INTEGRAL SEEPAGE MONITORING ON EMBANKMENT DAMS BY THE DFOT HEAT PULSE METHOD

MARKUS AUFLEGER  
*Unit of Hydraulic Engineering, Universität Innsbruck, Technikerstrasse 13*  
Innsbruck, A-6020, Austria

MATTHIAS GOLTZ  
*Unit of Hydraulic Engineering, Universität Innsbruck, Technikerstrasse 13*  
Innsbruck, A-6020, Austria

SEBASTIAN PERZLMAIER  
*Division Engineering Services, TIWAG- Tiroler Wasserkraft AG*,  
Eduard-Wallnöfer-Platz 2, Innsbruck, A-6020, Austria

JÜRGEN DORNSTÄDTER  
*GTC Kappelmeyer GmbH*,  
Heinrich-Wittman-Strasse 7a,  
Karlsruhe, D-76131, Germany

**ABSTRACT:** The functional efficiency of the sealing element is crucial for the stability of an embankment dam. Therefore leakage detection plays an important role in today’s dam monitoring. Applications of the distributed fiber optic temperature measurement (DFOT) have been developed since 1996. Meanwhile the fiber optic sensing has been successfully applied in many hydraulic structures with focus on temperature sensing and leakage detection. The intensity of heat transport in soil changes completely if there is a significant amount of water migrating through the soil matrix. Even a small fluid flow within a dam or a foundation leads to an adaptation of the soil temperature to the temperature of the percolating water. The resulting temperature anomalies respectively heat transport anomalies are very sensitive markers for the leakage detection. For more difficult situations, especially where the sealing system is close to the reservoir, the so called Heat–Pulse Method has proved its suitability to detect leakages with a high spatial resolution. Generally the Heat–Pulse Method is suitable to distinguish between dry, moist and infiltrated conditions of the porous material. The Heat–Pulse Method furthermore appears to be suited for the evaluation of risk of internal erosion, since the decisive parameter of particle transport, the seepage velocity, can be measured. This technique is based on the physical relation between the convection on a surface of a cylinder and the seepage water velocity.

**KEYWORDS:** Embankment Dams; Seepage, Innovative Dam Monitoring, Internal Erosion, Distributed Seepage Velocity Measurement

**INTRODUCTION**

Embankment dams have to be monitored continuously and carefully. Beside the indispensable visual inspection and the measurement of the seepage flow, different monitoring systems are used to asses the hydraulic and static behavior of the structure.
Usually dam monitoring systems employ different types of instruments, 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 represent the physical behavior 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 fiber optical measurements allow for continuous measurements along a cable, ensuring an extremely high information density.

DISTRIBUTED FIBER OPTIC TEMPERATURE MEASUREMENTS (DFOT)

Distributed temperature sensing (DTS)
The DTS is based on the temperature-sensitive properties of the fiber which itself represents the sensor. An optical impulse is sent into a fiber integrated in a cable, using a powerful laser. The signal is backscattered with low intensity at every fiber position. Beside the main part of the backscattered light (Rayleigh) there are additional peaks of low intensities (Raman and Brillouin). The frequency shift and in a certain amount the intensity of the Brillouin Light depends on both temperature and strain at the scattering point. The widely used Raman – systems are using 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 fiber 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 cables 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 fiber optical measurement systems, which are using the Raman Effect, are under operation successfully for more than a decade (Aufleger et al. (1997), Aufleger (2000) and Johanssen and Sjödahl (2004)).

DTS performance
Today DTS Instruments are available from several distributors, which differ quite a lot in price and performance. Concerning applications in hydraulic engineering, the reliability, the range (maximum length of the fiber to measure) and the resolution in temperature and in spacing of data points are of interest.

Reliability is of particular interest if the device is used in a fixed installation (e.g. as alarming system). Standard measuring ranges go from 4 km to 10 km. The absolute temperature accuracy (constant offset on the whole fiber) is about ten times less compared to the relative accuracy. The latter is quantified by the standard deviation, either over a set of measurements (time step resolution) or over a number of data points.
along the fiber (spatial resolution). Figure 1 shows the principal dependency of the resolution on cycle time, fiber length and spacing of data points. The resolution can go down as far as 0.05 K with high end DTS devices (e.g. sensornet sentinel DTS-LR). Some DTS devices take several data points along the fiber to display steep temperature gradients or steps (see Figure 2).

![Figure 1. Impacts on the temperature resolution of DTS results.](image1)

![Figure 2. DTS results at a temperature step in comparison to the real temperature distribution from Perzlmaier (2007).](image2)

**Application for leakage detection**

Due to its high information density, the DTS technology is ideally suited for monitoring temperature fields in hydraulic engineering structures and therefore has become a standard tool for leakage detection in embankment dams and dykes (Aufleger *et al.* (2005)). The system is typically implemented by two major approaches: the Gradient Method (passive method), which uses temperature as a tracer to detect anomalies in the flow pattern, and the Heat-Up Method (active temperature method) describing presence and movement of water in soil by evaluating the thermal response caused by a heat pulse. Recent development of these methods focuses on quantifying rather than only localizing leakage.

**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 a precise localization of the anomaly, and moreover quite precise delimitation of the area affected by leakage. The method also allows determining the source of the anomaly by comparing the abnormal temperature to the external temperature history. Magnitude and extend of leakage can be estimated by means of the time lag and the intensity of the temperature anomaly at a given location (see Figure 3).

![Figure 3](image-url)

Figure 3. Use of temperature fluctuations to trace thermal anomalies and estimate seepage velocities in leaking canal embankments from Porras (2007).
Figure 4. Temperature distribution over a schematic cable cross section with transient conduction and steady state convection from Perzlmaier (2007).

Heat-Pulse Method (active method)
Originally, the Heat-Pulse Method was developed for applications where the Gradient Method was inapplicable, which is the case if there are neither sufficient temperature gradients between reservoir water and location of the temperature measurement (e.g. under facings) nor adequate seasonal temperature variations of the reservoir water.

The method requires an adequate distributed heat input along the cable for a certain time interval. A.C. or D.C voltage produces the required linear heat input if applied on the copper wires integrated in a heat-up cable (linear ohmic resistance).

The thermal response in 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 (see Figure 4, left) or by convection in presence of flow velocities faster than $10^{-5}$ m/s (see Figure 4, right). Accordingly, the temperature difference $dT_i$ between the initial state $T_i$ 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 flow velocity measurement
The relation between flow velocity and heat transfer coefficient at the wall valid for the heat transfer from a heated cylinder in presence of seepage in soil enables the Heat-Pulse Method to measure the Darcian flow velocity (Perzlmaier (2007)). 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 dependent on flow velocity. It is superposed by free convection only in very permeable soils ($k_D \geq 10^{-2}$ m/s) and else by conduction at slow flow velocities (see Figure 5).
DETECTION OF LEAKAGE AND INTERNAL EROSION

General
First of all, detection of internal erosion shall answer the question ‘where and to which extent does internal erosion take place and influences the dam stability?’. Therefore, the impact of internal erosion on the seepage pattern is focused. Since continuation and progression of internal erosion often go hand in hand with increased leakage, detection of internal erosion is frequently considered equivalent to leakage detection. Excessive internal erosion may be ruled out by reliable leakage detection proving the absence of any leakage anomalies.

However, the risk level related to internal erosion is hard to quantify by leakage detection exclusively. Even without any apparent seepage anomalies, the erosion process might already have started. Estimating the margin left between an actual no leakage stage and the different phases of internal erosion, needs a more detailed consideration of the parameters dominating potential particle transport. Comparing the hydraulic load on the particles derived from detection with their theoretical drag force may help estimating the likelihood of the different erosion phases to take place and continue. Similar concepts are required, if leakage has already been detected in times and places.

Finally, the parameters dominating internal erosion like particle size, cohesion, filter performance, hydraulic gradient, permeability, flow velocity and others are known to vary a lot, even within one dam. Failure occurs at random spots, where this set of parameters exceeds critical limits. Even though, certain areas in an embankment dam are known to bear a disproportional high risk of initiation the detection needs adequate spatial resolution over the whole structure to be successful and reliable.

Leakage detection

In the last decade distributed fibre optic temperature measurement has become a standard tool for leakage detection and installation of a corresponding monitoring system should
be considered in embankment dam construction. As described above in many cases the
detection of internal erosion is put on a level with leakage detection. Therefore, the
obvious advantages of the method for leakage detection applications are as well valid for
the detection of internal erosion. Leakage detection by means of the Heat-Pulse Method
has to be taken into consideration if:

- the length of the observed structure makes standard detection methods like
  seepage water discharge measurement unfeasible or inefficient,
- any required re-instrumentation of an existing dam does not allow for
  conventional detection strategies,
- the site conditions (e.g. dam structure, damage potential) require special
  measures like automated alarming systems,
- the high spatial resolution, inherent to the active temperature method, helps
  making the evaluation more precise and reliable,
- the gradient method is inapplicable because neither sufficient temperature
  gradients between reservoir water and location of the temperature measurement
  (under surface sealing or at the downstream toe) nor adequate seasonal
  temperature variations of the reservoir water are given,
- if the local information on degree of saturation and flow velocity are rather
  required than integral information on leakage anomalies provided by the passive
  method.

APPLICATION EXAMPLES

Asphalt surface sealing
In 1996 in the course of the rehabilitation of the “Mittlere Isarkanal Haltung 1” in
Munich fiber optic cables have been installed for leakage detection below the new asphalt
surface sealing for the first time. Monitoring of the canal dykes is done by using the
passive method. The first implementation of the active method has been carried out while
refurbishing the asphalt surface sealing of the Ohra Dam in Thuringia. Further
applications of the active method for monitoring asphalt surface sealing are among others
the Bautzen Dam in Saxony and the Al Khadra Reservoir in Libya.

Concrete surface sealings
The first application below concrete surface sealing has been carried out simultaneously
to the application below the asphalt surface sealing since part of the “Mittlere Isarkanal
Haltung 1” has been repaired with a concrete surface sealing. Further applications of fibre
optic based leakage detection systems in dams and dikes with concrete surface sealing are
the “Isarkanal Speichersee” (see Figure 6 left), and the “Mühltalkanal”, both hydropower
channels which divert water from the river Isar. In the two last mentioned projects the
active method is used while in the “Haltung 1” the passive method is applied.
Geomembranes
The first application for monitoring of geo-membranes was realised at the “Strogenbauwerk Isarhaltung 4b”, followed by installation of the monitoring system at the Alzkanal and the Brändbach Dam both in Germany, the Winscar Dam in England and the Kadamparai Dam in South India. A particularity in this field of application is the Bevertal Dam in Germany, where a central sealing consisting of steel sheets was extended to the dam crest using a PE-HD geo-membrane. The joint between the steel sheets and the geo-membrane is monitored by means of a fiber optic cable.

Dam toe
In all aforementioned application examples the monitoring system has been installed in the course of a fundamental rehabilitation of the sealing element or a new construction. In constructions where no rehabilitation is necessary or foreseen, the monitoring system can be installed a drainage drench or a berm on the downstream dam toe. Examples therefore are the Isarkanal Haltung 4b, the Havel-Oder-Wasserstrasse, the upper reservoir of the pumped storage plant Hohenwarte II, all in Germany, and the headrace channels of the hydropower stations Gabersdorf and St. Dionysen in Austria.

Construction joints
Another field of application is the monitoring of construction joints, in particular the perimetric joint (plinth) in dams with surface sealing. Differential settlements in the dam body may cause damage on the joint between subsoil sealing and surface sealing. The first application of fibre optic based leakage detection system for monitoring the plinth was realised on the Midlands Dam in Mauritius. The cable is installed in direct vicinity of the joint between the cut-off wall and the asphalt surface sealing. A further example is the Merowe Concrete Faced Rockfill Dam in Sudan (see Figure 6 right), currently under construction.

Fig 6. Installation of fiber optic cables for leakage detection on Isarkanal Speichersee (left) and Merowe CFRD (right).
CONCLUSION

Distributed fiber optical measurements contain 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 detections in CFRDs and canal embankments to temperature monitoring in RCC dams. Further developments of the instruments for distributed temperature sensing and the method itself make DFOT measurements to 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.

REFERENCES