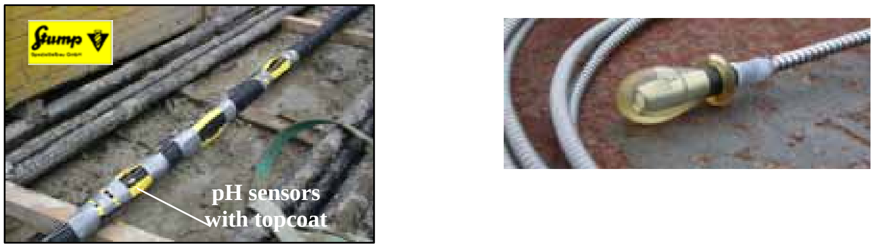

Figure 10. Fixing of the pH sensors in the prefabricated anchors. To prevent dehydration of the pH sensitive membrane, the sensor head is protected by a topcoat (right).

The sensor concept has been prepared for commercial supply. Relating to this, special attention was put on optimizing the robustness of sensor elements and integration technology. Moreover, a series of investigations have been carried out to clarify whether the membranes are capable of recording pH changes in concrete structures appropriately. For this purpose, several sensor heads were embedded in fresh mortar test prisms (Fig. 11) according to the standard protocol /4/. After a one-month curing period in water, the mortar samples with integrated sensor heads have been stored in an acid bath for simulating an environmental attack and thus the pH decreases under very harsh conditions (Fig 11). From this moment the sensor signal has been monitored at regular time intervals and has showed expected pH changes of the concrete matrix. Using these mortar samples, microscopic studies will be performed in the coming months to confirm the intimate contact between the sensitive membrane and the concrete matrix.

Figure 11. Mortar test samples with integrated sensors (left); acid bath for simulating environmental attack (right).

Fibre Sensor-Based Geosynthetics for Early Detection of Failure in Geotechnical Structures with High Potential of Risk

Monitoring of extended structures such as dykes, dams, slopes, tracks and highways in mining or critical soil areas requires sensor technologies with gauge lengths in the range of hundreds of meters, or even several kilometres. Sensing systems using the stimulated Brillouin scattering (SBS) allow the design of fully distributed fibre-optic sensors that monitor strain and temperature along optical fibres over a length of more than 10 km. This makes them highly suitable for the applications listed above.

Currently, a cost-effective field-applicable sensing system employing the Brillouin frequency-domain analysis technique (BOFDA), especially dimensioned for the requirements of dyke monitoring, is being developed. Research is being carried out within the framework "Risk Management of Extreme Flood Events (RIMAX)“ that the German Federal Ministry of Education and Research initiated against the background of the extreme floods on the rivers Oder in 1997 and Elbe in 2002. Coordinated by the Saxon Textile Research Institute (STFI e. V.) in Chemnitz/Germany and in cooperation with German universities and SMEs, a method for integration of optical fibre sensors into geosynthetics is being investigated. The geosynthetics are commonly used in dykes, where they act as filter, drainage or reinforcement. Equipped with optical fibre sensors, they form a smart sensing structure which is embedded into the soil along the landside dyke foot, as outlined in Fig. 11.

The feasibility of this novel combination of coated optical fibres and geosynthetics has been proven in field tests. Fig. 12 shows such a geotextile with integrated sensor fibres during the installation in a gravity dam in Solina/Poland.

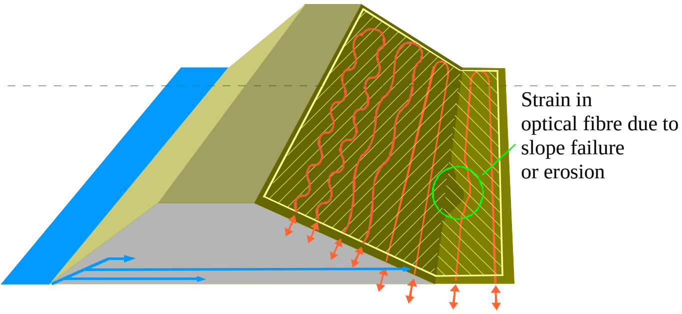

Figure 11. River dyke with sensor-based geosynthetics on the landside dyke foot.

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Figure 12. Sensor-based geotextile mat during installation on a construction site of a gravity dam in Solina/Poland.

In case of a critical deformation of the dyke body caused by erosion, slope failure, wave overtopping or piping, the soil displacement is transferred to strain experienced by the optical fibre. The strain is detected by a cost-efficiently configured BOFDA system with a spatial resolution of 5 m or better which fits the requirements for the risk management system.

When strain of up to 40 % is expected or in case of less extended structures such as endangered slopes with dimensions in the range of few hundred meters the sensing capabilities of polymer optical fibres (POF) have proven to be very promising. Sensing technology using optical time-domain reflectometry analysis (OTDR) is being investigated.

CONCLUSION AND OUTLOOK

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This paper described different types of fibre optic sensors used for non-daily monitoring tasks in civil and soil engineering. FBG sensor arrays were used to monitor anchor deformations in difficult soil areas; fibre Fabry-Perot interferometer sensors were used as acoustic emission (AE) sensors embedded in concrete piles to characterize its integrity and bearing capacity. Concrete-embeddable pH sensors were installed in soil anchors to monitor the pH value of steel-reinforced concrete structures in the range from 9 to 13. And finally, distributed fibre sensors using the Brillouin frequency-domain analysis for strain measurements were integrated into geosynthetics commonly used for reinforcement of dykes, dams and unstable or endangered slopes.

On-site fibre sensor use requires special expertise and experience especially when long-term measurements have to be done. Measurement systems have to work stably under very different environmental conditions, such as temperature variations, moisture influences, chemical attacks to components of the sensor system, chemical interactions between the sensing element or specific sensor materials, and the measureand or environment, characterization of the sensor behaviour under specific operational conditions. Packaging and ingress/egress areas for optical fibre sensors must be very robust. However, the most relevant issue for long-term monitoring sensor systems concerns the application of the sensing element and/or sensor fibre itself. Application, gluing, crimping or fixing must resist cycling thermal and mechanical loads. In order to consider all quality-related aspects, the only way is the use of validated sensor systems and validated application methods. Using this methodology, users get the confirmation that the sensor or the measurement system works and is as reliable as demanded. Further activities should be also concentrated on development of fibre sensor application and validation guidelines. This requires an international platform or international expert groups such as the newly established RILEM Technical Committee “Optical fiber sensor”.

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