Distributed fiber optic temperature measurements in embankment dams with central core – new benchmark for seepage monitoring

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ABSTRACT: The Knezovo Dam is located in the upper stream of the Zletovica River, about 80 km east of the Macedonian capital Skopje. It is the main element of the Zletovica Basin Water Utilization Improvement Project, with the purpose of water supply, irrigation and power generation. The Knezovo Dam is an asphalt core rockfill dam with a maximum height of 82 m, a crest length of 270 m and a total dam embankment volume of 1,700,000 m^3. The effective storage capacity is 22,500,000 m^3. The instrumentation of the dam comprises among others piezometers, total pressure cells and extensometers. For leakage monitoring a leakage detection system based on fiber optic temperature measurements is installed directly downstream of the asphalt core. The paper deals with the measurement technique and design aspects of the leakage detection system. Furthermore results of laboratory tests are presented that prove the applicability of the monitoring system in the central part of embankment dams.

1 INTRODUCTION

Distributed fiber optic temperature (DFOT) measurements are employed in several embankment dams to detect and localize leakage. The method has been successfully used during the last 15 years, and has continuously improved with regard to both monitoring and evaluation. The key feature of DFOT measurements is that the fiber optic cable is the sensor and the temperature can be measured along the entire length of the cable. For existing dams installations of the fiber optic cable in the dam toe, below a refurbished surface sealing or in existent standpipes, are the most common applications (Aufleger et al. 2007, Johansson and Sjödahl, 2007). During the construction of new dams the cable can be installed at locations where monitoring will be most useful. So far the typical application has been the monitoring of the perimetric joint of embankment dams with surface sealing (Aufleger et al. 2005). For these applications the fiber optic cable is largely protected against mechanical loading due to deformation and stress in the dam. However, the monitoring system presented in this paper uses fiber optic cables installed in the D/S filter of a dam with central core to detect outflow areas. It is expected that the cables will be exposed to tensile forces and lateral pressure due to the deformations and the stresses in the dam. To evaluate the influence of deformations and stresses on the results of DFOT measurements, laboratory tests have been carried out in which realistic loads on the cable have been simulated. In the following conducted laboratory tests and their results are discussed and the design aspects of the leakage detection system as well as measuring results are presented.

2 LEAKAGE DETECTION USING TEMPERATURE MEASUREMENTS

The technology of distributed fiber optic temperature sensing offers the possibility to measure the temperature along fiber optical cables of a few kilometer length continuously with high accuracy. This technique possesses compared to conventional measuring methods a much higher information density and improves therefore considerably the evaluation of the temperature distribution in large structures. The method is based on the fact that the optical properties of the fiber are dependent on the ambient temperature. A highly developed measuring technique enables the analysis and evaluation of property changes with the result of a reliable temperature distribution along the fiber (Dakin et al. 1985).

In embankment dams and their foundation, the internal temperature field is dependent of the flow field. Temperature gradients can exist in the form of permanent or seasonal temperature differences, or in the form of significant temperature fluctuations at the probable source of seepage. If leakage is present, temperature anomalies will be transported into the structure by means of convection and will propagate throughout the earthen body, distorting the temperature field. Distributed measurements allow for a precise localization of the anomaly, delimiting quite precisely the area affected by leakage. The substantial prerequisite for leakage detection using absolute temperature measurements is a temperature difference between the reservoir water and the dam material.

The second approach to interpret temperature measurements is the active method or heat pulse method. The method is based on the thermal response of the cables surrounding to the additional heat and can indicate whether the cable is within a moist, a partially saturated or fully saturated medium, and whether seepage flow is present or not (Perzlmaier 2007). Originally the active method was developed for applications where absolute temperature measurements were meaningless, which is the case if there are neither sufficient temperature gradients between reservoir water and location of temperature measurement (e.g. under facings) nor adequate seasonal temperature variations of the reservoir water.

By applying an electrical voltage to the electric conductors integrated in a hybrid fiber optic cable, the cable is heated up. The temperature increase depends on the thermal capacity and conductivity of the surrounding material (Fig. 1). In case of seepage water the conductive heat transport is superposed by the more effective convective heat transport. Thus, the heat input from the cable is transported away more quickly. Consequently, these sections show distinct anomalies in the temperature increase. Typically the analysis of the measurement data includes the evaluation of the temperature difference between the heated stage and a reference stage before heating.

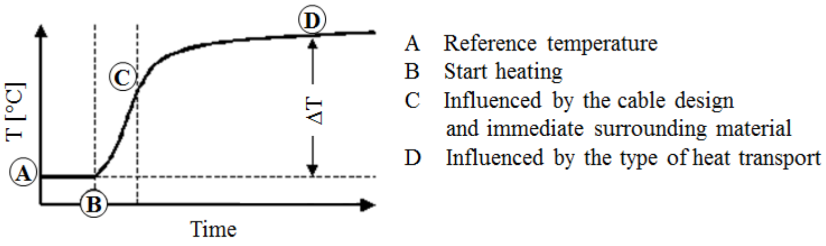


Figure 1. Temperature development inside the cable

3 LABORATORY TESTS

3.1 *General*

DFOT measurements provide a wide range of application for monitoring technical structures. In particular, the possibility of distributed monitoring of sealing elements and joints is of importance for hydraulic structures. Depending on the application and type of structure, the conditions to which the cable is exposed vary considerably. For example, a fiber optic cable which is placed in the central part of a dam (Fig. 2, left) to monitor the sealing core is exposed to greater load caused by deformation of the dam and overburden pressure, than a cable placed underneath a surface sealing (Fig. 2, right).

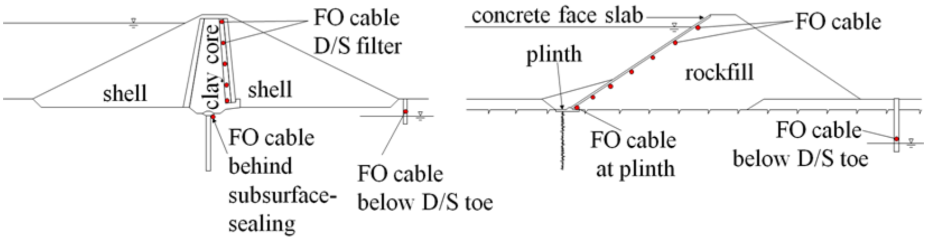


Figure 2. Application of DFOT measurements in embankment dams ECRD (left), CFRD (right)

In general ordinary fiber optic cables as used for telecommunication purposes are used for DFOT measurements. However, the specifications of these cables, which are based on standardized testing methods, give only limited information regarding applicability of the cables for installation in embankment dams. Furthermore, there was no experience from similar projects so far, how the results of DFOT measurements are affected if the cable is exposed to loads caused by overburden pressure and settlement. Therefore, to ensure the applicability of the proposed leakage detection system for embankment dams with central core laboratory tests were carried out at the University of Innsbruck. In several test series installation conditions and expected loads due to overburden pressure were simulated.

3.2 *Description of laboratory tests*

The laboratory tests for determination of the effects of pressure perpendicular to the cable axis on the results of DFOT measurements were carried out using the testing facility shown in Figure 3. The cable is installed in a 3.78 m long, 0.6 m wide and 0.6 m high reinforced steel box using different bedding materials. The load was applied forced-controlled using a fatigue testing machine with a capacity of 1,600 kN. This guaranteed constant loading during the different load steps. Different plungers were available for indirect loading.

In addition to the DFOT measurements, conventional temperature sensors (PT 100) were used. With the sensors the temperature in the steel box and the air temperature were recorded for the duration of the tests. Thus it was possible to check if the thermal boundary conditions remained constant. If changes in the ambient temperature occurred it was possible to consider their influence for the evaluation of the DFOT measurement data.

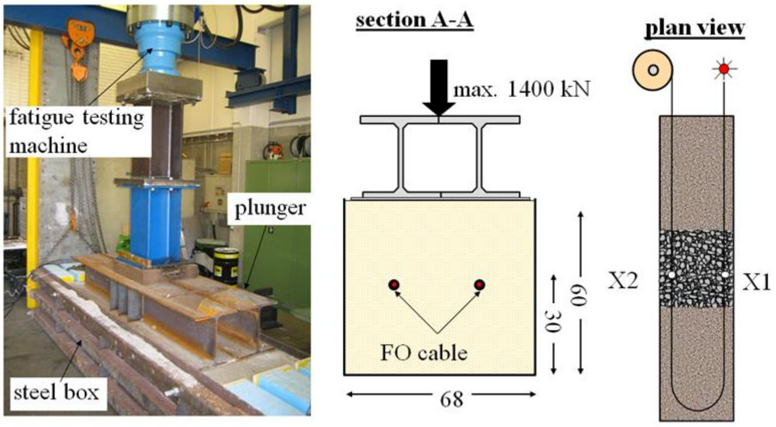
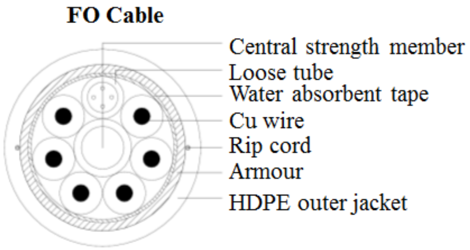


Figure 3. Setup for laboratory tests

After installation of the cable in the soil material it took a certain time until stationary thermal conditions were reached which were necessary to start the tests. Before applying the load, reference measurements were conducted for about 10 minutes. The load was applied in load steps of 125 kN. Each load step took 6 minutes. After completion of the final load step the sample was unloaded.

3.3 *Performed tests*

The tests were carried out with a standard hybrid cable as shown in Figure 4. For the tests sand, gravel and sand-gravel mixes were used as bedding materials. To investigate the influence of particle shape both natural and processed material were used. The grading curves of the soils used as bedding material are shown in Figure 5.



Manu-facturer	D [mm]	No. of conductors	Material	Cross section [mm^2]	No. of fibres	Remark
Leoni	12.9	6	CU	6 x 1.5	4	Strength member

Figure 4. Fiber optic cable used for laboratory tests

3.4 *Results of the laboratory tests*

The evaluation of the results mainly focused on the measuring points just below the stamp. To determine the influence of pressure perpendicular to the cable axis on the DFOT measurement data, the temperature difference between the reference temperature measured in the unloaded state and the temperature measured in the loaded state was calculated and plotted against the applied load. Changes of the thermal boundary conditions during the tests were considered by means of the temperature data obtained from the conventional temperature sensors. Figure 6 exemplarily shows the results of the DFOT measurement depending on the applied load perpendicular to the cable axis.

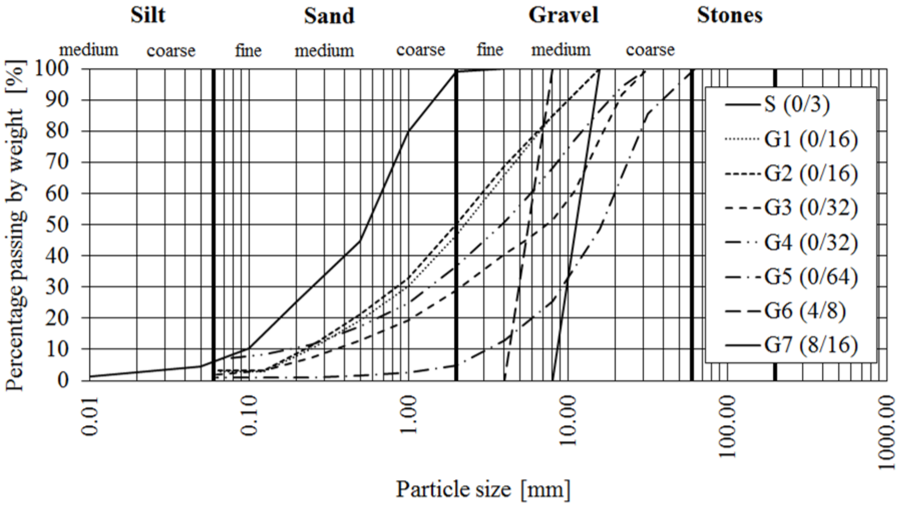


Figure 5. Grading curves of the soils used as bedding material

Because of the used bedding material in test P-7-B, which is a processed sand gravel mix 0/16, the temperature results are not affected by the applied load. In contrast, the results of the DFOT measurements for test P-10-B, which uses a uniform natural gravel 8/16, are affected significantly by the applied load.

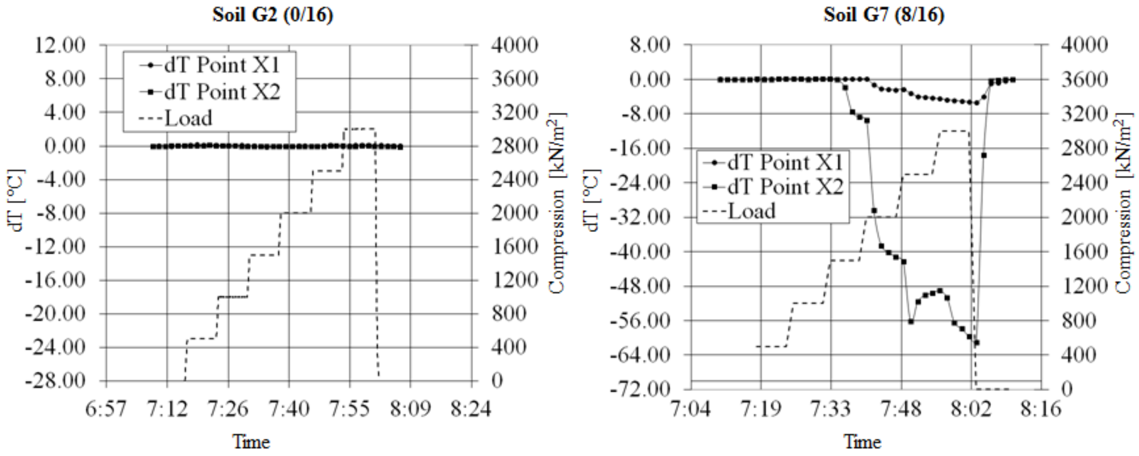


Figure 6. Results of laboratory tests for investigation of influence of lateral pressure

Primarily the experiments provide knowledge of the maximum admissible load for a specific cable depending on the bedding material used. For the different test series bedding materials with a maximum particle size between 3 mm (S 0/3) and 64 mm (G5 0/64) were used. The test results show the influence of the maximum particle size of the bedding material. The decrease of the maximum permissible load without causing temperature anomalies for bedding materials with larger particle sizes was recognized.

The results of the laboratory tests show that pressure perpendicular to the cable axis can have significant influence on the measuring results of DFOT monitoring. In Figure 7 the maximum load without affecting the measurement results is plotted against the maximum particle size of the bedding material for the tested cable. Based on the results it is recommended to limit the maximum particle size of the bedding material to 16 mm and to use well graded material. Whilst bearing these recommendations in mind installation of fiber optic cable in dams with a height of up to 85 m should not cause problems regarding the reliability and accuracy of the measurements. As a result of the applied loads in some tests damages to the cable sheath occurred and high optical losses led to distortion of the measurement data. However, the applied loads did not cause the rupture of the optical fiber in any of the tests. By analyzing both, the raw data (optical losses) and the temperature data, temperature anomalies caused by mechanical loading can be detected.

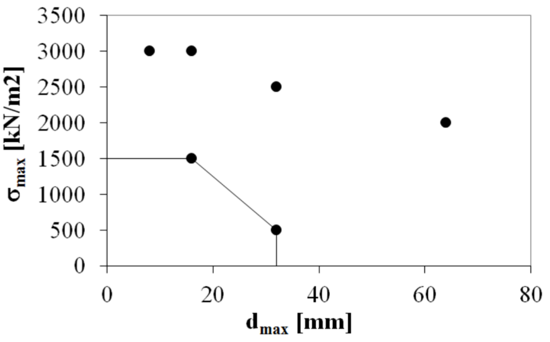


Figure 7. Maximum load without influencing the measurement results

4 KNEZOVO DAM

4.1 *Project description*

The Knezovo Dam is located in the upper stream of the Zletovica River, about 80 km east of the Macedonian capital Skopje. It is the main element of the Zletovica Basin Water Utilization Improvement Project, with the purpose of water supply, irrigation and power generation. The Knezovo Dam is an asphalt core rockfill dam with a maximum height of 82 m, a crest length of 270 m and a total dam embankment volume of 1,700,000 m^3. The effective storage capacity will be 22,500,000 m^3. According to the monitoring concept of the dam, a leakage detection system is installed to control the intactness of the sealing core. The leakage detection system is based on distributed fiber optic temperature measurements using the heat pulse method.

4.2 *Leakage detection system*

According to the design the monitoring system comprises only one cable, with measuring levels at the foundation level, at el. 1010 m.a.s.l, el. 1035 m.a.s.l and el. 1055 m.a.s.l. (Fig. 8). The cable was placed in the drainage and transition zone 2A downstream of the asphalt core. According to the specification, the maximum grain size for 2A material varied between 25 mm to 60 mm. To avoid damaging the cable during compaction of 2A material, uniform sand ($CU \leq 2$) with a maximum grain size of 2 mm to 5 mm was used as cushion material around the cable. All necessary facilities such as measuring hut, reference section and power supply will be located on the right bank above the dam crest.

The cable used for the leakage detection system is a standard outdoor fiber optic hybrid cable. The main field of application of the cable is leakage detection in hydraulic engineering structures. The layout of the cable is similar to the cable used for the laboratory tests (Fig. 4), but it is considered to be more robust. It has a central supporting element, four copper conductors with a total cross-section of 6 mm^2. The external diameter is 17.0 mm. For the time being the DTS system used for the measurements is a mobile unit and only on site during measuring periods. However, it is planned to install a permanent monitoring system.

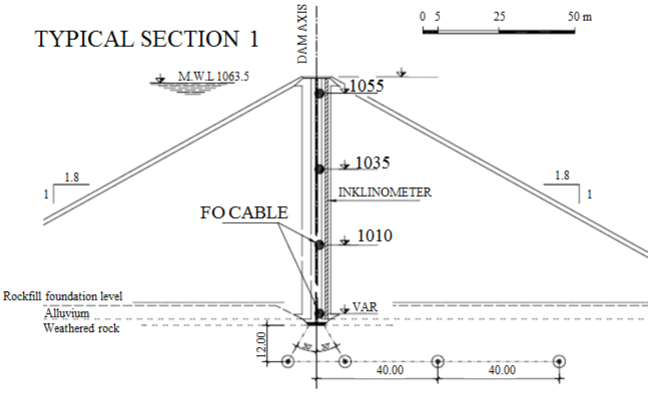


Figure 8. Allocation of the cable (cross section)

4.3 *First measurements and simulation tests*

To evaluate the change of seepage conditions in the dam due to impounding of the reservoir and during operation of the dam, reference measurements before filling the reservoir are necessary. The reference measurements were carried out when impounding of the reservoir was started (14-7-2010). The obtained temperature differences are shown in Figure 9.

In most parts of the dam the results of the reference measurement show no anomalies. Only at the lowest part of the dam the temperature differences indicate that the material around the cable is saturated or minor percolation is present. In general, the variations of the temperature differences are mainly caused by different thermal conductivities of the surrounding soil material. The thermal conductivity of a soil depends among others on mineralogical composition, the bulk density and the water content.

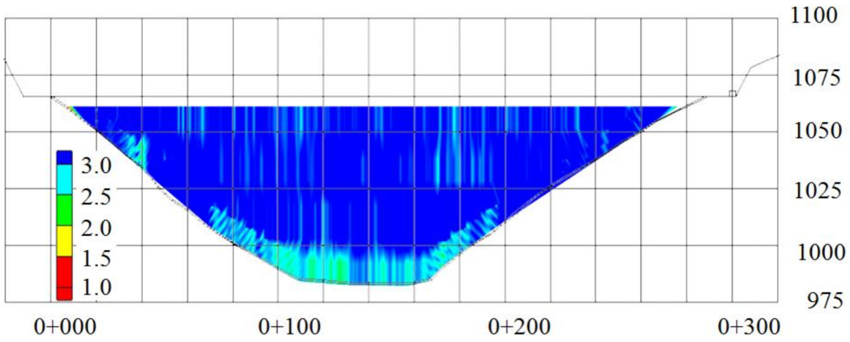


Figure 9. Results of reference measurement

A leakage simulation test was carried out to check for proper operation of the installed system. For this purpose a water tank was placed at the dam crest. The amount of seepage was adjusted to approximately 0.15 l/s (Fig. 10, left) to prove the sensitivity of the system. Water was infiltrated at two different points (Fig. 10, right). The infiltration at the first location was started at 9:45h and lasted for about 3 hours. Since it was assumed that the infiltrating water flows along the slope, infiltration was started at a second point at 13:30h. This infiltration lasted for about 5 hours.

Figure 10. Leakage simulation test with 0.15 l/s

Figure 11 shows significant anomalies at the right slope between el. 1025 and el. 1050 which are caused by the infiltration at the first point. As already anticipated during the test, the infiltrating water runs off the slope causing an anomaly between St. 235 and St. 250. The anomaly increases with continuing infiltration. The anomaly caused by infiltration at the second point is shown in Figure 12. Further temperature anomalies are observed at the lower part of the dam especially around St. 120. The anomalies intensify during the measurements. Both time characteristics and position suggest that the anomalies are caused by the increase of water level due to impounding of the reservoir.

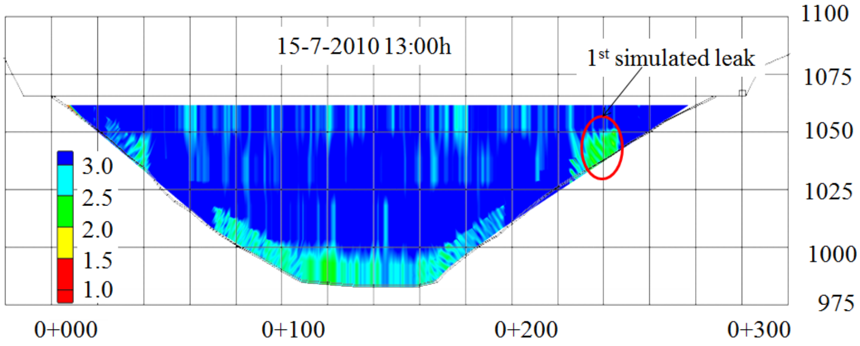


Figure 11. Results of leakage simulation test at 13:00h

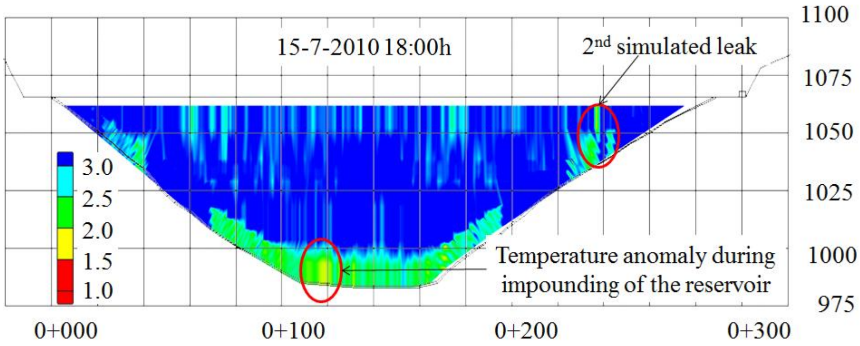


Figure 12. Results of leakage simulation test at 18:00h

5 CONCLUSIONS

The paper presents a leakage detection system based on distributed fiber optic temperature measurements for which the fiber optic cable is installed in the central part of the dam. Additionally information on the effect of deformation and stress in embankment dams on DFOT monitoring results are given.

In summary, it can be said that the fiber optic leakage detection system for the Knezovo dam is ready to use. Since the reference measurements were carried out at the beginning of impoundment, the results will serve as guide values to assess changes of the seepage conditions during impounding of the reservoir. The results of the leakage simulation test prove the proper operation of the system and the suitability of the system to detect small changes in the seepage behavior of the dam.

Laboratory tests were carried out at the University of Innsbruck, in which possible installation conditions and expected loads due to overburden pressure were simulated. Based on the results it is recommended to limit the maximum particle size of the bedding material to 16 mm and to use well graded material. As proved by the Knezovo dam installation of fiber optic cable in dams with a height of up to 85 m should not cause problems regarding the reliability and accuracy of the measurements.

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