

DISTRIBUTED FIBRE OPTIC TEMPERATURE MEASUREMENTS FOR DAM SAFETY MONITORING: CURRENT STATE OF THE ART AND FURTHER DEVELOPMENTS

Axel Fabritius¹, Barbara Heinemann¹, Jürgen Dornstädter² and Thomas Trick³

1. GTC Kappelmeyer GmbH, Karlsruhe, Germany
2. GTC Consult GmbH, Bruchsal, Germany
3. Solexperts AG, Mönchaltorf, Switzerland

PRESENTER: AXEL FABRITIUS

ABSTRACT

The experience from the last 20 years showed the great advantage of the use of distributed fibre optic temperature measurements (FO-DTS) for the efficient monitoring of dams. The temperature can be permanently measured with a high spatial resolution, analyzed and visualized in near real time on a Web platform to enhance the dam safety. Leakages can be detected at an early stage before causing potential hazards. Different monitoring techniques were developed and successfully implemented in different types of dams during the last two decades. The principal measuring method and different applications as well as further developments are presented.

1. INTRODUCTION

Leakages along fissures in or under concrete dams and internal erosion processes within or underneath embankment dams are significant deterioration processes which often lead to a complete dam failure. Thus, an early (premature) leakage detection method is essential for a long dam life time. The most reliable premature leakage detection method for water retention systems is the observation of temperature variations vs. time and temperature anomalies. In 1955, Kappelmeyer (1957) was the first who used ground temperature measurements for the detection of leakages within and under the embankment dams of the Dortmund-Ems Channel in Germany. At that time Kappelmeyer was using conventional temperature sounding methods. However, until the mid 1990's distributed temperature sensing technology was developed and became economically feasible in particular for the application of temperature measurements in large dams. The German GTC Kappelmeyer company founded by Kappelmeyer in 1992 installed over 80 leakage detection monitoring systems since 1996 worldwide. Today more than 500 km of dams and embankments have been investigated and about 100 km equipped with a FO-DTS monitoring system.

2. TEMPERATURE AS TRACER FOR LEAKAGE DETECTION

The principle of using the temperature for leakage detection is to apply temperature as a tracer for the characterization of groundwater flow paths. Temperature gradients between the surface water and the ground, which are due to the yearly cyclic variations, are used to detected temperature anomalies along and below a water retaining system (see Figure 1). This method is suitable for regions with sufficient temperature variations during the cold and warm seasons. However, in tropical and subtropical climates the temperature variations are too small for this method. Therefore, the heat pulse method was developed which is based on generating a well defined heat disturbance of the ground represented by a line heat source (Patent No. DE 198 25 500).

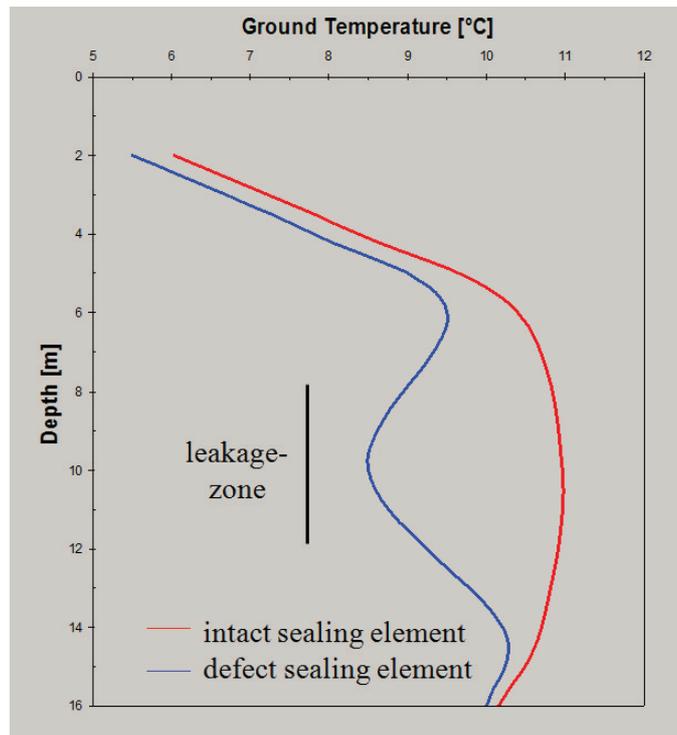


Figure 1. Temperature anomaly in a ground temperature depth profile. Red line indicates the natural temperature distribution. The blue line indicates a leakage zone in a depth between about 8 and 12 m

The best practice is to use electrical wires for the heat source. As soon as the heat source is switched on, the temperatures within the measuring device rise quickly and then tend towards some asymptotic values – the final temperature (see Figure 2). According to its thermal conductivity, the material surrounding the temperature measuring device dissipates the induced heat. The final temperature is rather high when no fluid flows and it will theoretically never reach a constant value when heat is solely transported by conduction. The larger the pore velocity is, the larger the heat dissipation, i.e. the lower the final temperature. A similar phenomenon is observed when switching off the heat source (relaxation): No fluid flow generates a slow cooling process and the undisturbed ground temperature is reached after a long time. An existing fluid flow results in a fast adaptation to undisturbed ground temperatures.

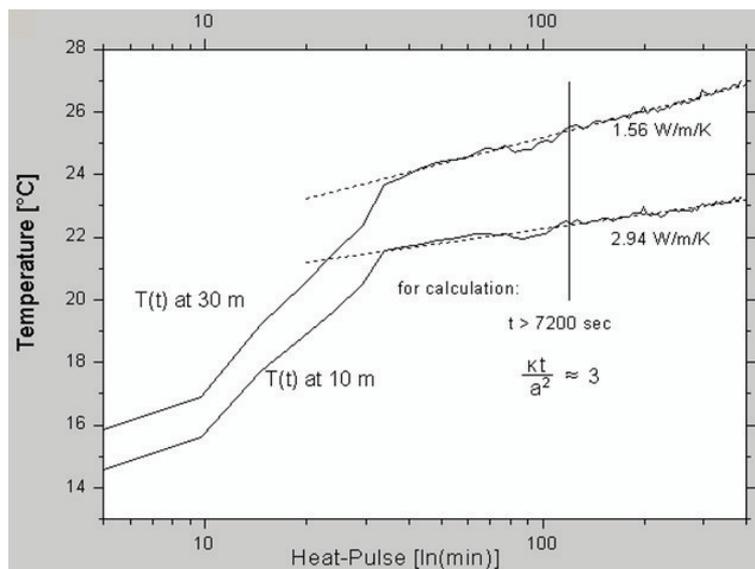


Figure 2. Example of a temperature evolution due to heat pulse (here used for an Enhanced Thermal Response Test)

3. DISTRIBUTED TEMPERATURE MEASUREMENT METHOD, FIBRES AND CABLES

Fibre optic temperature sensing operates by sending a short laser pulse (< 10 ns) into an optical fibre. The backscattered light is analysed with Raman spectroscopy, providing Stokes and anti-Stokes intensities (see Figure 3). The ratio of Stokes to anti-Stokes intensities is proportional to the temperature at the scattering point (equals the measuring point, see Figure 4). The localisation of the measuring point is the distance along the fibre calculated from the duration the backscattered light needed and the velocity of light. The Raman backscattering effect was first described by Smekal (1923) and was proofed by Raman and Krishnan in 1928. The application of this effect provides a temperature profile distributed along the entire optical fibre.

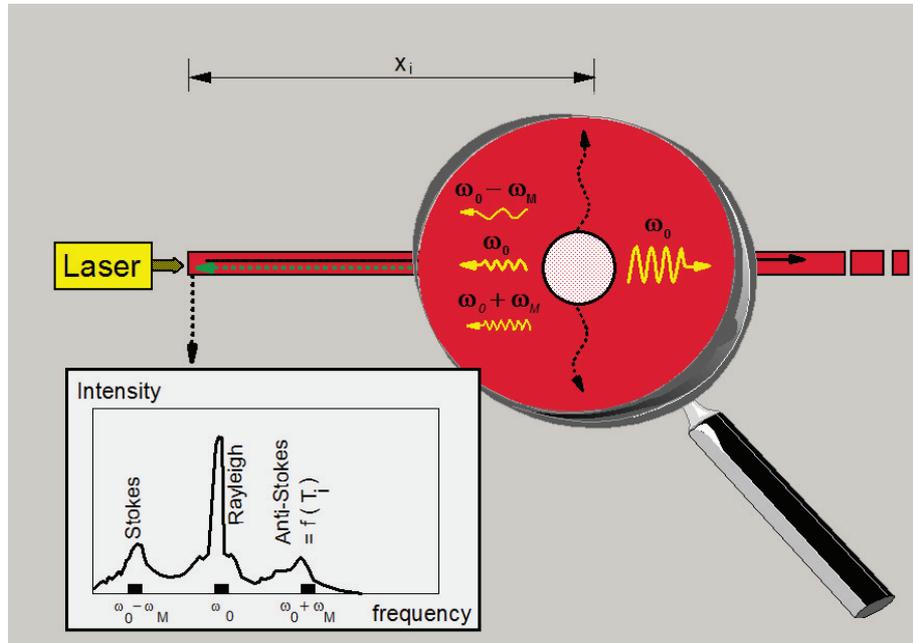


Figure 3. Schematic drawing of the DTS method: The backscattered light is analysed with Raman spectroscopy providing Stokes and anti-Stokes intensities which are proportional to the temperature at the scattering point

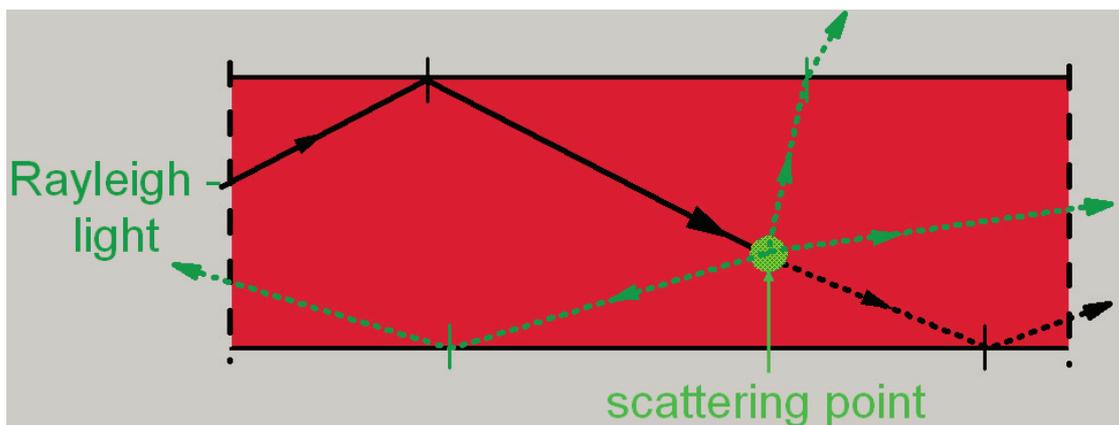


Figure 4. Schematic drawing of the scattering point or measuring point where the light is backscattered

The distributed fibre optic temperature sensing method enables high resolution temperature measurements along a conventional optical fibre with a length of up to 12 km allow with a spatial resolution of about 0.5 m. The temperature resolution in general ranges between about 0.1°C and 0.05°C depending on the measurement time. This means that the method is very sensitive to small temperature variations and therefore suitable to detect even small leakages. Longer distances up to 50 km are possible with a lower temperature resolution

The fibres are very delicate and their application requires multiple protection layers. Generally a fibre optic cable consists of a core (single or multiple), the cladding and the buffer coating (see Figure 5). The cables are available in two versions, one for absolute temperature measurements with fibres in a central stainless steel tube, and the other, hybrid cables for artificially induced temperature increases with additional coaxial layers of electrical conductors. The electrical conductors are used to heat the cable to apply the heat pulse method (active method) for leakage detection, if needed (Dornstädter et al., 2010).

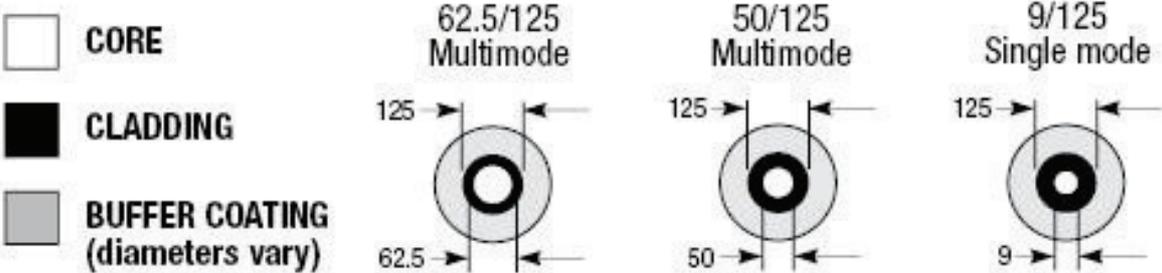


Figure 5. Schematic drawing of the fibre optic cable

4. FO - DTS MONITORING SYSTEM OF CONCRETE-, ROCK FILL- AND MASONRY DAMS

At concrete dams, possible water flow paths are joints (including sealing joints) and the rock- or soil - concrete interfaces, intersection structures and leaky sealing elements (e.g. at the upstream dam wall). A FO-DTS leakage surveillance system is therefore focused on detecting flow along this preferential path ways.

A typical application of such a system was installed at the Midlands Dam in Mauritius, shown in Figure 6. The dam was equipped with cables at the lateral interface concrete dam and the impervious layer of the rockfill dam. In addition, a fibre optic cable was installed below the (impervious) bituminous concrete layer of the rock fill dam behind the cut-off wall (perimetric joint) (see Figure 7).



Figure 6. Fibre optic cables installed at the Midlands dam in Mauritius

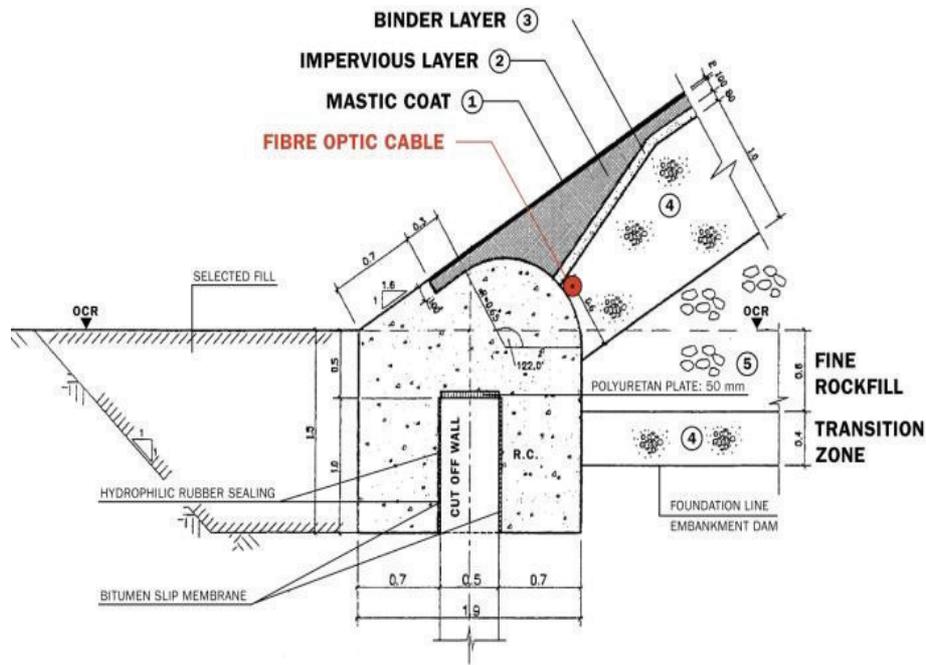


Figure 7. Fibre optic cable installed behind the perimetric joint, i.e. below the interface surface sealing of the rock fill dam and cut-off wall

At the 75 meter high Knezevo rockfill dam in Macedonia fibre optic cables were installed at different elevation levels in the filter zone downstream the asphaltic core in order to monitor the functionality of the core and the abutments (see Figure 8). The fibre optic cable installation was integrated within the dam construction. GTC-Kaplemeyer instructed the construction crew such that the construction company was able to mount the cables by themselves. Subsequently to the completion of the cable installation GTC Kaplemeyer connected all the FO cables and installed the DTS system. An initial measurement was recorded, the system was calibrated and a leakage simulated to verify the system function. The data are processed by the GTC-Kaplemeyer software and transmitted to the internet. The analyzed and visualized data set is displayed on a password protected Web portal which the responsible persons of the dam safety can easily access to check the status of the monitoring system and the dam sealing. Figure 9 is showing the temperature distribution, the calculated thermal conductivity and the status of the sealing system as "control results". The traffic light control system indicates one leakage (red spot) on the right side of the graph where an artificial leakage was simulated to verify the system function.



Figure 8. Knezevo rock fill dam in Macedonia installation of the FO cables (left side)

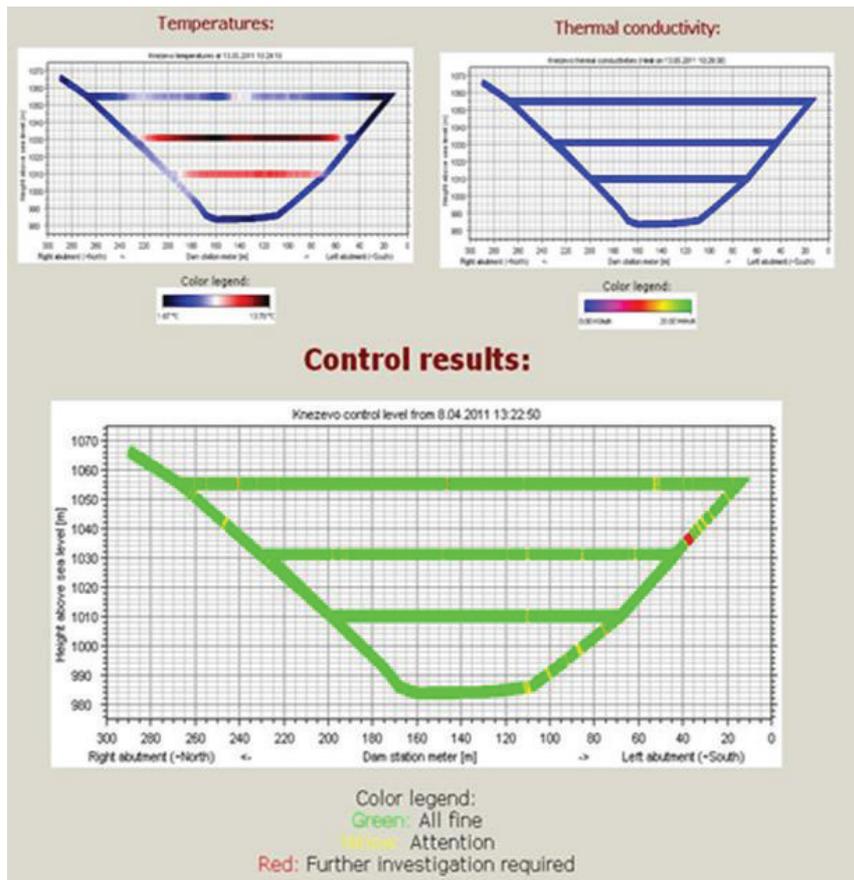


Figure 9. Temperature and thermal conductivity distribution at different elevations in the filter zone and the dam abutments (top graphic). The bottom graphic shows the status of the leakage system.

Nowadays a large number of older dams exist. These are often masonry dams constructed mainly of stone, brick or concrete blocks that may or may not be joined with mortar. The older masonry dams and some older concrete dams often require a rehabilitation including a sealing element (e.g. geomembrane) at the upstream dam face. The installation of fibre optic cables just behind the sealing element first allows a function check of the sealing system after the installation and secondly can be used for the deterioration monitoring of the membrane (see Figure 10).

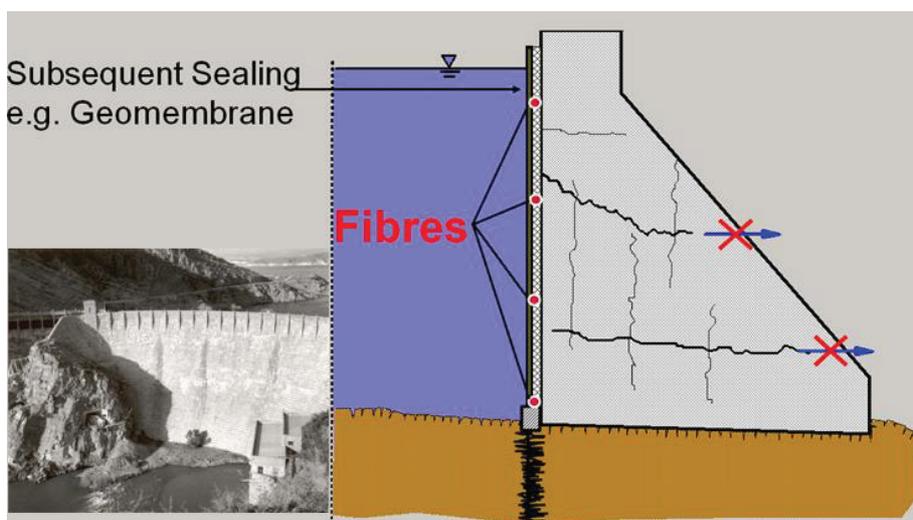


Figure 10. Schematic drawing of a dam rehabilitation with an upstream dam face sealing and a setup for a further leakage monitoring with FO-DTS. Left side: example of an old masonry dam (Roosevelt dam, Arizona - USA)

5. FO - DTS MONITORING SYSTEM OF EMBANKMENTS

Internal erosion is one of the most frequent reasons of failure and deterioration of embankment dams. Internal erosion is controlled by construction properties (e.g. filter and drain design, grain and pore sizes) and hydrodynamic conditions within the dam. While construction properties are usually known, poor information is available on the local hydrodynamic situation inside the embankment. Hydrodynamic parameters vary strongly inside the dam due to local inhomogeneities and the most critical hydrodynamic parameter inducing internal erosion (material transportation phenomena) is the pore velocity of the seeping water. The onset of internal erosion starts at low pore velocities. Thus a method for the detection of seepage zones of low pore velocities can prevent the development of damages.

Present research state that the critical pore velocity initiating material transportation phenomena inducing deterioration of dams is of the order of 10^{-3} m/s. Using the temperature of seepage water as a tracer showed to be a reliable method to detect leakage zones and monitor in-situ flow velocities of orders $> 10^{-7}$ m/s (pore velocity). The monitoring of the seepage flow conditions leads to the detection of internal erosion at an early stage of development. The computation of flow velocities is the qualification for the automatic release of an alarm – either by indicating a change in flow velocities, i.e. in flow conditions, or by exceeding a threshold of a fixed critical velocity. The detection of seepage zones of low pore velocities and their monitoring can prevent the development of damage and possible failure of the structure.

FO-DTS cables can be integrated along interfaces and behind sealing elements during the construction of new embankments. Surveillance of internal erosion processes with FO-DTS cables in existing dams is a recent development by GTC Kappelmeyer (Patent DE19621797, 2011). The new technology was successfully applied during the last years at several embankments in different European countries.

The key to the new solution are bend-optimized fibres which can be bent to a very small radius without too much attenuation of light intensity when a laser pulse travels through them. The cable with a typical outer diameter of 4 to 6 mm including armouring and water-tight protection has a minimum of two fibres inside. At the far end of such a cable one of the internal fibres is bent through 180° and welded to a second fibre by fusion splicing. This optic loop is then protected against mechanical damage by a cover with a typical outer diameter of 8 mm. The cable with fibre optic loop at the end is inserted into the small diameter tube of a temperature probe that has been previously installed into the dam (Dornstädter et. al., 2017).

Individual fibre optic cables are inserted in each probe and a connecting cable runs in a shallow cable trench from probe to probe and finally to the instrumentation cabinet. The fibres of each individual probe are spliced to the fibres of the connecting cable in a way that allows the laser pulse from the DTS instrument to travel along the connecting cable, running down and up each probe from one end of the dam to the other as shown in Figure 11.

The carrier of the FO-DTS cables are small diameter, high grade steel tubes which are vibrated into the earth fill dam and its foundation along the dam axis from its crest. Maximum depth ever reached is 45 m. The probes are rammed vertically into the dam at regular intervals (Dornstädter, 1997).

At the protected instrumentation house all signal cables end in splice connection boxes and the DTS interrogator. The instrumentation house should be located near the dam and electricity should be available. However, today autarkic electricity systems based on battery buffered photovoltaic energy systems are also available for remote areas (Figure 12).

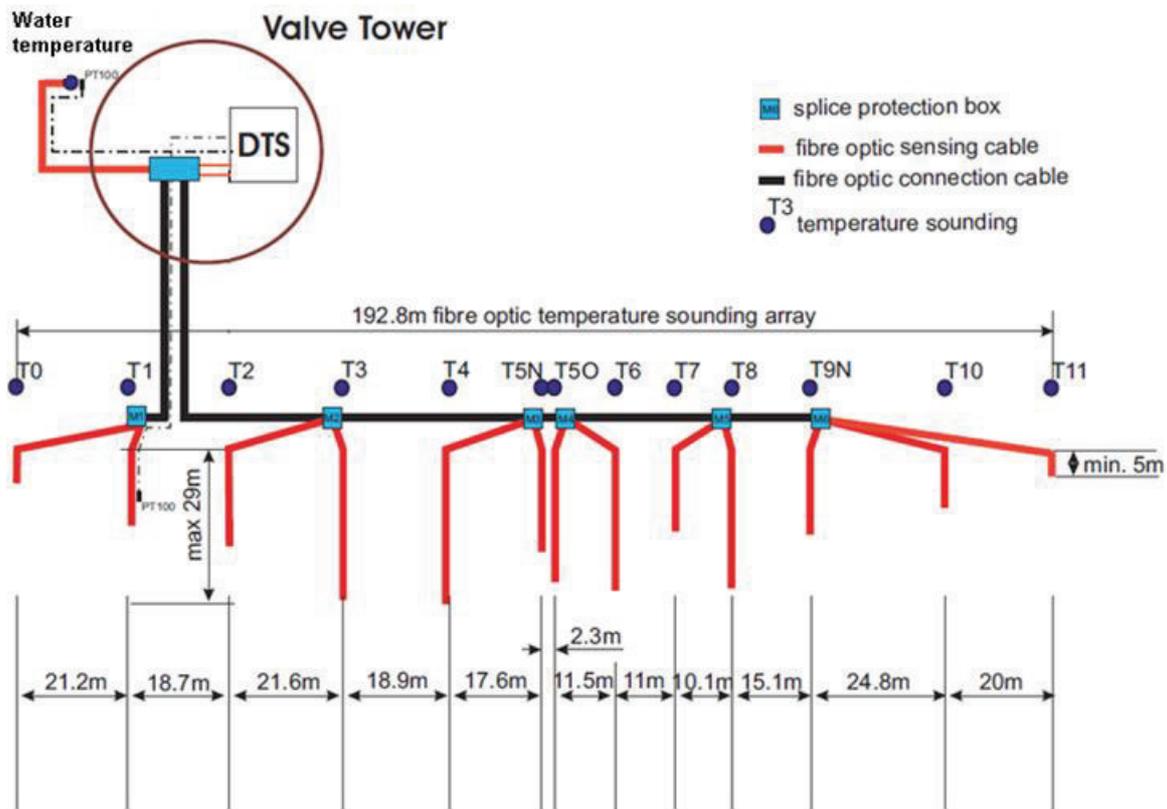


Figure 11. Example sketch of a typical layout of fibre optic cabling

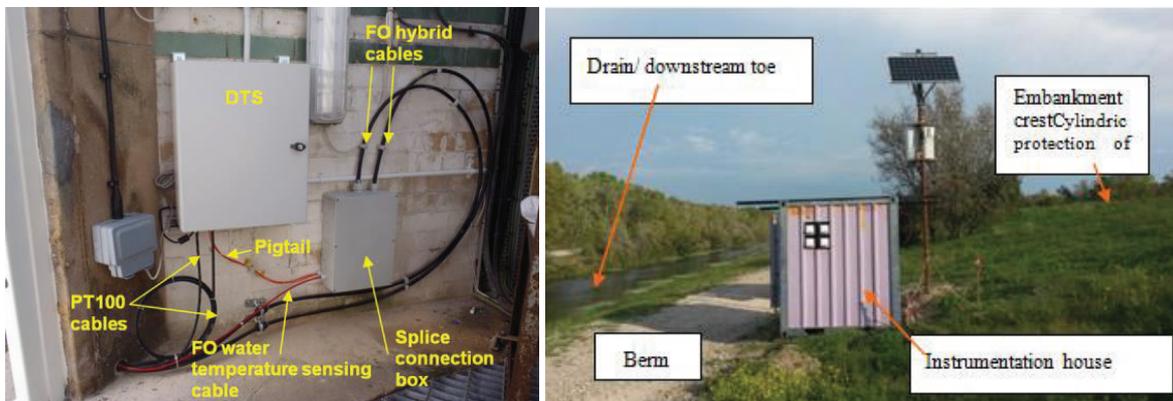


Figure 12. Examples for instrumentation house setups

An example for a FO-DTS internal erosion surveillance system during a dam rehabilitation phase is the embankment of the river in the southern parts of France (Dornstädter, 2017). The embankment is about 11 m high and has a long history of leakage and transport of fines. For the detection of the leakage zones inside the embankment and its foundation, a total of 37 temperature probes were installed to a depth of 16 m along a 430 m long section of the dam. The array runs along the downstream edge of the embankment crest. Fibre optic cables were installed in all probes and connected by a connecting cable in a small trench. Since the site was having leakage problems combined with transport of fines, the client decided to build a slurry trench cut-off wall in Spring 2015. The temperature evolution before, whilst and after the construction of the cut-off wall was remotely monitored with automatic data analysis. During the construction work the client followed the success of the procedure by the automatic temperature monitoring system (remote condition monitoring).

The 2-dimensional temperature distribution about 3 weeks before the beginning of the construction of the cut-off wall is shown in Figure 13. A strong temperature anomaly is indicated in the centre by blue

colours corresponding to low water temperatures of the river in winter. The strongly percolated area extends from probe T6 to Probe T21 from 7 m to 14 m depth below crest level, showing severe leakage flow through the lower part of the dam and through its foundation. Two minor percolated areas are seen at T2/T3 and from T5+ to T7+ at the interface of the embankment and its foundation.

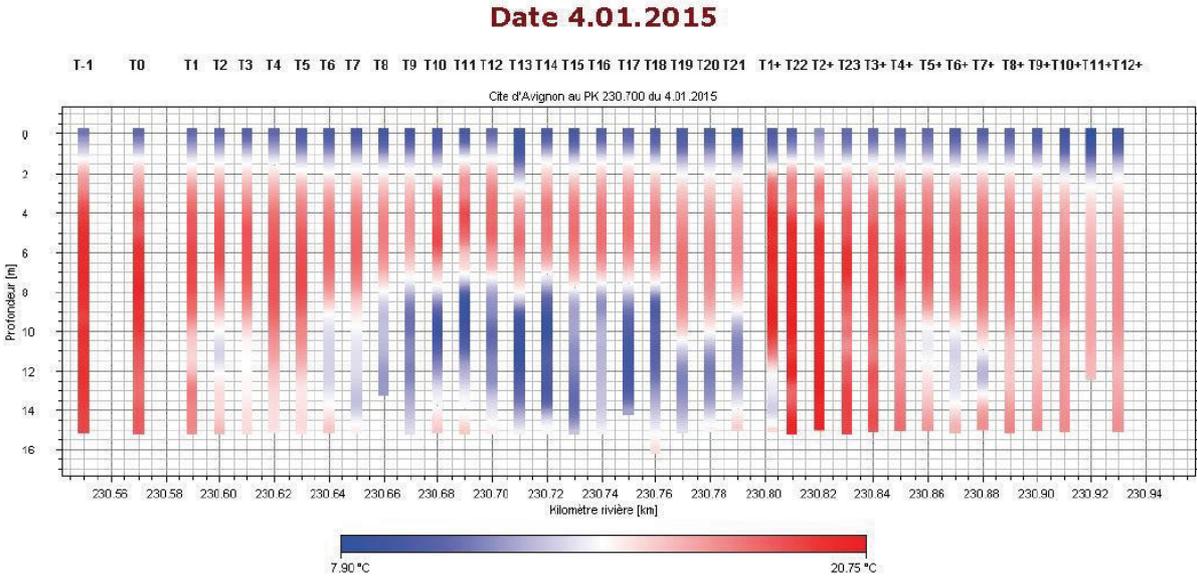


Figure 13. Temperature distribution before construction of the cut-off wall; low water temperature

Figure 14 shows the temperature distribution some months after completion of the cut-off wall constructed from probe T0 to probe T2+. The results show the disappearance of the anomalies seen before and confirm the successful installation of the new cut-off wall.

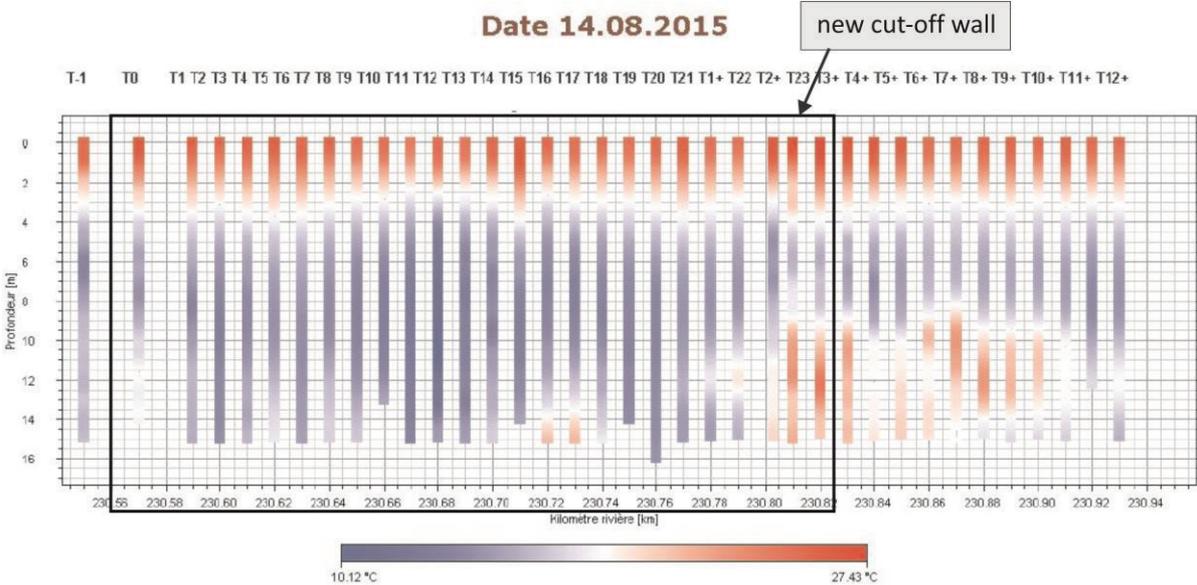


Figure 14. Temperature distribution after construction of the cut-off wall, high water temperature (red)

6. CONCLUSIONS AND FURTHER DEVELOPMENTS

Temperature sensing for leakage detection in concrete and masonry dams and embankments is a well-established and reliable method for the dam safety monitoring. FO-DTS systems were applied successfully in numerous projects worldwide. During the last few years a new development from GTC-Kappelmeyer for the retrofit of two-dimensional FO temperature measurements in existing

embankments was applied to an increasing number of dams worldwide. This novel approach facilitates FO-DTS dam safety monitoring with a high spatial resolution at a relatively low cost.

Further developments of FO distributed sensing will include strain measurements for the surveillance of joints and rock/soil-dam interfaces in combination with FO-DTS. A strain measuring system would be designed to monitor the size and position of cracks in the concrete dams. In particular in areas where the natural seismic risk is high or where induced seismic events are probable (e.g. in mining areas or large dam sites) a rapid detection of a fracture is crucial to reduce the hazard of larger damages and further disasters. With a distributed FO strain and DTS measurement system large areas can be monitored with a relatively low cost. Therefore, this technique is very suitable in particular for larger dams.

For new dams, FO-DTS measurements might be used for quality assurance and to optimize the construction process: The concrete curing process can be monitored with a high two-dimensional resolution for quality assurance purposes including the determination of the thermal conductivity, heat capacity and the thermal diffusivity. Prior and after a dam subsurface sealing process, flow velocities can be determined to check the proper function of a grout curtain.

Nowadays FO-DTS and strain measurements can contribute to an optimized dam construction, a longer dam lifetime and an enhanced dam safety. These methods are therefore a high added value for all stakeholder e.g. dam operators, local people etc. and the environment.

7. REFERENCES

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