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Praktische Anwendungen Zerstörungsfreier Prüfungen und Zukunftsaufgaben

Assessment of Structures using Fibre-optic Sensors

(Diagnose des Bauwerkverhaltens mittels faseroptischer Sensorik)

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Abstract: Monitoring of structures and assesment of their component's behaviour such as girders, anchors, ropes, dams, and dikes require a number of sensors which are able to deliver measurement data over a period of months and years. Mostly, mechanical quantities such as deformation, strain or vibration are requested. However, measurement of chemical quantities in materials and structure components such as pH value in steel reinforced concrete members also provides information about the integrity of concrete structures. Different measurement tasks as well as the use of different sensor technologies require special application methodologies.
The paper presents the use of different fibre optic sensor types for monitoring of engineering and geo-engineering structures. One example concerns the assessment of ultimate bearing capacity and the bearing behaviour of large concrete piles in existing foundations, or during and after installation. Highly resolving fibre Fabry-Perot sensors were used to design concrete-embeddable acoustic emission sensors for analysis of concrete pile integrity as well as bearing capacity. They were installed over the pile length and deliver more precise pile response. FBG sensors were attached to an anchor steel (micro piles) to measure the strain distribution during straining and pull-out tests. On the basis of measurement results, load distribution and load transfer to the soil was evaluated. Geotextiles are increasingly used to stabilize dams, dykes, slopes, railway embankments against damage and failure. Several Kilometres long sensor fibres integrated into textiles allow early detection of beginning damage during flooding or in sliding areas. If strain above 1 % until about 40 % has to be detected, polymer optical fibre sensors provide outstanding characteristics. First results with sensor-equipped geotextiles will be presented; experiences from field tests are described. Steel reinforcement in concrete structures is susceptible to corrosion if the pH value approaches 9.5 and less. Therefore pH monitoring in chemically highly loaded areas is needed. Very tiny fibre-optic pH sensors have been developed and first installed in the fixing area of anchors. Long-term measurements over 2 years revealed amazingly well function. This pH sensor is being prepared for commercial applications.

Kurzfassung: Das Monitoring des Verhaltens von Bauwerken, z. B. Dämmen, oder deren Komponenten, z. B. Tragseile, Anker, unter besonderen Beanspruchungen oder über lange Zeiträume gewinnt bei der Konzipierung von Neubauten bzw. bei der Instandsetzung zunehmend an Bedeutung. Intelligente Sensorsysteme, die wichtige Messinformation aus der Struktur liefern und dem Überwacher eine bessere Diagnose ermöglichen, sind vielerorts integraler Bestandteil des Bauwerks. Eine inzwischen weitverbreitete Monitoring-Technologie ist die faseroptische Sensorik. Unterschiedlichste faseroptische Messverfahren liefern physikalische und chemische Messgrößen aus der Struktur; am häufigsten jedoch mechanische Größen zur Bewertung des Verformungs-, Schwingungs- oder Bewegungsverhaltens.
Der Beitrag zeigt anhand von Anwendungsbeispielen die unterschiedlichen Möglichkeiten der faseroptischen Sensortechnik für sowohl Langzeitmonitoring als auch periodisch erfolgende diagnostische Maßnahmen. Es werden in Geotextilien integrierte Verformungssensoren für die Überwachung von Deichstrukturen, Hängen und potentiellen Setzungszonen vorgestellt. Ebenso werden dynamische und statische Diagnoseverfahren auf Basis eingebetteter Sensoren für die Tragfähigkeits- und Integritätsbewertung von

Betonpfahlgründungen erläutert. Da Korrosion von Betonstahl nach wie vor großen volkswirtschaftlichen Schaden anrichtet und ebenso die technische Sicherheit eines Bauwerks beeinträchtigen kann, wurde eine faseroptische Sonde in Bleistiftgröße entwickelt, die den pH-Wert des Betons überwacht. Das faseroptische Sensoren einschließlich Zuleitung außerordentlich klein sind, können diese in kleinsten Räumen untergebracht werden. Auf diese Weise wurde der Lastabtrag entlang von Micropiles (GEWI-Stahlanker) für eine Auftriebssicherung im Wasserbau experimentell bewertet.

1 INTRODUCTION

Fibre optic sensor (FOS) technology has gained worldwide recognition due to their specific characteristics. In Engineering, it is mainly used to monitor deformations and/or the overall integrity of structure components with high level of risks or with high safety requirements. Especially in steel-reinforced concrete structures, such fibre optic sensors are demanded that have the potential to provide early online information about danger of corrosion. Fibre optic sensor-based monitoring methods are highly welcome for non-destructive assessment of all types of engineering structures because they

- cannot be destroyed by lightning strokes,
- survive in chemically aggressive environments,
- can be integrated into very narrow structural components, like anchor rods, ropes, and
- enable to deliver sensor chains by using one single fibre.

The fibre optic use in structural engineering can be distinguished into two main parts: first, installation or integration of sensors which will be activated during testing of the structure integrity or to collect data about the performance of structure components. These testing procedures will mostly be carried out periodically, and the sensor state can then be considered as ‘zero-point’ state. In contrast to this procedure, second, sensors that have been integrated into structures or components to deliver data from the measuring object continuously or from time to time with reference to the previous measurement; they must work very reliable and stable over years. They must not loose the reference value from the beginning of the signal recording. In the latter case, 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, …). If zero-point drifts over time occur, they must be separated from the summarized measurement information. This task might be challenging because recalibration of sensing elements is, in general, not possible after installation respectively after test loading.

In the following chapters, the use of different fibre sensor types in structrual and geotechnical engineering is described: short-gauge length sensors (FBG and EFPI technique) and long-gauge length sensors (Brillouin frequency-domain analysis technique and OTDR technique) [1].

2 SHORT-GAUGE LENGTH SENSOR APPLICATIONS

2.1 Assessment of large concrete foundation piles by fibre optic AE sensors

2.1.1 Assessment problem

Assessment of the integrity and ultimate bearing capacity of large concrete piles in existing or newly constructed 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 the pile head, and propagating waves are then excited by an impact at the pile head. The sensors record the acoustic emission (AE) signals from the concrete structure. The bearing capacity and the pile performance can then be estimated using the one dimensional theory of wave propagation. Especially for cohesive soil areas, one can only make vague assumptions about pile-soil interaction as well as material and subsoil conditions. Often, the commonly used instrumentation at pile head does not provide sufficient information.

2.1.2 Sensor development and pile tests [2]

In order to improve the performance analysis of large concrete piles, highly resolving fibre optic AE sensors based on Fabry-Perot technology have been developed for embedment into concrete piles at several levels. Fibre Fabry-Perot sensor elements enable recording 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 pile length especially using dynamic pile test methods.

Prefabricated model piles were and tested in laboratory to prove the appropriateness of the developed concrete embeddable sensors which will be subjected to high impact energies during testing. Different sensing elements are attached onto the sensor body (see Fig. 2). 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.

These two small scale model piles have been investigated in dynamic low-strain tests; high-strain and static load tests [2]. All signal responses from integrated sensors have been recorded and compared with signals obtained from common methods of instrumentation.

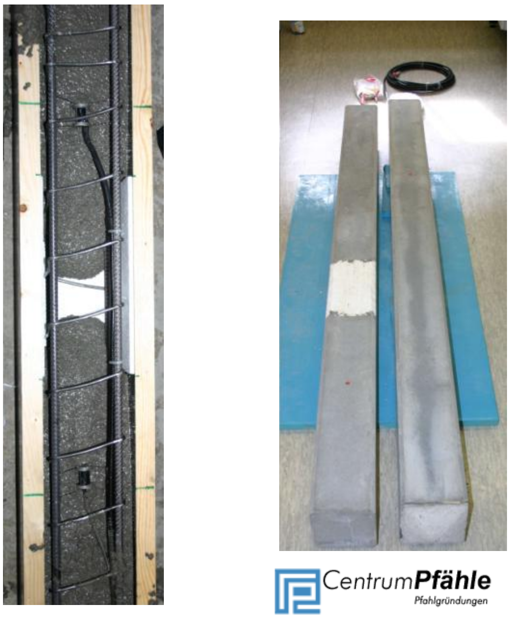

Figure 1: Casting of sensor-equipped model piles. Sensors are fixed at the cage of reinforcement (left); one pile has got an imperfection (left pile in the right picture)

Figure 2: Sensor body fixed at the reinforcement steel

2.1.3 Test results from low-strain integrity method

Fig. 3 compares strain responses of EFPI sensors from one pile without imperfection (above) with one with imperfection (below) during low-strain integrity testing. From the undamaged pile response (Fig. 3, above), it can be seen that the introduced wave travels from 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 with dotted circles in the lower picture of Fig. 3.

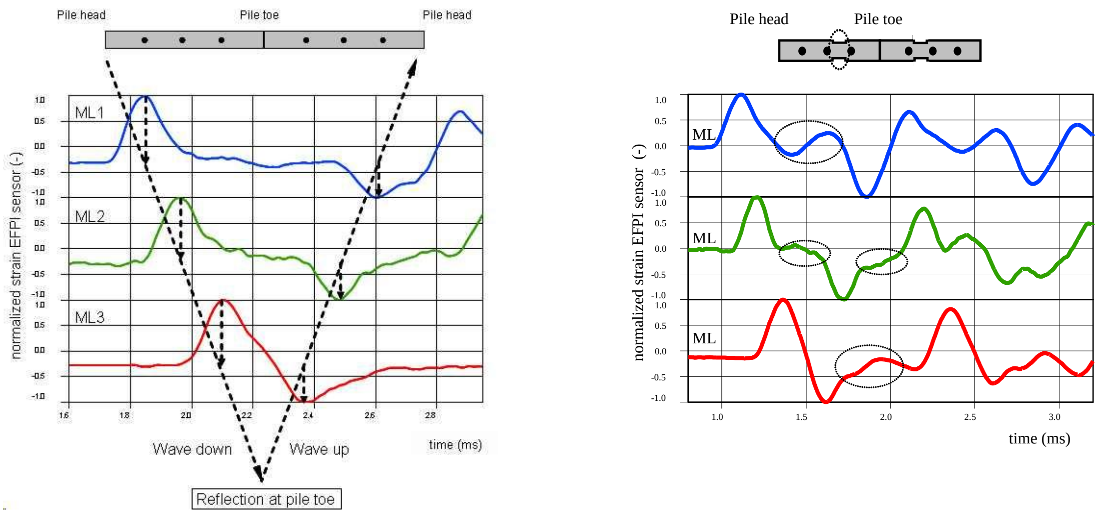

Figure 3: Strain responses of EFPI sensors over time from one pile without imperfection (left) and one with imperfection (right) during low-strain integrity testing; impact was generated by steel ball with a diameter of 40 mm (falling height: 60 cm).

The length of the defect could be calculated from the measured travel time differences from pile head (sensor is installed at the pile head) to the secondary peaks at pile 2 to 31.7 cm. By applying the same procedure, however using 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 definitely better consistent with the real defect length of 30 cm. It must be noted that ML2 did not show significant secondary peaks caused by superposition of reflecting wave parts from the very closely located defect and the applied impact wavelength. The tests carried out confirmed the application concept for Fabry-Perot sensors on the inner surface of the sensor body.

2.1.4 Results from load testing

Strain results from all applied strain gages (RSG and EFPI) for high-strain pile testing are shown in Fig. 4. The reduction in EFPI strain intensity from one measuring level to the next one caused by friction forces can clearly be seen. This reduction in strain is also caused by radiation damping losses at 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 %.

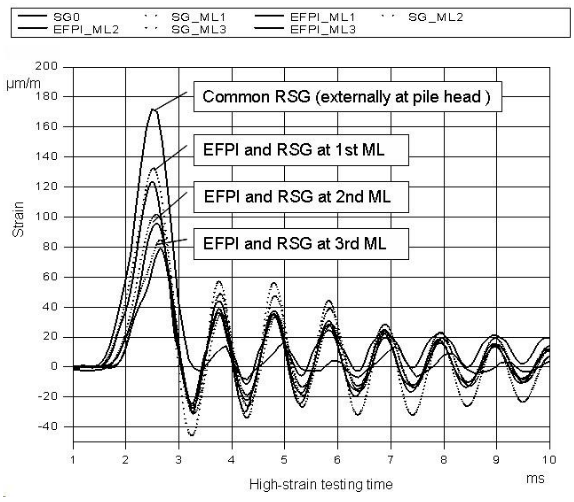

Figure 4: Measured strains during high-strain testing.

Figure 5: Sensors fixed at the cage of reinforcement for a 19 m long concrete pile (above right: sensor body)

Although the concrete embeddable strain sensor was developed for AE signal recording, static load tests were carried out as well at both model piles. Loads were applied in three cycles. 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 differed 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 body. Detailed description of the tests is given in Schallert et al [2].

The main outcome of the measuring results is that EFPI sensors embedded as described above can be used for both dynamic pile testing under low-strain as well as high-strain loading conditions and for static load tests. It is possible to calculate bearing capacity of piles in the same way as made with standard methods which use additionally embedded accelerometers. In addition, calculations can be made on the basis of measurements at different locations which provide more precise information about the pile's bearing behaviour. Therefore, the usually required number of assumptions for calculation of bearing capacity can strongly be reduced.

2.1.5 Outlook for this application

Field tests are being prepared. For this purpose, the design of the sensor body was matched to the concrete mixture (aggregate size) and dynamic loading conditions of the real concrete pile. A total of 8 sensors were located in 5 measuring levels along a 19 m long concrete pile. The locations were defined depending on the soil stratification. Fig. 5 shows the cage of reinforcement with the fixed sensors before concreting carried out by Centrum Pfähle GmbH Hamburg/Germany.

2.2 Evaluation of bearing behaviour of large steel anchors and micro piles

2.2.1 Evaluation problem

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

Fibre Bragg grating sensor arrays attached to the surface of steel bars of micro piles or within the anchors provide 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 are to be used for fixing of foundation plates of a sluice in the German river Weser against uplift. Second, these sensors can provide at the same time long-term monitoring of the bonding behaviour of heavy anchors. A similar method of anchor monitoring with embedded sensor fibres is described in Habel et al. [3].

2.2.2 Measurement concept and sensor installation

In order to find an economic method to reach the necessary information, a measuring concept was developed and implemented 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 sensor arrays 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. 6 shows the attachment of one grating of the FBG array in the STUMP GmbH anchor factory, Fig. 7 (left) shows the splice 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 several 100 km. Fig. 7 (right) shows the egress area for the fibre optic cable at the anchor head. Fig. 8 shows the introduction of one anchor into the borehole.

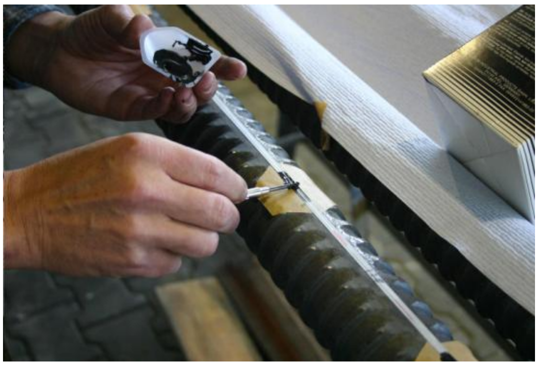

Figure 6: Application of FGB sensor to the steel bar

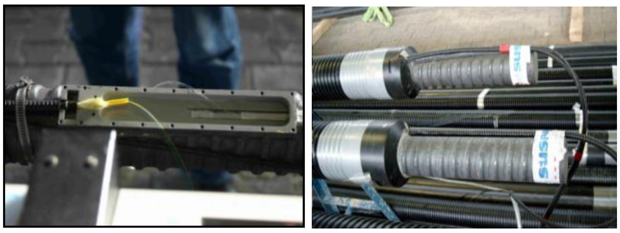

Figure 7: Splice box (left) and cable protection at the anchor's pile head (right).

Figure 8: Introduction of the micro pile into the bore hole.

2.2.3 Tests and results

After the grout was cured, pull-out tests have been 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. 9 shows strain results from embedded fibre Bragg grating sensors 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. Fig. 10 shows an example for interpretation of measured strain distribution along one anchor. Above the solid line, the strain distribution along the steel which is not fixed in soil (free anchor length) is plotted; below the line, the strain distribution along the fixed anchor length represents the load transfer into the soil (load bearing).

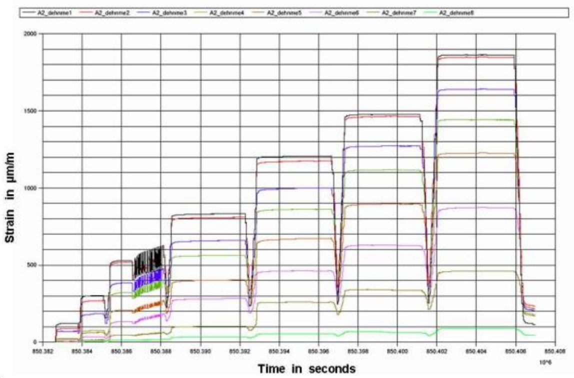

Figure 9: Original strain distribution data from FBG sensors during stepwise loading of anchor A2. Diagram: BAM

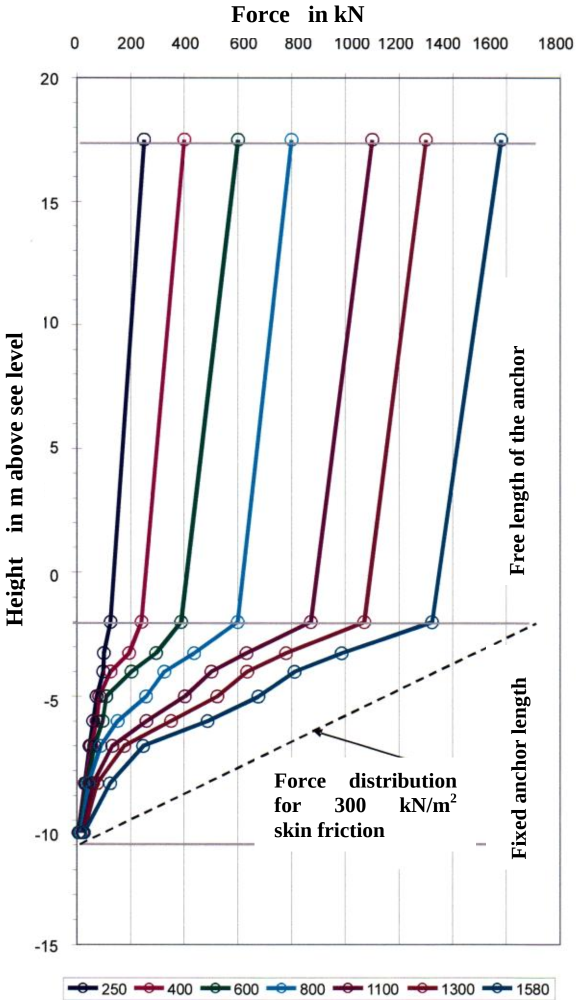

Figure 10: Load transfer of anchor A1 measured with applied strain sensors. Diagram: German Federal Waterways Engineering and Research Institute (BAW) Karlsruhe

3 EARLY FAILURE DETECTION OF GEOTECHNICAL STRUCTURES USING FIBRE SENSOR-BASED GEOSYNTHETICS

3.1 Distributed silica-based fibre sensor for monitoring of geo-structures with large dimensions

Monitoring of extended structures such as dykes, dams, tracks and highways in mining or critical soil areas requires sensor technologies with gauge lengths in the range of several 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 application in geo-engineering and monitoring of extended structures such as pipelines.

Because of extreme floods on two large German rivers (Oder in 1997 and Elbe in 2002), the national "Risk Management of Extreme Flood Events (RIMAX)" research programme has been started by the German Federal Ministry of Education and Research to develop intelligent monitoring systems which are able to detect incipient effects of failure of hydraulic engineering's structures. Within this framework, the idea was to integrate optical fibre sensors into geosynthetics, which can be used for stabilization of dykes, dams or similar geotechnical structures. 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 can be embedded into the soil along the landside dyke foot, as outlined in Fig. 11.

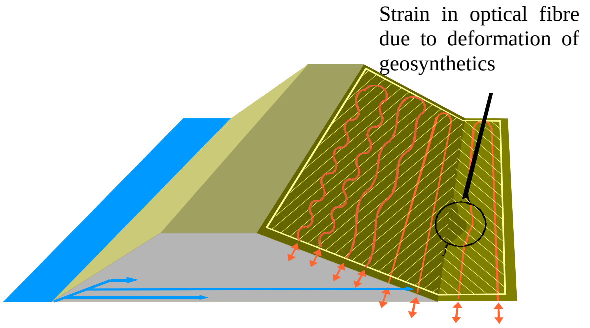

Figure 11: River dyke with sensor-based geosynthetics

Figure 12: Sensor-based geotextile mat during the installation on a construction site of a gravity dam in Solina/Poland (Textile: STFI e.V. Chemnitz).

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 can be detected by a distributed fibre optic strain sensor.

Currently, a cost-effective field-applicable sensing system using Brillouin frequency-domain analysis technique (BOFDA) technology, especially dimensioned for the requirements of dyke monitoring with a spatial resolution of 5 m or better, is being developed in cooperation with German universities and SMEs, especially the Saxon Textile Research Institute (STFI e. V.) in Chemnitz, Germany. Such a cost-efficiently configured BOFDA system fits the requirements for a risk management system.

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. Measurement system, test results and application are described in detail in Nöther et al. [4].

Distributed strain measurement using stimulated Brillouin scattering in silica optical fibres reaches its limits when strong deformation of the structure lead to strain of more than 1 %. When strain clearly exceeds few percent, and when such large strain values have to be measured in less extended structures such as endangered slopes or limited soil areas with dimensions in the range of few hundred meters, the sensing and monitoring capabilities of polymer optical fibres (POF) have proven to be very promising. Recent research results will be presented in the following chapter.

3.2 Distributed polymer optical fibre sensor for monitoring of large deformations in geo-structures

Slopes, railway embankments or soil areas which show endangering stability behaviour like slipping, creeping or depression have usually less extended dimensions than dykes. However, deformations to be detected can require monitoring systems with the capability of measuring strain > 1 %. In such cases, polymer optical fibres (POF) have some advantages. They are able to measure strain of up to 40 % and more without significant distortion of light guiding properties; they are robust, allow easier handling and have an acceptable price. Currently, the usable length of POF sensor fibre is about 100 m.

In order to get smart geotextiles for application in areas with limited extensions, POF have been integrated into nonwoven geotextiles using a warp-knitting technique [5]. The knitted fabrics can either be used as drainage or as narrow tape which poses a carrier for the sensor fibre. Fig. 13 shows two samples of smart geotextiles. One important point during integration concerns the transfer of the geo-structure’s deformation to be monitored into the polymer optical sensor fibre. It could be found a method to integrate POF sensors without loosing their sensitivity.

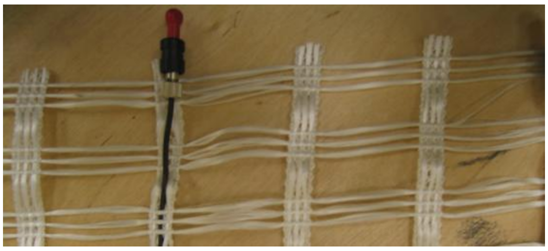

Figure 13: Geotextiles with integrated POF sensors (Photo and textile: STFI e. V. Chemnitz)

Deformation of the geotextile is evaluated by measuring the POF elongation using the optical time-domain reflectometry analysis (OTDR). This technique is well known and mainly used to locate errors in fibre optic communication cables. However, it is also used as sensing method such as to monitor the bonding behaviour of heavy rock anchor in a gravity dam in Germany[2]. In principle, the time interval from launching the pulse into the fibre until the return of the backscattered light (pulse response) is measured. It depends linearly on the distance of the scattering location initiated by a local or integral deformation. Using the OTDR technique, it is known that the level of the backscattered light increases at locations where strain is applied to a polymer optical fibre. This effect is exploited for this new sensing technology whereas some special questions concerning backscattering behaviour due to mechanical influences are being investigated. Basically, it must be possible to differentiate backscattered light due to strain from such light due to undesired effects such as bending and plastic deformation. For this purpose, a special test facility has been developed and used to introduce strain into the fibre. Fig. 14 shows this facility. This test facility allows applying almost any desired strain distribution along the fibre by spooling it onto a coil under defined stress. The stress is applied by guiding the fibre along a dancing roll which is loaded with weights. In order to prevent the fibre from relaxing to a uniformly stressed state, the frictional force on the coil is increased by notching the coil.

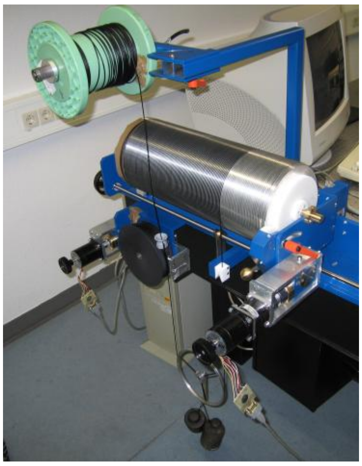

Figure 14: Specially developed test facility to apply distributed strain along an long optical fibre (Photo: BAM)

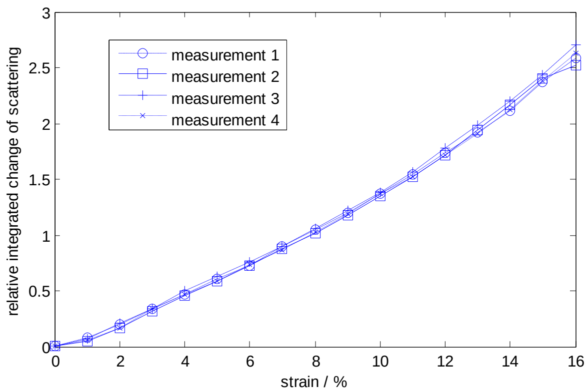

Figure 15: Strain measurements (4 test series) at different locations along the POF [5]

Fig. 15 shows the increase of scattered light for applied strain up to 16 %. The relatively weak nonlinearity in this strain range becomes stronger for strain values up to 40 %. Above 40 %, the polyethylene coating has partially broken which led to significant attenuation. Test results also revealed that the level of scattered light due to constant strain decreases with time. It is being investigated whether this decrease converges to a stable value. Some other experimental results and an outlook concerning perfluorinated POF for sensor length > 100 m are described in Lenke et al [5]. The next steps in the research programme concern the increase of spatial resolution.

POF sensors have been integrated in geotextile which were prepared for construction sites in Poland and in Germany. It could be demonstrated that the sensor structure itself as well as the integration procedure into geotextile tape is appropriate for use on-site. The sensing fibres endured the construction work of the dam.

4 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 is one of the most relevant damaging processes in steel-reinforced 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 and pre-stressed concrete structures. The lifetime of steel-reinforced concrete structures depends strongly on their pH state as embedded steels in concrete structures are only passivated at pH values higher than about 9. For this reason, long-term monitoring of pH value in the range from 9 to 13 with a resolution of about 0.5 pH units is relevant for early detection of potential corrosion condition.

Commercially available structure-integrated sensors 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 strokes. In order to draw benefit from these advantages, 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 within the pH range between 13 and 9 over a period of at least 25 years. The sensor has to be integrated in harsh environments and inaccessible places. 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 immobilized in a solid substrate. As a result of intense investigations, the absorption method was preferred because only this method provided reliable measurement results. In order to overcome instability problems resulting from decrease of the indicator concentration due to photodegradation or leaching out, drifts of the light source intensity or bending of optical fibres, a 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. Such a ratio of intensities is not altered by external factors. The measurement principle and some more details are described in Dantan et al. [6] Fig. 16 shows the design of the sensor head.

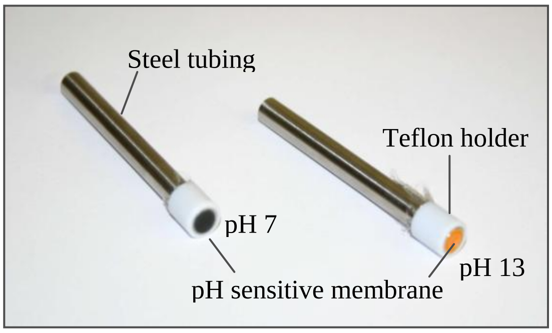

Figure 16: pH sensor head design; the head is pluggable and can be replaced. Photo: BAM

The diameter is 8 mm; the sensitive layer is protected but sufficiently sensitive for contact to the concrete matrix. The sensitive membrane must not exceed a definite thickness because the ion diffusion is hindered. In order to ensure a reliably stable thickness of the sensitive membrane, a special powder compacting tool for manufacturing of pH-sensitive membranes was developed.

The measurement resolution of the sensor for pH values between 9 and 12 is in the range from 0.1 to 0.6 pH units depending on the pH value. The highest resolution can be achieved in the middle of the measurement range (between 9.7 and 11). 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 must be protected by a small watertight topcoat (see Fig. 17).

Figure 17: Water filled topcoat for the pH sensitive membrane to prevent dehydration. Photo: STUMP GmbH

Figure 18: Prefabricated anchors with fixed pH sensors (arrows). Photo: BAM

Suitability of this sensor has been tested in steel anchors installed in the harbour of Rostock (North Germany). Fig. 18 shows two of totally 10 pH sensor prototypes that have been fixed on prefabricated anchor bodies (two in each anchor) before introducing them into the borehole. The topcoat (Fig. 17) was removed shortly before introducing the anchor into the borehole and concreting it. This procedure ensured that the membrane maintained its hydrophilic properties. Since sensor installation in July 2005, seven of 10 installed sensors have provided useful information about the pH value of the grout. (Two sensors were damaged already during installing the anchors, one sensor failed after few months.)

The sensor concept has been prepared for commercial supply. Relating to his, special attention was put on optimization of the robustness of the sensor components and integration technology. A series of investigations have been carried out to clarify whether the membranes are reliably capable of recording pH changes in concrete structures. For this purpose, several sensor heads were embedded in fresh mortar test prisms according to the standardized testing procedures [7]. After a one-month curing period in water, the mortar samples with integrated sensor heads have been stored in an acid bath for simulation of pH decrease. The sensor signal has been monitored periodically and showed expected pH changes of the concrete matrix. Currently, the transfer of the research results into production will be arranged by the research partners of the German research project: BAM Berlin, Schmidt & Haensch GmbH Berlin, MBF GmbH Berlin and Dietz Geotechnik Consult Hilden.

5 CONCLUSIONS

This paper described different types of fibre optic sensors used for non-daily monitoring tasks in geo-technique 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 large concrete piles to characterize its integrity and bearing capacity. Tiny concrete-embeddable pH sensors were installed in soil anchors to monitor the pH value of the grout over years. They can be used to monitor steel-reinforced concrete structures in the range from 9 to 13. And finally, distributed fibre sensors using the Brillouin frequency-domain analysis and OTDR-technique for strain measurements were integrated into geosynthetics commonly used for reinforcement of dykes, dams and unstable or endangered slopes. Special attention was paid to polymer optical fibres with the capability of strain in the range > 1 % up to 40 %.

Fibre sensor use on-site requires special expertise and experience especially when long-term measurements have to be done. Measurement systems have to work stable 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 measurand 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 to aim at validated sensor systems and validated application methods. Using this methodology, users get the confirmation that the sensor or the measurement system works as reliable as demanded.

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