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Innovative Dam Monitoring Tools Based on Distributed Temperature Measurement

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ABSTRACT

Distributed fibreoptic measurements contain a number of particular features. Even though they are nowadays used for strain measurements, actually the most interesting parameter to be monitored by distributed fibreoptic measurements in dams is temperature. Due to their enormous mass, large structures such as dams usually show very slow behaviour in terms of temperature changes. It is well known that temperature measurements have to be carried out in concrete dams in order to observe the development of the heat of hydration. Furthermore, seepage flows affect the temperature field within the dams and their foundations. The Distributed Fibre Optic Temperature DFOT measurement was identified to be ideally suited for monitoring the temperature fields of dams, both for leakage detection and for the observation of concrete temperatures. For almost one decade, DFOT measurement has proven to be a powerful tool to detect and locate leakage in hydraulic structures. Leakage detection by means of DFOT measurements has been typically implemented through two major approaches: the gradient method, which employs the temperature as a tracer to detect anomalies in the flow field; and the heat-up method, which allows detecting the presence and movement of water by evaluating the thermal response after external heat is induced. In the past years more and more DFOT projects are under progress. As for today, the DFOT measurement has to be considered as a state of the art tool in dam monitoring. Nevertheless, especially in the field of leakage detection, there is still an enormous potential to improve effectiveness. New additional applications will be developed and important parameters as the seepage velocity in soil material will be measured with DFOT technology in the future. Being robust and gaining a high density of *in-situ* information out of the dam, DFOT technology has to be considered as one of the key technologies in tomorrow's dam monitoring.

KEYWORDS: Innovative dam monitoring, Distributed temperature measurement, Leakage detection, Seepage flow velocity measurement, Internal erosion.

1. INTRODUCTION

Dams and dykes have to be continuously and carefully monitored. Beside the indispensable visual inspection and the measurement of the seepage flow, different monitoring systems are used to asses the hydraulic and static behaviour of the structure. Usually, dam monitoring systems employ conventional instruments based on electrical, hydraulic or pneumatic principles, which yield important information on the changes of different physical quantities such as pressure, stress, strain, displacement or temperature. Nevertheless, the values measured by these instruments refer to their location above all. Depending on their nature they

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represent the physical behaviour of a more or less extended volume of the structure. Between the positions of the instruments the distribution of the measured physical parameters has to be estimated. It is unavoidable that the use of these data for the assessment of the condition of the overall structure contains uncertainties. In contrast to the measurements employing conventional instruments, distributed fibre optical measurements allow for continuous measurements along a cable, ensuring an extremely high information density.

Fibre Optical Principles

The DFOT is based on the temperature-sensitive properties of the fibre which itself represents the sensor. An optical impulse is sent into a fibre integrated in a cable, using a powerful laser. The signal is backscattered with low intensity at every fibre position. Beside the main part of the backscattered light (Rayleigh) there are additional peaks of low intensities (Raman and Brilloiun). The frequency shift and in a certain amount the intensity of the Brillouin Light denpend on both temperature and strain at the scattering point. The widely used Raman – systems use the fact that the intensity of the so called Anti Stokes part in the Raman Light depends on the temperature at the scattering point. Hereby no strain in the fibre is allowed. The distance from the measured point to the laser can be determined by the runtime (time domain OTDR) or by the frequency (frequency domain OFDR) of the light pulse. The cycle time for one distributed temperature measurement ranges from seconds to minutes. One measurement delivers temperature values distributed along the cable with a spacing of 0.25 to 1.0 m. The resulted temperature readings can reach an accuracy of up to ±0.2°C. In dam engineering, fibre optical measurement systems, which are using the Raman Effect, have been successfully under operation for nearly a decade (Aufleger et al., 1997; Aufleger, 2000).

Temperature Monitoring in RCC Dams

In various projects in Brazil, China and Jordan, DFOT proved to be a suitable tool for highly sophisticated temperature monitoring in RCC dams. DFOT measurements stand for a differentiated quality control generally demanded for mass concrete.

Usually, mass concrete temperatures are monitored by conventional thermocouples and thermistors, permitting only spot measurements. In contrary, fibre optical cables provide the possibility of continuous online temperature measurements along the cables integrated in the dam structure. Due to their accuracy and the high information density, DFOT measurements allow the detailed and reliable visualisation of temperature gradients within the RCC structure (Conrard et al.,2002) (see Figure 1).

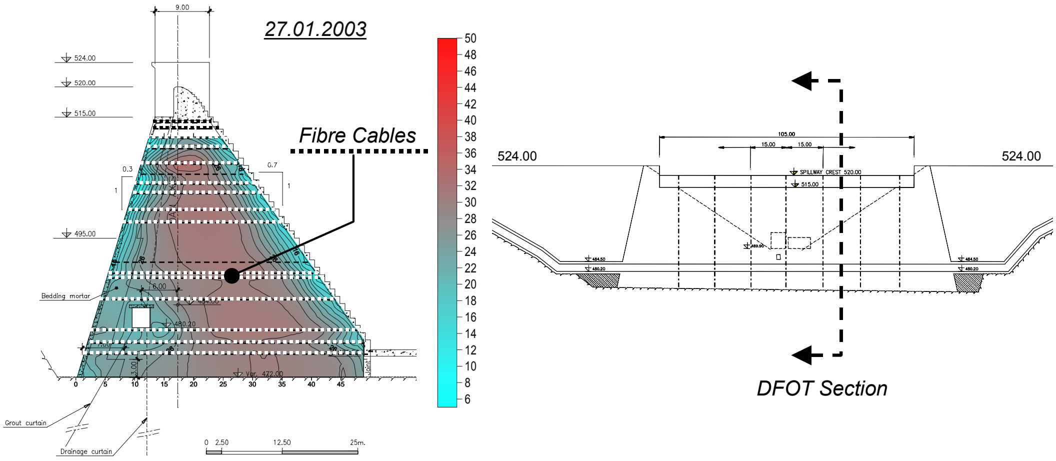

Fig. 1: 2D Temperature Distribution in a Dam Monitored by DFOT.

Resulting from the temperature distribution and distributed temperature gradients, a conclusion in terms of eigenstress may directly be made. As part of the monitored temperature development on the dam during construction, the hydration heat itself can be determined, delivering a clear picture of the concrete *in-situ* maturity in the dam. The assumption of many construction related parameters stated in the dam design can also be controlled, thus helping to find answers to such questions as (Duan,2004):

- Is correct concrete mix applied?
- Are the curing measures adequate and the eventual cooling systems efficient?
- Is the maximum dam temperature under control?
- Is the dam rising in the optimum speed?

Another advantage of the DFOT measurement system is the robustness of the sensor. Since heavy earthmoving equipment is involved in the rapid construction process of an RCC dam and therefore high loads are applied to the sensors, the application of robust fibre optical cables is much more suitable than that of conventional instrumentation. Installation of the fibre optical cables is performed during the continuous RCC placement operation. Practical experience shows that on the construction site the placement of fibre optical cable is less labour intensive and more flexible compared to the installation of individual instruments.

2. METHODS

Leakage Detection Using DFOT

Gradient Method – Passive Method.

In earthen hydraulic structures, such as embankment dams and dikes, the internal temperature field is a function of the flow field. The Gradient Method is an application of DFOT measurements used, to detect, locate and quantify leakage by using the natural-occurring temperature gradients and fluctuations. It is a passive method, since the sensors directly measure the existing temperature and do not actively alter the thermal conditions of their surroundings. Typical applications of leakage detection using DFOT are canal embankments or dams for which the functionality of sealing elements has to be monitored.

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 advection and will propagate throughout the earthen body, distorting the temperature field. The distributed character of the measurement allows for a precise localization of the anomaly, delimiting quite precisely the area affected by leakage. The method also allows for determining the source of the anomaly by contrasting the abnormal temperature to the external temperature history. Magnitude and extension of leakage can be estimated by means of the time lag and the intensity of the temperature anomaly at a given location (see Figure 2).

The Gradient Method constitutes already a standard tool for leakage detection. However, there are still issues that have to be addressed in order to improve the method and to define application and installation criteria. Research conducted at the Technische Universität München for the further development of the Gradient Method has been focused on the use of coupled seepage and heat transport numerical simulations, in order to gain insight into the propagation of anomalies, to determine an optimum location and arrangement of the sensors and to devise rules for the interpretation of the measurements.

A 3D-finite element groundwater flow is the main tool being employed. Figure 3 shows the temperature distribution within a homogenous dam being subject to seepage. The temperature distributions are shown both for normal seepage conditions and for a leakage induced by the fracture of the impervious layer underneath the dam. It becomes apparent that the leak at the upstream side of the dam influences the temperature distribution even at the downstream toe (Aufleger et al., 2005).

The experiences with numerical simulations have allowed to characterise the process of propagation of thermal anomalies and to identify the key hydraulic and thermal parameters that take part in the process. The numerical simulations and the field measurements showed that the temperature anomalies travel through the dam body at a rate correlatable with the seepage flow velocity. With the help of the simulations, it could be also verified that the dam toe is an effective cable location for leakage detection, since the anomalies in the temperature field generated by leakage propagate along the dam body and can still be detected at this point of the structure.

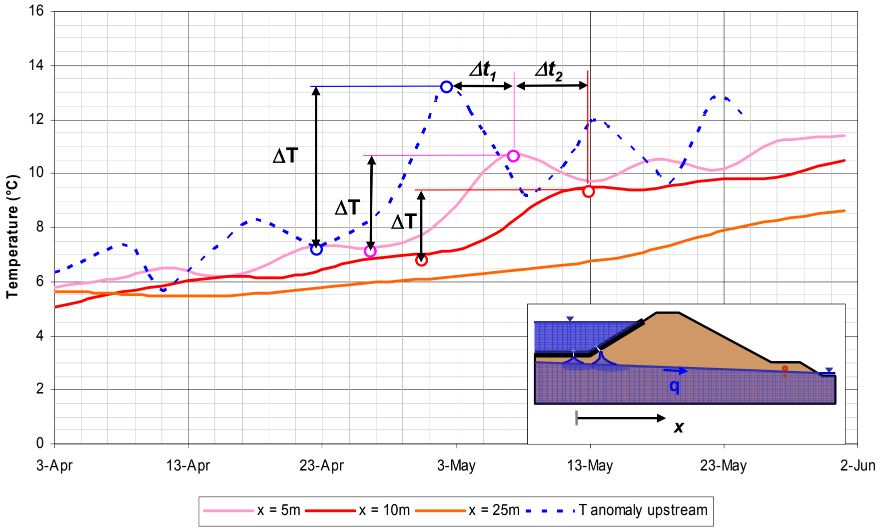

Fig. 2: Use of Temperature Fluctuations to Trace Thermal Anomalies and Estimate Seepage Velocities in Leaking Canal Embankments.

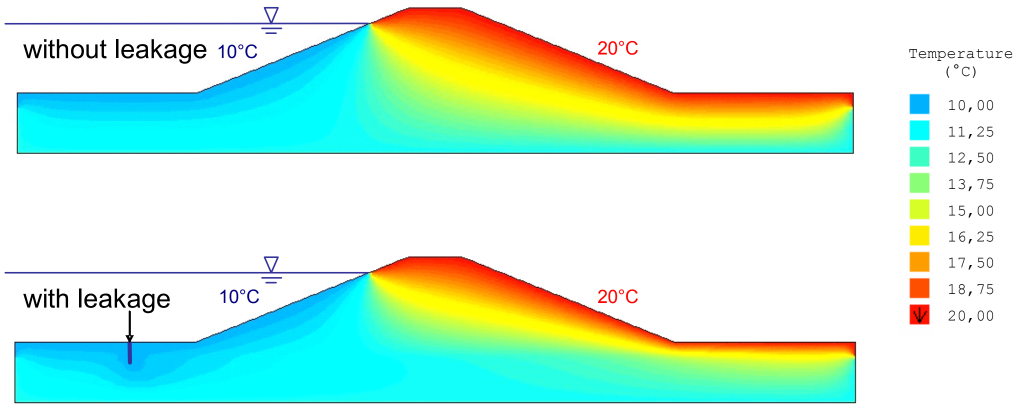

Fig. 3: Temperature Distribution in a Numerical Model of a Homogenous Dike Section with and without Leakage (Simulation in FEFLOW.)

Heat-up Method – Active Method

Functionality of the Heat-up Method

Originally, the heat pulse method was developed for applications where the Gradient Method was inapplicable. This is the case if there are neither sufficient temperature gradients between reservoir water and location of the temperature measurement (e.g. under facings, see (Schäfer et al., 2003)) nor adequate seasonal temperature variations of the reservoir water. Recent developments show that the DFOT heat pulse method can provide precise information on water content and movement in the direct surrounding of the cable. Accordingly, crucial needs of leakage detection in embankment dams are met, as information on seepage lone and flow velocity is obtained. The method requires an adequate distribute heat input in the cable for about one hour. A.C. or D.C. voltage produces such a linear heat input ranging if put on the copper wires integrated in a cable. Whereas for exclusive leakage detection a heat input from 3 to 5 W/m is sufficient, the distributed flow velocity measurement requires about 10 W/m. For cable sections of several kilometres, beside enough power, either high voltage (transformer) or large copper cross section area (limited by the cable diameter) is required.

The thermal response of the cable dT_i depends on the cable cross section (diameter, material) and the heat transport from the cable wall, either dominated by conduction in partly to fully saturated soils (Figure 4, right) or by convection at the presence of flow velocities faster than 10^{-5} m/s (Figure 4, left). Accordingly, the temperature difference dT_i between the initial state T_∞ and the heated state T_i is composed of the difference between cable core and wall dT_c plus the difference between cable wall and infinity dT_s.

Distributed Determination of the Degree of Saturation

The transient thermal response in the cable is dominated by conduction in partly to fully saturated soil and thus governed by the soil thermal conductivity. Soil thermal conductivity is dependent on particle thermal conductivity, porosity n and the degree of saturation S, which can either be shown by test results after Jessberger (1990) or by theoretical approaches. Johansen (1975) gives a formula (1) to derive the effective thermal conductivity of a partly saturated soil λ_{eff} from the thermal conductivity of the dry soil $\lambda_{eff,d}$ and the thermal conductivity of the fully saturated soil $\lambda_{eff,s}$ as shown in Figure 5.

$$\lambda_{eff} = \left(\lambda_{eff,s} - \lambda_{eff,d}\right)Ke + \lambda_{eff,d} \qquad \text{...(1)}$$

with $Ke = 0.68\ln(S)$

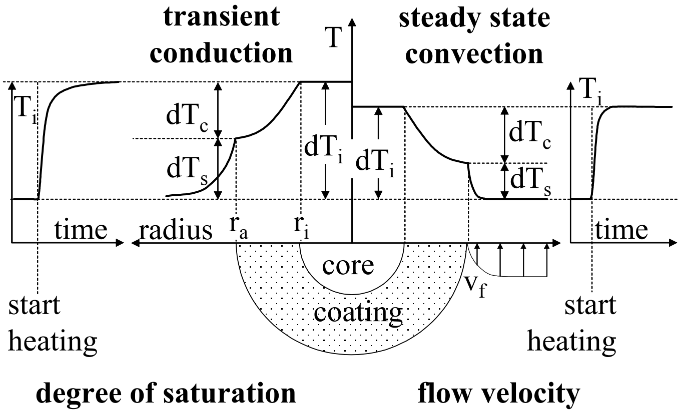

Fig. 4: Temperature Distribution over a Schematic Cable Cross Section with Transient Conduction and Steady State Convection.

The transient conduction on a heated cable in soil can be described by using a substitute system of a cylinder with infinite thermal conductivity coupled to the surrounding by a finite surface conductance H. The approximate solutions valid for long heating periods after Kristiansen (1982) allow for an easy description of the temperature difference between cable wall and surrounding dT_c

$$dT_c \cong \frac{q_l}{4\pi\lambda_{eff}}\left(\ln(t)+\ln\left(\frac{4\kappa_{eff}{}'}{r_a{}^2}\right)-0.58\right), \qquad \ldots(2)$$

where $\square_{eff}$' is the effective thermal diffusivity, r_a is the cable radius and t is the time. A detailed description of substitute systems and the analytical formulation of the transient conduction from a heated cable are given in (Perzlmaier et al., 2004). The theoretical thermal response versus the degree of saturation interrelationship described by (1) and (2) fits well to test data from DFOT heat pulse tests performed at the laboratory of the Institute of Hydraulic and Water Resources Engineering, TU München, as demonstrated in Figure 6.

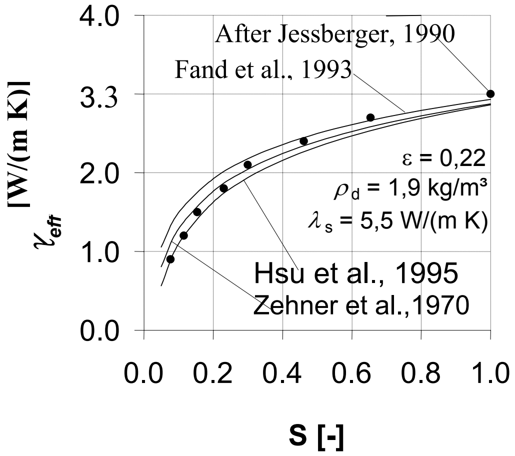

Fig. 5: Effective Thermal Conductivity ($\square_{eff}$) of Two Phase Mixes from Literature Modified after Johansen [8] for Partly-saturated Soils.

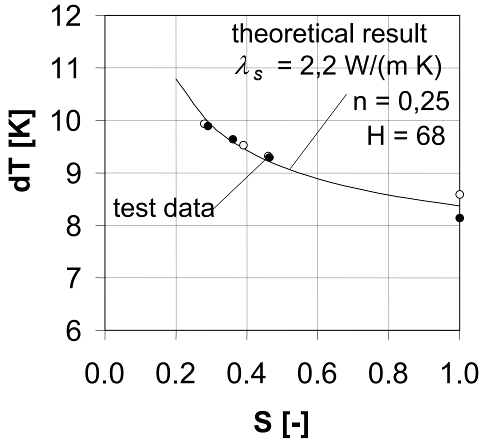

Fig. 6. Thermal Response dT after 110 Minutes of a 12 W/m Heat pulse versus Degree of Saturation S.

The degree of saturation S is less accurately displayed with the DFOT heat pulse method than with other methods available (e.g. TDR probe, dielectric aquameter). However, the method is adequate to distinguish dry, moist and saturated soil conditions and, furthermore, is outstanding in terms of information about density. Hence, the method is relevant for dam engineering applications (e.g. location of line of seepage in coarse soils). An additional geotextile fleece cable coating (thickness s several mm) makes the differentiation of moist and saturated soils even more reliable.

Distributed Flow Velocity Measurement

The relationship between flow velocity and heat transfer coefficient at the wall, valid for the heat transfer from a heated cylinder in soil at the presence of seepage, enables the DFOT heat pulse method to measure the Darcian flow velocity. The flow boundary layer and accordingly the thermal boundary layer on the wall decrease in thickness with increasing velocity. This forced convection effect makes the thermal response of the heated cable depend on the flow velocity. It is superposed by free convection only in very permeable soils ($k_f \geq 10^{-2}$ m/s) and else by conduction at slow flow velocities (Figure 7). While the cable influence dT_c can be quantified in tests, the heat transfer coefficient and thus dT_s can be calculated from empirical equations, e. gbafter (Fand et al., 1993), using dimensionless heat transfer coefficients (Nusselt number). The theoretical thermodynamic fundamentals have been proven with a large number of tests at the laboratory of the Technische Universität München in the past three years.

Detailed information on the thermodynamic background and several hundred tests carried out for calibration with different cables, DTS devices and heat input, in water and different soils (silt, sand, gravel), with and without additional geotextile fleece coating, at different flow velocities and different flow directions against vertical and against the cable can be found in (Perzlmaier et al., 2004) and (Perzlmaier, 2006). This key work for the development of distributed flow velocity measurement gave the following general insights:

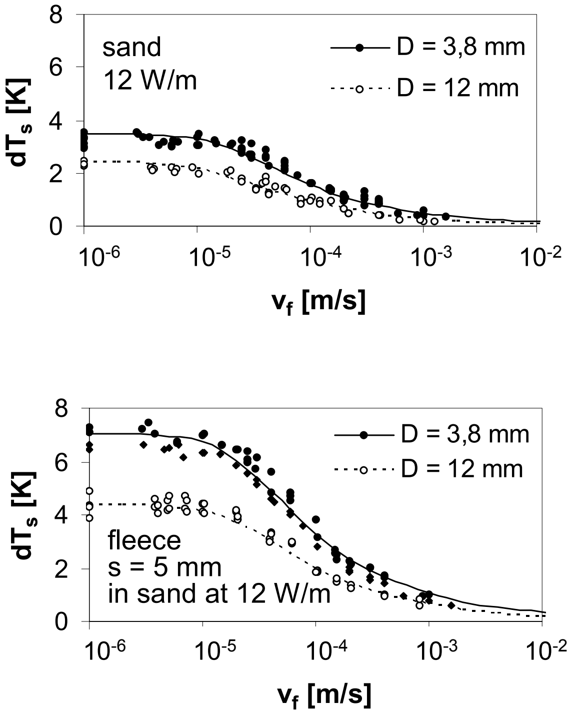

Fig. 7: dT_s after 60 min versus Flow Velocity at Different Cable Diameter D in Pure sand and with Additional Fleece Coating:Ttest Data (Dots) and Theory (Line).

(1) Distributed *in-situ* flow velocity measurements can be realized by the DFOT heat pulse method for the first time.

(2) Different soil materials with permeability less than or equal to 10^{-2} m/s only show small variations concerning the dependence of the thermal response on the flow velocity (calibration).

(3) The measuring range varies from 10^{-5} m/s to 10^{-3} m/s and is suited to detect velocities suspected to initiate internal erosion and suffusion.

(4) The angle of the flow against the cable has a negligible effect on the dependence of the thermal response on the flow velocity as long as it does not differ more than ±30° from perpendicular.

(5) The accuracy of the distributed flow velocity measurement increases with decreasing cable diameter, increasing heat input, increasing accuracy

of the DTS devices and additional cable coating of a thick geotextile fleece (3 to 8 mm).

(6) The temperature accuracy of most of today's DTS devices (temperature resolution 0.1 ÷ 0.2 K) requires a heat input not less than 10 W/m, limiting the range to 1 ÷ 2 km using 400 V or to 3 ÷ 4 km if the voltage is transformed to 1000 V. Any present or future device with better temperature accuracy will either allow for less heat input or higher accuracy of the distributed flow velocity measurement.

3. CONCLUSION

Distributed fibre optical measurements have a number of important technological advantages such as the high information density, the suitability for rough site conditions and the simple and flexible installation of the cables. As for today, DFOT has to be considered as a state of the art tool in dam monitoring with applications reaching from leakage detection in CFRDs and canal embankments to temperature monitoring in RCC dams. Further development of the instruments for distributed temperature sensing and the method itself make DFOT measurements a key technology in dam monitoring. Especially the further development of the heat-up method has led to a new unique tool for distributed determination of water content and flow velocities in soils.

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