Continuous Monitoring of a Large Concrete Arch Dam Using Fibre Bragg Grating Sensors

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Abstract

Conventional structural monitoring systems of water dams consist of geotechnical and geodetic measurements and are optimized to depict deformations due to seasonal temperature changes and due to slow water level changes of the reservoir.
In this paper we report about the development of a new monitoring system for the continuous and high resolution monitoring of expansion joints of concrete arch dams in pump-storage operation. The developed system was installed in autumn 2013 in a 122 m high concrete arch dam in Austria with a crest length of 614 m. Fifteen expansion joints of one inspection corridor were equipped with fibre bragg grating (FBG) sensors. We report about the installation and the monitoring results and demonstrate that the impact of small water level changes can be depicted reliably.
The developed monitoring system is the basis for modern structural monitoring of concrete arch dams with pump-storage operation. The high measurement resolution gives new insight into the structural behaviour of dams and can potentially improve the design of new dams.

1. Introduction

Water power plants are an important source of sustainable energy. In Austria more than 50% of the power production is based on water power plants. Within the last years many of the large Austrian hydroelectric power plants were modified to pump-storage plants where the same water is used several times, see Fig. 1. Such an upgrade is a significant financial investment but also offers the benefits of:

- Increased profitability: At times of high energy prices power can be produced and at times of low energy prices the already used water can be pumped up from a collecting basin back to the reservoir at higher altitude.
- Storage of electric energy: Hydroelectric power plans are the only way to efficiently store electric energy. The upper reservoir can be seen as giant battery which is charged by pumping water from lower altitude to higher altitude.
- Power grid stabilization: The increased production of renewable energy from wind turbines and photovoltaic plants causes instabilities in the electric grid which can potentially result in blackouts. Pump-storage power plants are needed to stabilize the electric grid by consuming power during spikes in the production (at times of intense solar radiation or strong wind) and by power production in case of sudden peaks in the power demand. Modern pump storage power plants can switch from 100% power production to 100% power consumption (pump mode) within a few seconds.

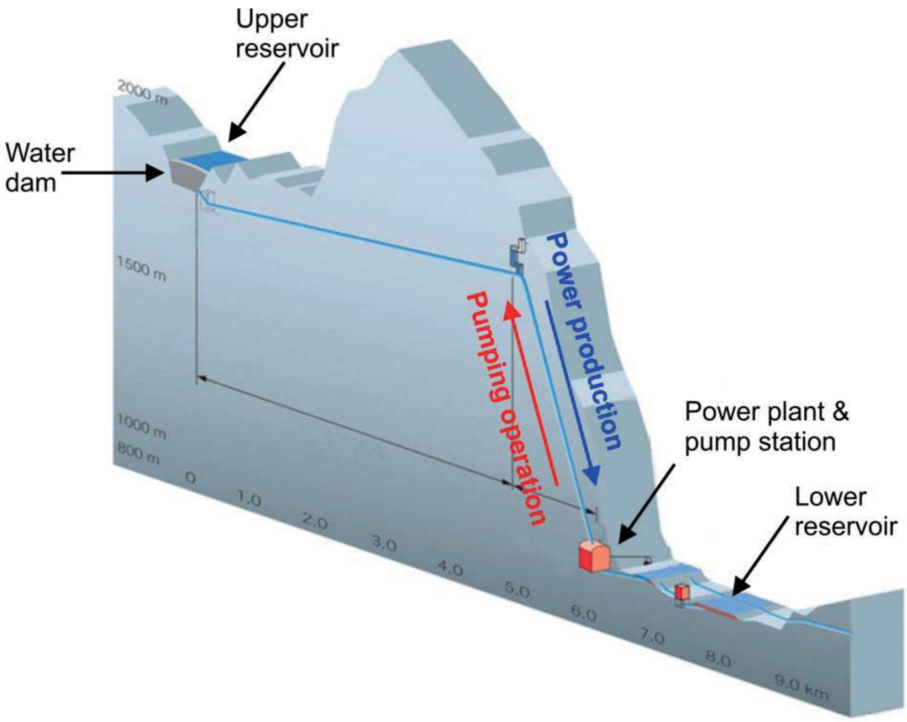

Fig. 1: Components of a hydroelectric pump-storage power plant (after Illwerke, 2014)

Austria's large water dams are owned by energy companies like VERBUND, VIW (Vorarlberger Illwerke AG), TIWAG (Tiroler Wasserkraft AG) or by ÖBB (Austrian Federal Railways). The goals of these operators are to optimize efficiency and profitability of the power plants but also to guarantee the safety of the structures.

2. Conventional Concrete Joint Monitoring

The International Commission on Large Dams (ICOLD) defines large dams as higher than 15 m (ICOLD, 2011, p. 3). According to this classification more than 160 dams in Austria are large dams. 30 of these dams are higher than 50 m. The largest dams in Austria are usually arch dams which are built with reinforced concrete in vertically aligned blocks, see Fig. 2.

Fig. 2: Vertically aligned concrete joints of arch dam Kops (maximum height 122 m)

The individual concrete points are connected by joints which are significant parameters for the monitoring of the behaviour of a dam (ICOLD, 2012, p. 16). The concrete joints immediately react to water level changes of the reservoir and to changes of the concrete temperature. This is especially important for gravity dams. In the traditional reservoir operation the water level changes slowly with a yearly cycle. Conventional monitoring approaches detect the resulting deformations by manual dial gauges measurements within the maintenance corridors of the dam (Fig. 3).

Fig. 3: Maintenance corridor (left), reference points (centre, white circles), manual concrete joint measurements (right)

These measurements are labour intensive and only quarterly performed. Therefore, only one measurement value is available every three months. Furthermore, like with all manual measurements, reading errors are possible.
As a consequence the current measurement concepts are best suited for the traditional storage operation but not for the pump-storage mode where the number of load cycles of the dam is significantly increased. A pump-storage power plant switches up to several times a day between power production and pumping of water. In order to obtain a better understanding of the dam behaviour in this new operation type new measurement solutions are needed which fulfil the requirements of:

- Continuous and automated operation (no data gaps, no personnel needed)
- Electromagnetic immunity (no signal distortion in the vicinity of electromagnetic fields)
- Low installation effort (minimum cabling)
- No power supply within the dam (increased safety)
- No access needed to perform measurements (no security issues)
- High sensitivity (capable to depict deformations due to pump-storage operation)
- High robustness in harsh environment (no failure due to high humidity or large temperature differences)
- High long term stability (no drifts or data jumps in decades)

3. Fibre Optic Monitoring Concept

The idea in this project was to use fibre optic cables as sensing elements since light transmission intrinsically fulfils many of the requirements like electromagnetic immunity.

Fibre optic sensors (FOS) are used already for leakage detection in water dams (see for instance Inaudi, 2010, Inaudi and Church, 2013 or Habel and Krebber, 2011). We selected Fibre Bragg grating (FBG) sensors as sensitive elements. FBG sensors belong to quasi-distributed sensors because several sensitive elements can be placed on a single fibre. This significantly reduces the required number of cables and measurement channels.
FBG sensors are created through a periodic change (Λ_G) of the refractive index (n_G) of the core of a glass fibre. When light from a broadband light source is coupled into the fibre, light with the Bragg wavelength ($\lambda_G = 2n\Lambda_G$) gets reflected at the position of the grating. This reflected signal can be measured with an optical spectrometer. When the length of the FBG changes, the spacing of the grid changes and thus the reflected wavelength shifts, see Fig. 4. This wavelength shift ($\Delta\lambda$) can be measured and converted into length changes.

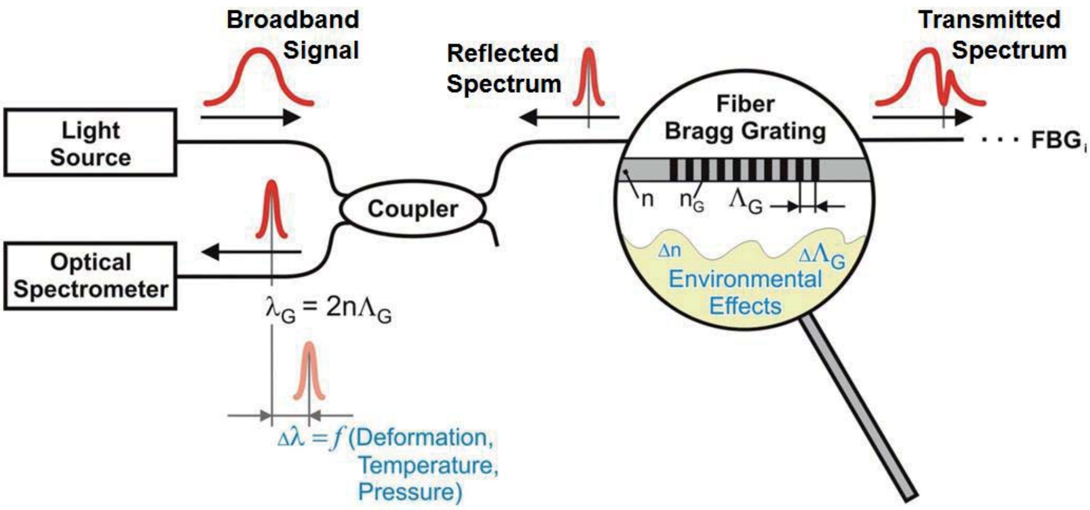

Fig. 4: Principle of FBG measurements

Several FBG sensors can be placed along the same fibre as long as the wavelengths of the gratings do not overlap. FBG sensors have been successfully used for the monitoring of structures like bridges, ships, spacecraft and airplanes but were not applied yet to the measurement of concrete joint deformations of water dams due to the following reasons:

- Standard recoated FBG sensors cannot withstand the large joint deformations and break
- The relation between wavelength shift and length change is not known with sufficient accuracy. Therefore the sensors cannot be used for safety critical applications
- The long term stability cannot be guaranteed which makes the sensors not suitable for long term installations
- Some suppliers provide FBG sensors only with a small selection of different wavelengths. These wavelengths may overlap taking into account the expected deformation pattern of a water dam. As a result, the signals of individual expansion joints cannot be separated.
- The attenuation of standard FBG sensors is too high to cover long fibre lengths which are needed for large structures like water dams.

4. Development

In our measurement concept we solve these problems by using several approaches. Firstly, draw tower gratings are used, where the grating is written into the fibre directly during the fibre production and therefore the robustness of the glass fibre is not reduced. Secondly, a unique fibre optic calibration facility was developed to accurately determine the relation between wavelength shifts and length changes (Woschitz et al., 2014). Thirdly, the developed sensor layout also includes a reference sensor in stable bedrock which can be used to determine the long term stability and if required can be used to correct sensor drifts. Finally, to avoid overlapping wavelengths and to enable long distances, each sensors was produced with an individual base wavelength and where possible fusion splices where used instead of mechanical connectors.

4.1 Sensor Chain Layout

Based on these approaches a detailed measurement concept was developed for 15 concrete joints in one of the maintenance corridors of the water dam Kops, Austria. The measurement chain was split up into three individual chains A, B, and C. An overview and a detailed layout of chain A can be seen in Fig. 5. The interrogator (light source and spectrum analyser) is placed approximately 500 m from the sensor positions in the inspection building of the water dam.

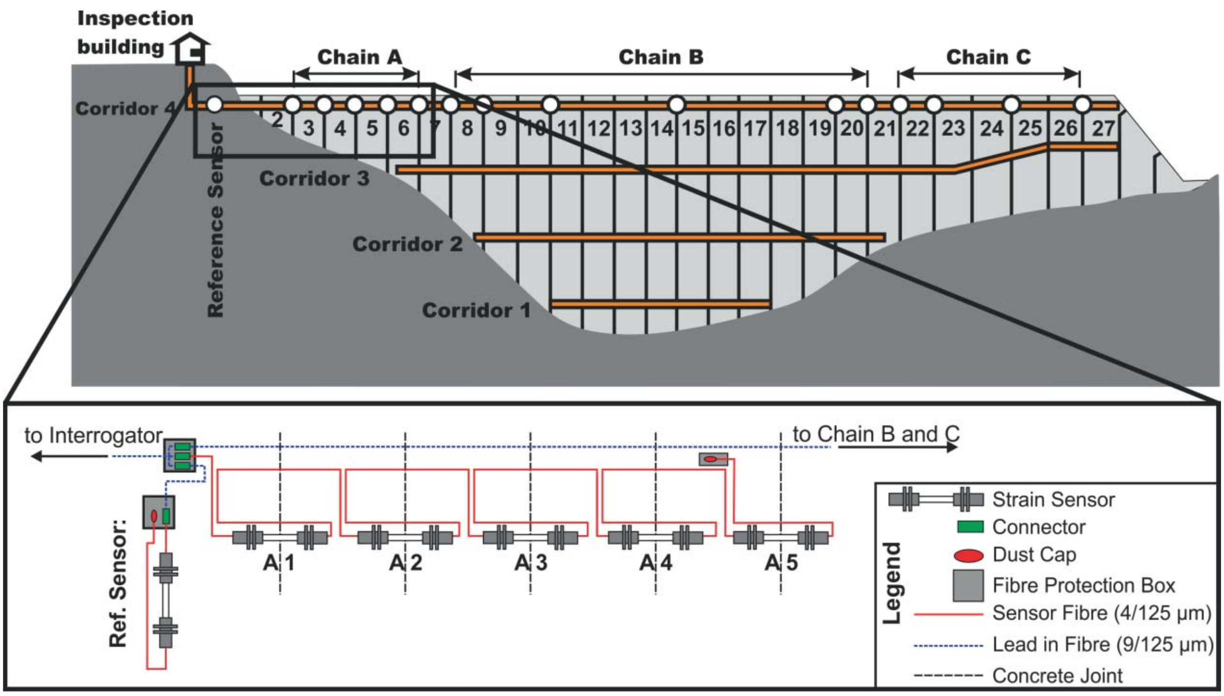

Fig. 5: Fibre optic monitoring layout within water dam Kops

FBG sensors are sensitive to length changes (also denoted as strain $\varepsilon = \Delta L/L$) and temperature changes. For accurate measurements of length changes the temperature impact has to be compensated. We therefore selected SYLEX SC-01 sensors which include a second FBG that is encapsulated and does only experience temperature changes (Fig. 6). This second FBG can be used to correct the temperature impact of the strain FBG.

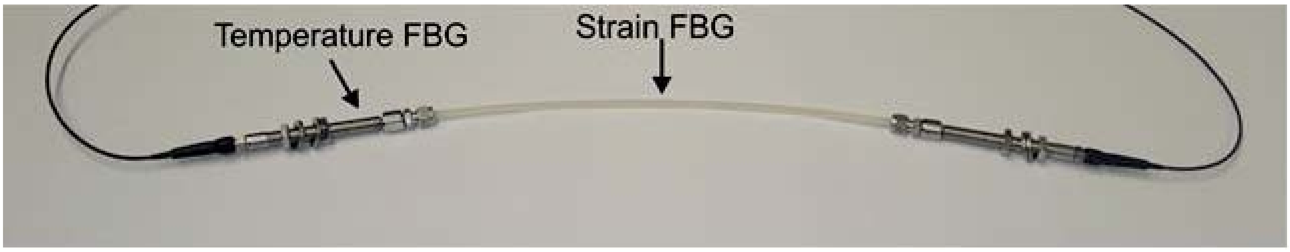

Fig. 6: SYLEX SC-01 strain sensor with additional FBG for temperature compensation

Part of the system development was to develop software which prepares the raw measurement data for further use in the control software of Vorarlberger Illwerke AG. The developed software automatically performs temperature compensation of the strain measurements and applies the calibration functions to convert wavelength shifts into length changes.

4.2 Installation

The measurement system was installed in the water dam Kops in autumn 2013. As can be seen in Fig. 7-left the fibre optic sensors were placed in the vicinity of the manual measurement points in order to enable a comparison between both measurement systems. Fig. 7-right displays the control panel of the fibre optic monitoring system with all strain and temperature data.

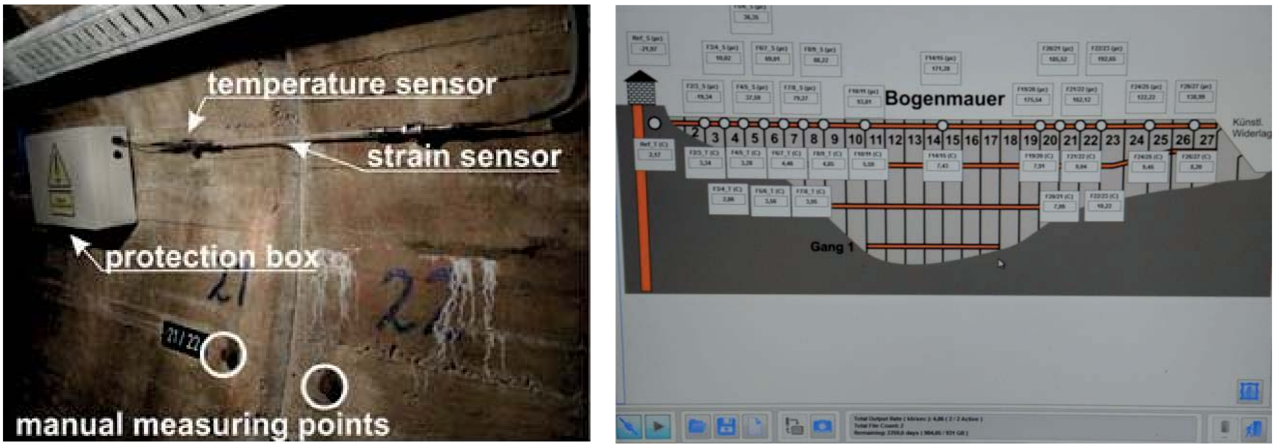

Fig. 7: Installed fibre optic sensor (left), control panel of developed monitoring system (right)

4.3 Performance Verification

The precision of the monitoring system can be assessed by analysing the measurement data of the reference sensor which is installed in stable bedrock. Fig. 8 shows 60 minutes of measurements of the temperature and strain FBG taken with a sampling rate of 1 Hz. The raw measurement values (wavelength changes) are already converted into temperature and length changes. The standard deviation of the data series is 0.1 K for the temperature measurements and 0.3 µm (300 nanometre) for the measurement of length changes. As will be shown in the next section it is possible to monitor concrete joint deformation of water dams only because of the high precision of the developed monitoring system.

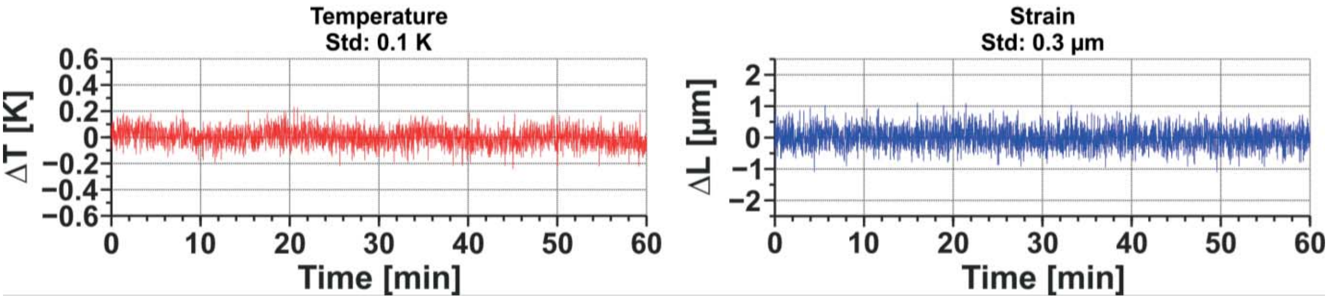

Fig. 8: 60 minutes of measurement data of the reference sensor collected on July 8th 2014

5. Operational Phase

The developed monitoring system is now in its operational phase. As was initially stated the goal of this project was to develop a monitoring system which is capable to measure the concrete joint deformations in pump-storage operation. Fig. 9 shows a typical data series of the continuously operating system. During the displayed 14 days the water storage level was kept almost constant and increased only by a few metres (Fig. 9-top). Within this time frame the ambient temperature varied in a range of 20°C (Fig. 9-bottom).

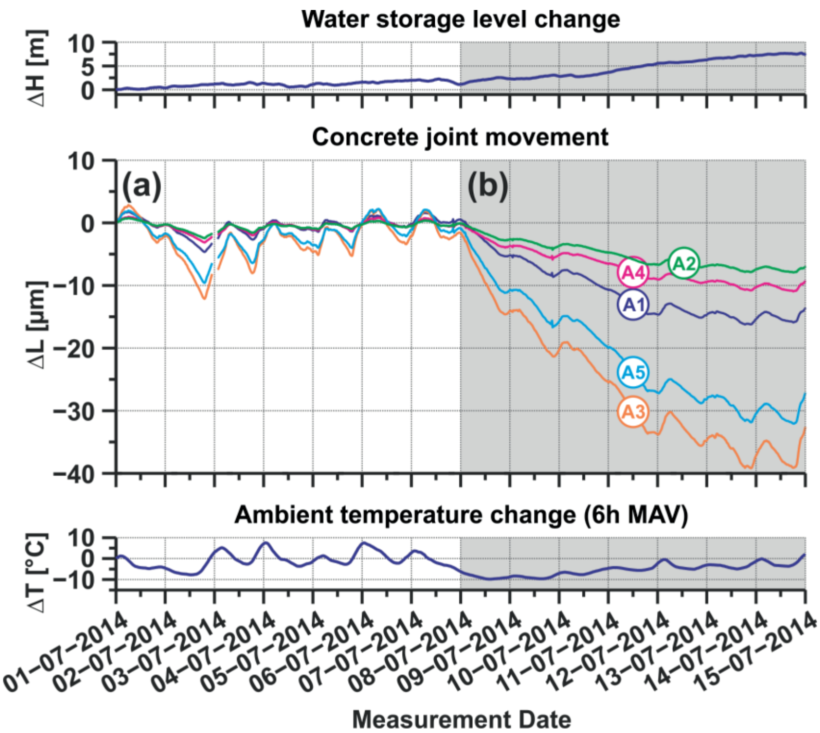

Fig. 9: Continuous measurements of water level (top), deformations (centre) and air temperature (bottom)

During the first seven days of the displayed data series the water level is almost constant. Therefore the concrete joint deformations are mainly caused by the cyclic daily temperature variations Fig. 9-a. Starting with July 8th the water level was increased by several meters. As a result the concrete joints are closing (Fig. 9-b). This reaction is stronger than the reaction to temperature change. It can also be seen that the same water level rise causes deformations of different size for different joints. This can be investigated in greater detail by a least squares estimation. In our case the combined reaction of the concrete joints to water level changes and air temperature changes was modelled by a linear model where the time delay of the reaction to ambient air temperature has been taken into account. The resulting parameters and their standard deviations are stated in Tab. 1. It can be seen a water level change of 1 m 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 fibre optic monitoring system. Within sensor chain A the joint at location A3 reacts strongest to water level changes. There a 1 m water level change causes a length change of 5.5 µm. As already stated, the reaction to changes of the ambient air temperature is much smaller. A temperature change of 1 K causes length changes of 0.15 µm to 0.83 µm.

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

Sensor	Reaction to 1 m water level change	Reaction to 1°K 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. 10 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.

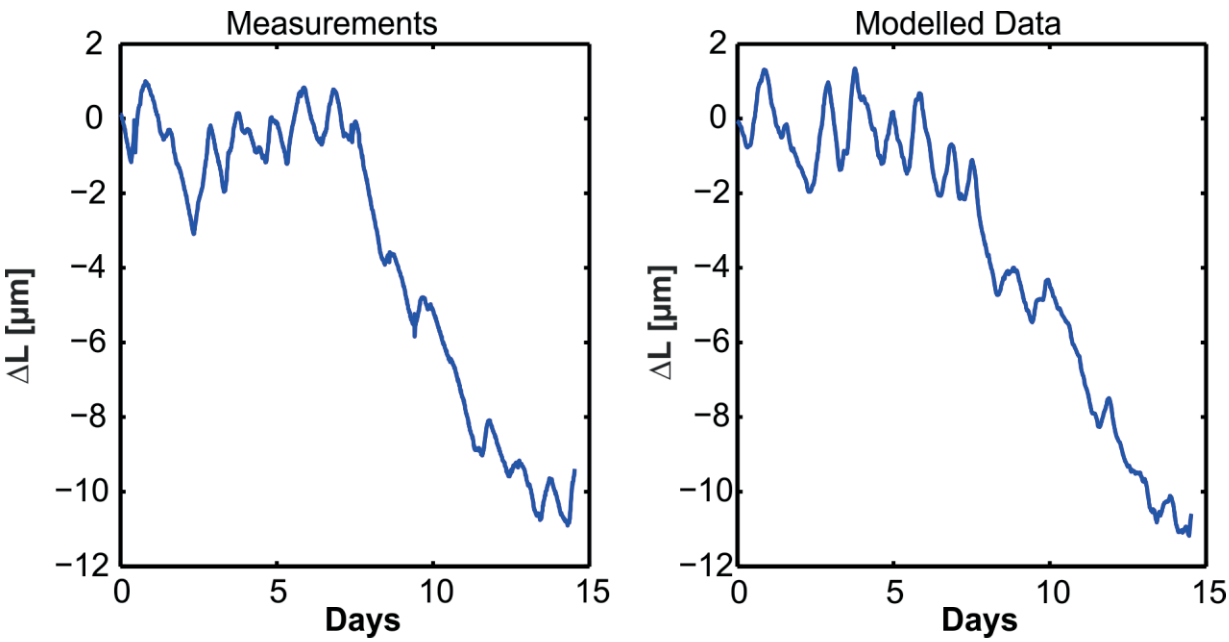

Fig. 10: Measurements (left) and modelled data (right) of sensor A4

A longer time series of about four months is shown in Fig. 11. It can be seen that in this time frame the water level was increased by 16.5 m and afterwards reduced to almost the initial amount. The same cycle is also visible in the joint deformations which closed between -95 µm (A3) and -19 µm (A2). The data gaps of in Fig. 11-right are caused by an instable data communication to the remote water dam and not by malfunctioning sensors. More than one year after installation all sensors are still fully operational and no drifts have been observed. Additional results of the long term monitoring can be found in Klug et al. (2014).

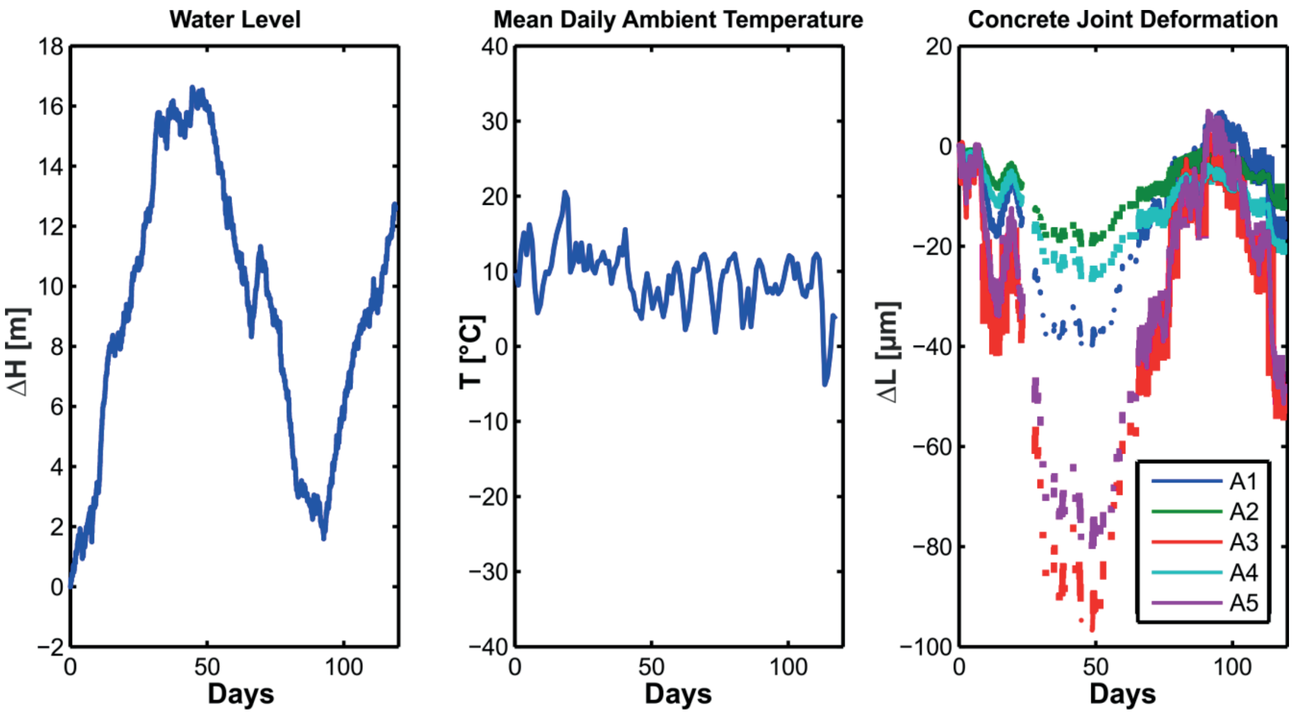

Fig. 11: Continuous measurement data from 30.06 to 27.10.2014: water level (left), air temperature (middle) and joint deformations (right)

6. Conclusions

In this paper we presented a new method for the continuous concrete joint monitoring of water dams based on quasi-distributed fibre optic sensors. 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 behaviour of the dam can be detected immediately. Furthermore, there is no need to access the water dam for performing the concrete joint measurements.

When installing an FBG monitoring systems in water dams special measures are needed in order to fulfil the high requirements of water dam monitoring with respect to accuracy, long term stability and robustness. Crucial are an accurate calibration of the sensors and setups to verify the long term stability. We therefore calibrated all sensors individually and installed a reference sensor on site in stable bedrock.

We proved in our research installation that the reaction of an arch dam to small water level changes of less than 1 m can be detected reliably. Furthermore, we demonstrated that joint deformations caused by daily temperature variations are also 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.

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