COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT-CINQUIÈME CONGRÈS
DES GRANDS BARRAGES
Stavanger, Juin 2015

NEW CONCEPTS FOR THE MONITORING OF CONCRETE JOINTS MOVEMENTS OF WATER DAMS IN PUMP-STORAGE OPERATION (*)

Werner LIENHART, Ferdinand KLUG
Institute of Engineering Geodesy and Measurement Systems, GRAZ University of Technology

AUSTRIA

1. INTRODUCTION

Hydro-electric power plants are an important source of renewable energy in Austria. The structural safety of the required water dams is usually assessed by proven geotechnical and geodetic measurement techniques.

Within the last 10 years new sensors based on fiber optic cables were developed which can also be used for civil infrastructure monitoring. However, applications of fiber optic sensors in water dam monitoring focused previously on leakage detection and not on deformation measurements.

Within a research project we developed a new monitoring system for the continuous and high resolution monitoring of expansion joints of concrete arch dams. This system was installed in one of the largest water dams of Austria (Fig. 1) in 2013. The goals of the research project were to assess the long term stability and the achievable accuracy of fiber optic sensors in the harsh environment within a concrete dam. Furthermore, it should be proven that fiber optic sensors are suitable to depict the small deformations caused by small water level changes in pump-storage operation mode.

(*) *Nouveaux concepts pour la surveillance des joints de béton des barrages pendant le fonctionnement d'une centrale de pompage-turbinage.*

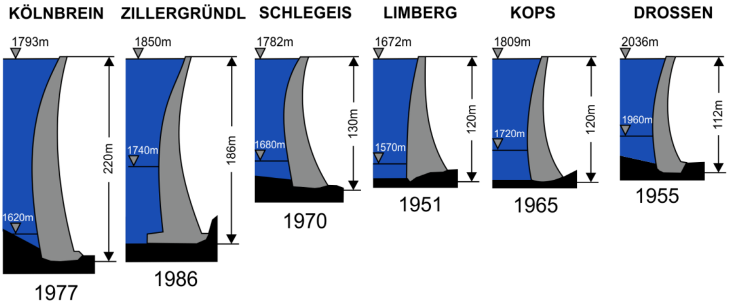

Fig. 1
Large concrete arch dams in Austria (based on [1], p. 81)
Grands barrages voûtes en béton en Autriche (basé sur [1], p. 81)

2. THE WATER DAM KOPS

The Kops dam is located in the western part of Austria, at a sea level height of 1800 m. It has an active storage volume of 42.9 mio. m^3. The concrete dam consists of an arch dam and a gravity dam which are connected by an artificial bearing (Fig. 2-left). The arch dam has a crest length of 400 m and a height of 122 m. The crest length of the gravity dam is 214 m and its height is 43 m [2]. The arch dam was built in 27 vertical blocks which are connected by concrete joints, Fig. 2-right. From 1965 to 2008 the dam was operated in standard storage mode. In 2008 the power plant was modified to pump-storage operation.

Fig. 2
Overview of the water dam Kops (left) [2] and the vertically aligned concrete blocks connected by joints (right)
Aperçu du barrage réservoir Kops (à gauche) [2] et des blocs de béton alignés verticalement et reliés par des joints (à droite)

The health of the dam is evaluated based on geotechnical measurements and periodic geodetic measurements. The geodetic measurement program consists of precise leveling in maintenance corridors and at the dam crest. Furthermore, geodetic traverse and network measurements are carried out within the corridors and on the dam surface. The geotechnical instrumentation includes a wide range of sensors like extensometers, piezometers and inverted pendulums. Additionally, displacement dial gauges are used to measure relative movements of the concrete blocks of the dam, Fig. 3. These manual measurements are carried out quarterly.

Fig. 3
Concrete joint between two concrete blocks with measurement anchors (left), manual displacement measurement with a dial gauge (right)
Joint de béton entre deux blocs de béton avec des ancres de mesure (à gauche), mesure manuelle du déplacement avec une jauge (à droite)

In the conventional reservoir operation mode, the seasonal variation of the expansion joint movement is up to 2 mm. After the change to pump-storage operation in 2008, the number of load cycles increased significantly. However, these high frequent changes induce deformations with smaller amplitudes. Due to the low measurement rate (1 measurement per every 4 month) and the limited measurement precision of the manual dial gauges (approximately 0.02 mm to 0.05 mm depending on operator) deformations of the concrete joints induced by small water level changes could not be measured until now. Therefore, the concrete joint deformations were the ideal test bed for the fiber optic measurement installation.

3. METHODS FOR CONTINUOUS HIGH RESOLUTION MEASUREMENTS OF CONCRETE JOINTS

Concrete joint deformations can be measured continuously with electric stain gauges based on strain foil measurements, vibrating wire sensors or inductive methods like linear variable transducers. However, using electric dial gauges for the monitoring of a large number of concrete joints result in a high installation effort because a separate cable is required for each sensor. Furthermore, the large temperature changes and the high humidity within a water dam can cause sensor failures in permanent long term monitoring installations with electric sensors.

Fiber optic sensors are better suited to fulfill the requirements since they do not need electric power at the sensor location and have a high measurement resolution. Most importantly, several sensors can be placed on a single fiber which results in low installation efforts.

Fiber optic sensors are already used for monitoring applications in hydro-electric dams. Examples are distributed temperature measurements for leakage detection [e.g. 3, 4 and 5]. However, it was not reported yet that fiber optic sensors were used for the monitoring of concrete joint deformations.

4. DEVELOPMENT OF THE FIBER OPTIC MEASUREMENT SYSTEM FOR THE KOPS DAM

The Institute of Engineering Geodesy and Measurement Systems (IGMS) of Graz University of Technology developed a fiber optic measurement system based on fiber Bragg gratings (FBG) for the monitoring of the concrete joint deformations of the water dam Kops.

The Kops arch dam has more than 60 dial gauge measurement points. Since the performance and lifetime of fiber optic sensors in this application were unknown it was decided to upgrade, in a first step, only 15 of the manual dial gauge measurement points with fiber optic sensors. All sensors are located in the highest maintenance corridor as can be seen in Fig. 4.

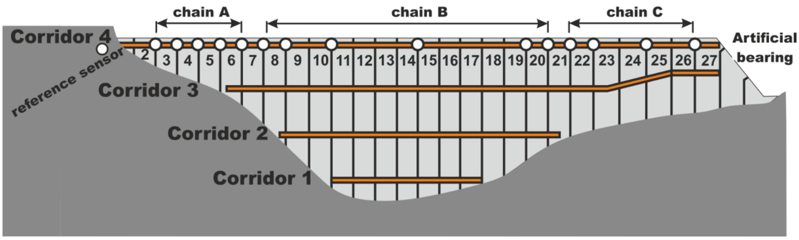

Fig. 4
Selected sensor positions (white circles) in the arch dam, distributed on three fiber optic chains
Positions de capteurs (ronds blancs) dans le barrage-voûte, répartis sur trois chaînes de fibre optique

FBG sensors measure wavelength shifts $\Delta\lambda$ which are caused by strain or temperature changes. The relation between strain and temperature induced wavelength shift can be approximated with the linear function

$$\frac{\Delta\lambda_{(\varepsilon,T)}}{\lambda_B} = k * \varepsilon + \alpha_T * \Delta T \qquad [1]$$

with
λ_B … Bragg wavelength at zero strain
k … gage factor
ε … applied strain
α_T … change of refraction index
ΔT … temperature change

Alternatively the FBG strain k_ε and temperature k_T sensitivity can be expressed in pm/µε and pm/K. Typical values are $k\varepsilon$ = 1.2 pm/µε for a strain sensor and k_T = 10 pm/K for a temperature sensor, e.g. [6]. Therefore, a temperature change of 1K and a strain change of 8µm/m (8µε) yield the same measurement signal. In order to separate temperature from strain, a FBG temperature sensor placed in the vicinity of the FBG strain sensor, can be used.

The appropriate selection of the center wavelength of the FBG sensors as well as the selection of a suitable FBG interrogator are crucial elements in the development of a monitoring system with many sensors and large strains. To separate the signals of two sensors, the FBG wavelengths must not overlap. This requirement can significantly reduce the maximum possible number of sensors on one single fiber. Another limiting factor is the dynamic range of the interrogator, which is especially important if the core diameter of the glass fiber in a strain chain changes.

For this project, the SYLEX SC-01 sensor (Fig. 5) was selected and its performance was intensively tested in laboratory investigations. The temperature sensing FBG is encapsulated in one of the anchors of the sensor where it does not experience strain. The strain sensitive FBG is stretched between the anchors and protected by a plastic tube. This sensor design allows a wide adjustment range for pre-tensioning and assures sufficient mechanical protection. Furthermore, the sensor is watertight (IP68 [7]) which is important due to the high humidity within the maintenance corridors of the dam.

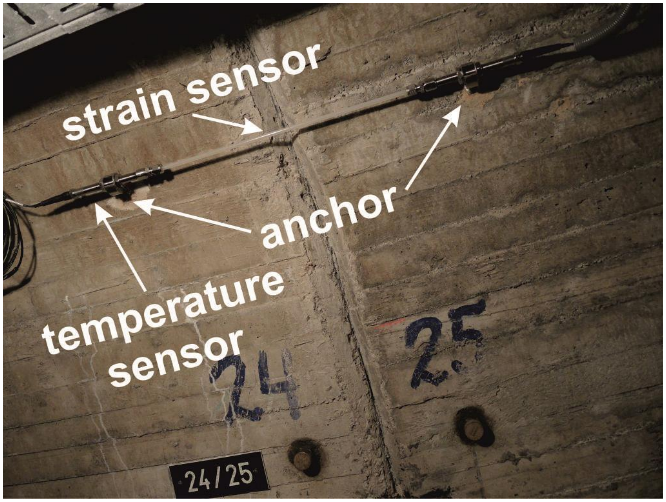

Fig. 5
Sylex SC-01 sensor [8]
Capteur Sylex SC-01 [8]

A SM130 reading unit from Micron Optics [9] was selected as measurement unit. This interrogator has a wavelength resolution of 1pm and a maximum sampling rate of 1 kHz. Furthermore, the instrument is equipped with four independent measurement channels. With a sensor free fiber length of 0.4 m and the high wavelength resolution of 1pm, the minimum strain resolution is 0.3 µm.

By using three measurement channels (A, B and C), all 30 FBGs (15 strain and 15 temperature sensors) can be measured simultaneously. A sixteenth sensor was installed as reference sensor in stable rock. This reference sensor is used to assess the long term stability of the measurement system and to detect any potential drift. Fig. 6 shows the installation plan for the first measurement chain (Chain A) with 10 FBG sensors (five strain sensors and five temperature sensors) and the reference sensor on a separate channel.

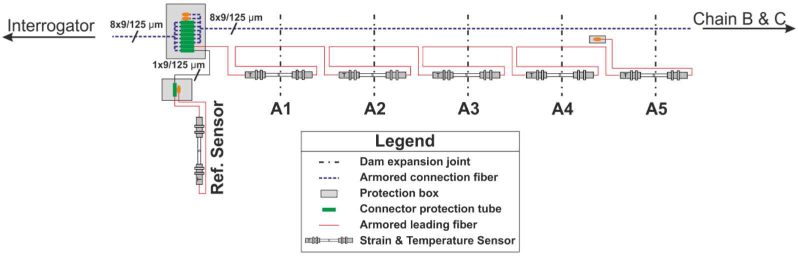

Fig. 6
Layout of sensor chain A with five SYLEX SC-01 sensors, each equipped with one strain FBG and one temperature FBG
Schéma de chaîne de capteurs A avec cinq capteurs Sylex SC-01, chacun équipé d'un FBG de dilatation et d'un FBG de température

The strain and temperature coefficients of the chosen sensors were determined on our unique fiber optic calibration facility [10]. The results of the sensor calibration as well as more details about the measurement system are reported in the publications [10], [11] and [12].

5. INSTALLATION OF THE MONITORING SYSTEM IN THE WATER DAM KOPS

The interrogation unit was positioned in the control center, about 500 m away in a building outside of the dam. For a direct comparison between the conventional measurement system and the fiber optic system, the instrumented joints were simultaneous measured with the dial gauge and the fiber optic system. For validation of the stability and further comparisons, the manual dial gauge measurements will also be continued in the future.

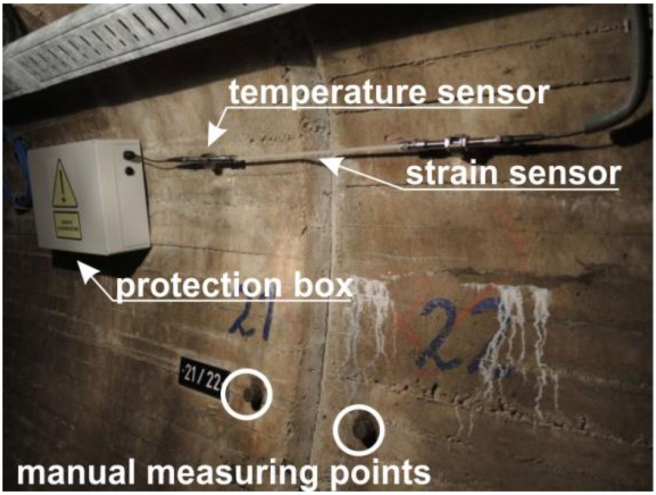

Fig. 7
Expansion joint between concrete block 21/22 with fiber optic sensor, splice protection box and dial gauge anchors
Joint de dilatation entre les blocs de béton 21/22 avec capteur à fibre optique, boîte de protection d'épissure et ancres de mesure

The installation of the fiber optic monitoring system was carried out in September 2013. In the upper maintenance corridor 15 block joints were instrumented with fiber optic strain and temperature sensors. The fiber optic sensors were installed above the dial gauge anchors as can be seen in Fig. 7. Specially designed anchors were used to connect the sensor with the concrete of the dam. After the concrete anchors were stable, the FBG sensors were mounted and pre-strained. The pre-strain value was based on the laboratory experiments and the current opening of the expansion joint.

6. MEASUREMENT RESULTS

The first continuous measurements were performed from September 2013 to November 2013. Within 48 days of permanent measurements, different sampling rates and the remote control were tested. The results of these measurements are discussed in [13]. In July 2014 a second continuous measurement campaign started. This paper focuses on the results of the second measurement campaign.

With the recorded data it was possible to validate the temperature compensation of the measured strain values. At the start and at the end of the continuous measurement periods, dial gauge measurements were carried out. Furthermore, the independent geodetic measurements of the reference sensor were performed at the same time. For comparison with dial gauge measurements, length changes, instead of strain values, are shown in all figures of this paper.

6.1. PRECISION AND STABILITY OF THE INSTALLED MEASUREMENT SYSTEM

The precision of the monitoring system can be assessed by analyzing the measurement data of the reference sensor which is installed in stable bedrock. Fig. 8 shows 60 minutes of 1Hz measurements of the temperature and strain FBG. The calculated standard deviation of the measured wavelength changes is 0.7pm for both FBGs. This corresponds to a standard deviation of the temperature measurements of 0.1K and a standard deviation of the length changes of 0.3µm at a measurement rate of 1Hz. As will be shown later this high precision enables the detection of the small length changes of the concrete joints due to the pump-storage operation.

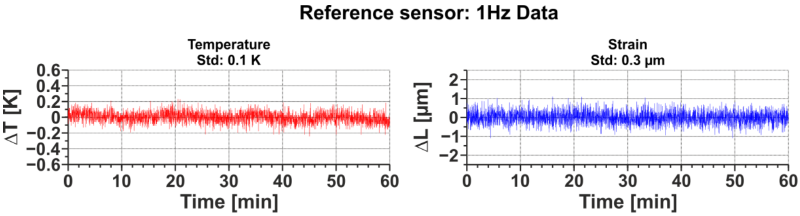

Fig. 8
60 Minutes temperature FBG (left) and strain FBG (right) signals of the stable reference sensor
Signaux 60 minutes des FBG température (à gauche) et FBG dilatation (à droite) du capteur de référence

Fig. 9 shows the length changes of the reference sensor for three discrete points in September 2013, October 2013 and July 2014. For these epochs the length changes varied in a range of 16 µm. The reference sensor is located in presumable stable rock. However, after discussions with the owner of the water dam it was found that there is possibly a crack in the rock between the sensor's anchor points. The width of this crack can vary in response to changing mountain water pressure or as a result of temperature changes of the rock. In order to verify the fibre optic measurement results, the length changes between the anchor points were also determined with geodetic methods. The resulting length changes are plotted in black in Fig. 9 together with their 95% confidence interval.

Plotted are length changes with respect to the second measurement epoch. It can be seen that the differences between the fibre optic and geodetic measurements are statistically not significant. As a consequence, it appears that the recorded length changes of the reference sensor are caused by deformations of the rock and not by drifts of the measurement system.

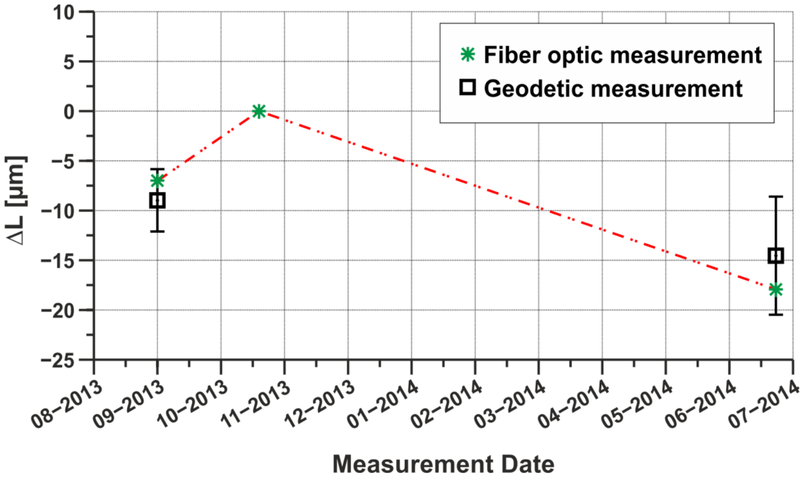

Fig. 9
Comparison between geodetic (black) and fiber optic (green) measurements
Comparaison des mesures géodésiques (noir)
et des mesures fibre optique (vert)

6.2. COMPARISON OF AUTOMATED FIBER OPTIC MEASUREMENTS WITH CONVENTIONAL MANUAL MEASUREMENTS

In this section the results of the automated concrete joint measurements are compared with the result of the conventional manual measurements. Fig. 10 displays the length changes at the time of the manual measurements of the sensors A1 to A4. In this graph all measurements are plotted with respect to the reference epoch in November 2013. The 95% confidence intervals are also displayed for length changes derived from manual measurement assuming a standard deviation of 0.02 mm (20 µm) for one individual manual measurement. As was discussed in 6.1., the precision of the fibre optic measurements is 0.3 µm. Therefore, their error bars are not visible in Fig. 10.

It can be seen that the results of both independent measurement techniques correspond well. The remaining differences are statistically not significant. The results of the measurement chains B and C are similar as the results of the sensors A1 to A4 of chain A and are therefore not displayed.

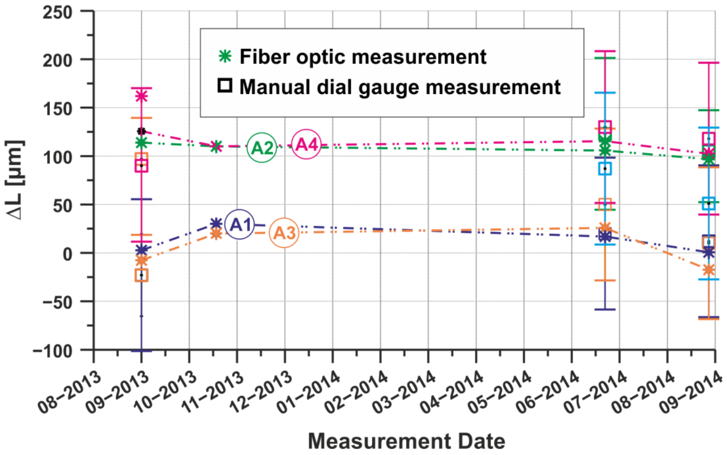

Fig. 10
Concrete joints A1 to A4: Comparison between manual and fiber optic measurements
Joints de béton A1 à A4: comparaison entre mesures manuelles et fibres optiques

Significant differences could only be found for one out of 15 sensors. At position A5 a significant jump occurred in the manual measurements between 2013 and 2014. It is assumed that the reason is a damage of one of the anchor points. This is currently investigated in greater detail.

6.3. ANALYSIS OF THE CONTINUOUS MEASUREMENT DATA

In the previous sections the high precision of the fiber optic system has been discussed. One further advantages of the developed monitoring system is the possibility to perform continuous measurements and thus the possibility to continuously assess the reaction of the water dam to changing ambient conditions.

In general the measured block joint deformations are a superposition of different effects. One of the main influences is the water storage level. Another effect is thermal deformation induced by changing ambient air temperatures. Fig. 11 shows these causative forces and the resulting deformations for 14 days in July 2014. The air temperature changes result in daily variations of block joint movements with amplitudes of approximately 4 µm to 6 µm [12] and [13].

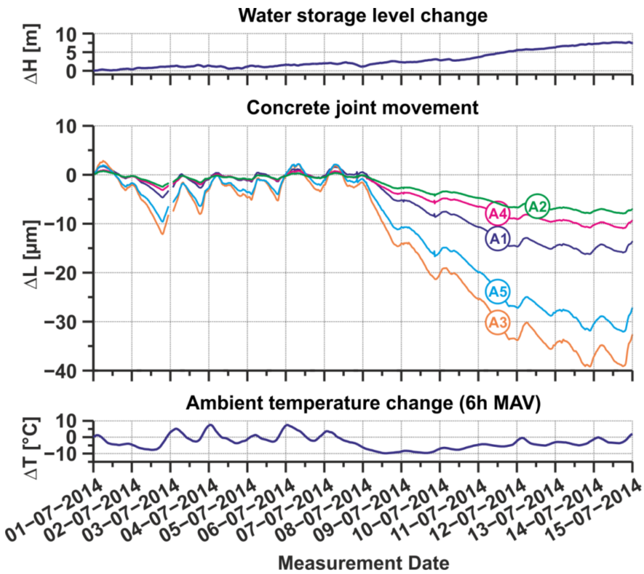

Fig. 11
Continuous measurements of water storage level (top), joint displacement (middle) and ambient temperature (bottom)
Mesures en continu de niveau d'eau (en haut), des déplacements des joints du béton (au milieu) et de température ambiante (en bas)

Displayed are 15min mean values of the block joint deformations relative to the measurements of July 1st, 2014. Also shown are the height changes (Fig. 11-top) of the water storage level which are recorded every 15 min. The ambient air temperature is also measured every 15 min. The variation of the temperature is plotted as 6h moving average values (MAV).

It can be seen that until 08.07.2014 the water level was almost constant and therefore the deformations from 01.07. to 08.07. are mainly caused by temperature changes. A cross correlation analysis revealed that the concrete joints react with a delay of about 4 to 4.5 h to a change of the ambient air temperature.

Starting with July 8th the water level was increased by several meters. As a result the concrete joints are closing. The combined reaction of the concrete joints to water level changes and air temperature changes was modelled in a least squares estimation process using a linear model. The time delay of the reaction to ambient air temperature was taking into account in this model. The resulting parameters and their standard deviations are stated in Tab. 1. It can be seen that different joints react differently to a water level change. A water level change of 1m results in a length change of only 1.11 μm of the joint A2. Such a small change can only be depicted due to the high precision of the developed fiber optic monitoring system. Within sensor chain A the joint at location A3 reacts strongest to water level changes. There a 1m water level change causes a length change of 5.5 μm.

The reaction to changes of the ambient air temperature is much smaller. A temperature change of 1K causes length changes of 0.15 μm to 0.83 μm, see Tab. 1.

Table 1
Reaction of the concrete joints of sensor chain A to water level and temperature changes

Sensor	Reaction to 1m water level change	Reaction to 1K temperature change
A1	-2.41 μm ± 0.02 μm	0.35 μm ± 0.01 μm
A2	-1.11 μm ± 0.01 μm	0.15 μm ± 0.01 μm
A3	-5.51 μm ± 0.05 μm	0.83 μm ± 0.03 μm
A4	-1.54 μm ± 0.01 μm	0.22 μm ± 0.01 μm
A5	-4.51 μm ± 0.04 μm	0.63 μm ± 0.02 μm

The estimated parameters can also be used to calculate modelled length changes based on measured water level and temperature changes. Fig. 12 displays the measured and modelled data of sensor A4. It can be seen that the modelled data fits the measured data well. The maximum differences are less than 2 μm.

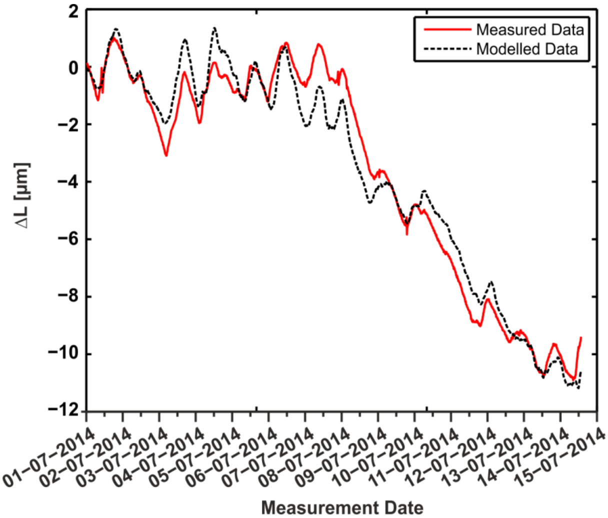

Fig. 12
Measured and modelled data of sensor A4
Données mesurées et modélisées du capteur A4

A detailed investigation of the temperature influenced movements and their time delay with respect to the ambient air temperature are part of future studies, which will be performed when data over a longer period are available.

7. CONCLUSION

In this paper a new method for the continuous concrete joint monitoring of water dams was presented. The monitoring system is based on quasi-distributed fiber optic sensors and has several advantages compared to conventional manual measurements. Compared to automatic measurement techniques based on electric sensors, fiber optic sensors are electromagnetic immune and only need a small amount of cabling.

The monitoring system is fully automated and thus manual measurement errors can be avoided. Furthermore, measurements can be made continuously. Therefore, a change of the deformation behavior of the dam can be detected immediately. Furthermore, there is no need to access the water dam for performing the concrete joint measurements. The reading unit can be placed several hundred meters or even kilometers away from the sensor position. This is important in areas with high security requirements. At the water dam Kops the reading unit is placed 500 m away from the sensor position in a building outside of the dam.

In our research installation only three fiber optic cables are needed to monitor 15 concrete joints. All sensors are still fully operational after one year of operation and no drift occurred. A first analysis of the data proofs that the reaction of the dam to small water level changes of less than 1 m can be detected reliably. Furthermore, the joint deformations caused by daily temperature variations are measurable.

ACKNOWLEDGEMENTS

We want to thank Vorarlberger Illwerke AG, especially Dipl.-Ing. Peter Staubmann, Dipl.-Ing. Rupert Zischinsky and Dr.-Ing. Ralf Laufer for the possibility to realize this research project and for their support during the installation of the sensors.

REFERENCES

[1] AUSTRIAN COMISSION ON LARGE DAMS, Dams in Austria: *Series “Die Talsperren Österreichs”,* 1991, Nr. 32. 333 p.

[2] VORARLBERGER ILLWERKE AG. Kopssee-Technische Daten. *http://www.Illwerke.at/inhalt/at/380.htm, 2014*

[3] INAUDI D. Overview of fiber optic sensing technologies for structural health monitoring. *Proc. 46th International Conference on Microelectronics, Devices and Materials*, Radenci, Slovenia, 2010, 10 p.

[4] INAUDI D., CHURCH J. Paradigm shifts in monitoring levees and earthen dams: Distributed fiber optic monitoring systems. *Proc. 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure,* 2013

[5] HABEL W.R., KREBBER K. Fiber-Optic Sensor Applications in Civil and Geotechnical Engineering. *Photonic Sensors,* 2011, Volume 1, No. 3, pp. 268-280

[6] OTHONOS, KALLI K. Fiber Bragg Gratings, Fundamentals and Applications in Telecommunications and Sensing. 1999, Artech House Publishers; Boston, USA

[7] IEC 60529:1989+A1:1990: Schutzarten durch Gehäuse (IP-Code); Deutsche Fassung EN 60529:1991+A1:2000*, Deutsches Institut für Normung Std.*

[8] SYLEX FIBER OPTICS, SC-01 Strain cable. *http://www.sylex.sk/sensing-systems/sensors/sc-01nbspnbspnbspstrain-cable/*, *2014*

[9] MICRON OPTICS, INC, Micron Optics sm130 datasheet. *http://www.micronoptics.com/uploads/library/documents/datasheets/instruments/Micron_Optics_sm130.pdf,* 2014

[10] PRESL R. Entwicklung eines automatisierten Messsystems zur Charakterisierung faseroptischer Dehnungssensoren. *Master thesis,* 2009, FH Oberösterreich

[11] WOSCHITZ H., LIENHART W., KLUG F. Fibre optic monitoring system for the determination of segment joint movements inside a hydro power dam. *Proc. SPIE,* 2014, Volume 9157, 4 p.

[12] LIENHART W., WOSCHITZ H., KLUG F. Faseroptische Überwachung von Blockfugenbewegungen einer Talsperre. *Proc. 17. Int. Ingenieurvermessungskurs, ETH Zürich,* 2014, pp. 371-380

[13] KLUG F., LIENHART W., WOSCHITZ H. High resolution monitoring of expansion joints of a concrete arch dam using fiber optic sensors, *Proc. 6th World Conference of the International Association for Structural Control and Monitoring,* 2014, pp. 3164-3176

SUMMARY

In this paper a new method for continuous concrete joint monitoring is introduced. The biggest advantages with respect to conventional electric sensor systems are the lower installation costs and the better measurement precision.

The developed monitoring system is based on quasi-distributed fiber optic sensors and was installed for the first time in a concrete arch dam in Austria in 2013. Data acquired in the first year of operation proofs that small water level changes caused by the pump-storage operation can be depicted reliably. A water level change of 1m results in length changes of several µm depending on the location of the concrete joint. Daily temperature induced deformations can also be measured due to the high precision of 0.3 µm of the monitoring system.

The developed monitoring system can be the basis for modern structural monitoring of concrete dams with pump-storage operation. The high measurement resolution gives new insights into the structural behavior of dams and can potentially improve the design of new dams.

RÉSUMÉ

Dans ce rapport, une nouvelle méthode de contrôle continu des joints de béton d'un barrage est présentée. Les principaux avantages par rapport aux

systèmes de capteurs électriques conventionnels tiennent dans les faibles coûts d'installation mais aussi dans une meilleure précision des mesures.

Le système de contrôle développé est basé sur des capteurs optiques également repartis et fut installé pour la première fois sur un barrage-voûte autrichien en 2003. Les premières données acquises ont montré qu'une représentation fiable de petites variations de niveau d'eau causées par les actions de pompage-turbinage était possible. Un changement du niveau d'eau de 1m provoque en effet une variation de longueur de plusieurs µm en fonction de la localisation du raccord en béton. De plus, la grande précision du système de contrôle (0,3 µm) permet de mesurer les déformations induites par les changements quotidiens de température.

Le système de contrôle développé peut ainsi servir de base pour la surveillance structurale des barrages en béton avec opération de pompage-turbinage. La haute résolution des mesures donne un nouvel éclairage sur le comportement des structures de barrages, permettant potentiellement d'améliorer les futures conceptions.