In Situ Detection of Internal Erosion

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Abstract

The existence of a reliable method for the detection of internal erosion is indispensable to anticipate the failure of embankment dams. Using the temperature of seepage water as a tracer, a reliable method is to monitor the in-situ temperature of the dam's interior. As the ground material has low heat conductivity, temperatures indicate seepage at extremely low velocities, i.e. internal erosion at an early stage of development. This paper demonstrates how to measure in-situ ground temperatures along an array of temperature probes and alternatively along optical fibres. The temperature of seepage water operates well as a tracer if it is different from ground temperature, i.e. during periods like summer and winter. A climate independent application of ground temperature measurements for the detection of seepage water is the Heat Pulse Method (Frost Pulse Method) in which a heat pulse is artificially induced into the ground. The generated ground temperature's differences from normal and its return to initial equilibrium are monitored. The temperature developments are characteristic for different heat conductivities and percolated zones are especially emphasized. The flow velocity in combination with the dam's fill composition is the critical value indicating internal erosion. Two methods for the estimation of in-situ flow velocities are described.

Introduction

Internal erosion (suffusion) 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. Several methods within the scope of seepage detection have been studied in the past 50 years. Reliable methods are in-situ measurements which are provided by in-situ temperature monitoring. If different from ground temperature, the temperature of seepage water operates as a tracer and, when percolating the dam, provokes temperature anomalies within the fill-dam body. Because ground temperatures are lower than the temperature of retained water during summer, percolating water in the dam induces positive anomalies to the temperature distribution of the embankment. The contrary phenomenon appears during winter: Because ground temperatures are higher than the temperature of retaining water, percolating water in the dam induces negative anomalies to the temperature distribution of the embankment. Furthermore, as ground material has a low heat conductivity, temperature anomalies develop as soon as the pore velocities exceed 10^{-7} m/s, i.e. at a very early stage of possible internal erosion.

The detection of temperature anomalies inside the dam with an in-situ temperature monitoring technique provides a reliable localisation of seepage zones. The development of an adequate technique for in-situ temperature measurements was started in 1955 [1].

In-situ temperature measurement techniques

The technique of temperature probes has been developed to measure in-situ temperatures at different depths (up to 30-40 m) within existing embankment dams [2]. The temperature monitoring along optical fibres has been designed for fast and convenient recordings of the temperature distribution in dams of any composition and geometry in which optical fibres have been included during construction.

Temperature probes

This technique provides temperature measurements in sediments and embankments down to depths in excess of 30-40 m. Metallic tubes, consisting of several threaded sections, are rammed into the ground along a profile to result in an array of temperature probes as shown in Figure 1. Chains of temperature sensors generally placed at 1 m interval are inserted in the tubes. The in-situ ground temperatures at different depths are monitored after the tube's temperature has adapted to ground temperature. As the measured temperatures are immediately mapped on the

field-computer, the initial spacing of the temperature probes can be reduced where temperature anomalies are detected. Thus, vertical and horizontal boundaries of seepage zones, as presented in Figure 2, are localised on site.

Figure 1: Installation of an array of temperature probes

To date, temperature probes have been applied to dam sections of about 500 km length in all and to other hydraulic structures, showing an increasing demand for reliable and successful detection of seepage zones and leaks and also anomalous flow in the foundations of dams. Temperature probes are appropriate for the quality control after construction or repair works.
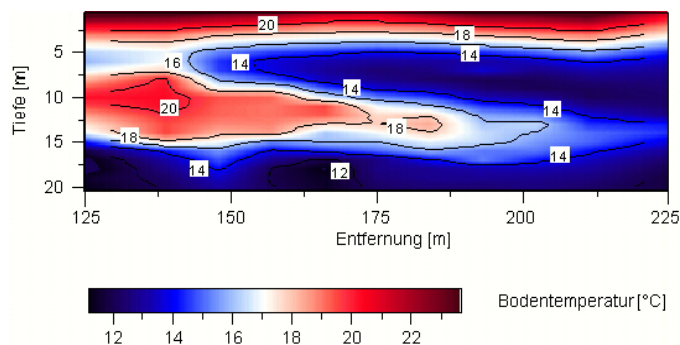

Figure 2: Temperature distribution resulting from a survey of an array of temperature probes

Distributed Temperature Sensing with fibre optics
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. The ratio of Stokes to anti-Stokes intensities is proportional to the temperature at the reflexion point (equals the measuring point). 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 method provides a temperature profile distributed along the entire optical fibre.

The distributed fibre optic temperature sensing method enables high resolution temperature measurements along a conventional optical fibre of up to 12 km of length. This method is suitable for the surveillance of dams, dikes and other hydraulic structures. The integration of optical fibres in the structure of new constructions or within the scope of renovation and repair works, as shown in Figure 3, provides the exact localisation of emerging leaks by temperature monitoring along the inexpensive fibre optic cable.

Figure 3: Optical fibres (hybrid cables) installed within a dam during construction (plinth of CFRD)

In the scope of repair works, optical fibres are often installed right behind sealing devices where the temperature shows no difference to the temperature of the retained water. For such situations the optical fibre has been enhanced by an electrical wire in order to generate heat in the vicinity of the cable. Both, the optical fibre and the electrical wires, are combined within the same cable named hybrid cable. The installation of hybrid cables provides fibre optic temperature measurements while heating (kind of heat pulse method, HPM, see next paragraph). The electrically induced heat is dissipated at locations of seepage water or increased flow and the temperature along the fibre does not increase as far as at places where no flow exists (see Figure 4). Leak detection using HPM is thus independent of temperatures of the retaining water relative to the ground's temperatures.
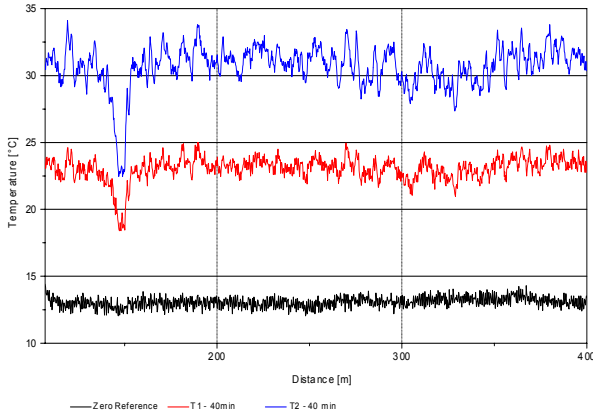
Figure 4: Temperature measurements along optical fibres at different times of heating, showing distinct seepage zones

The fibre optic sensing method was first applied in 1996 [3]. Since then, worldwide more than 150 km of hybrid cables were considered in the scope of many new constructions and rehabilitation works as a continuous surveillance device or for occasional inspection [4].

Furthermore, a more elaborate analysis of HPM reveals an estimation of pore velocities.

Heat Pulse Method (HPM)

The heat pulse method has been developed to measure local in-situ thermal conductivities and to estimate pore velocities of seeping water in existing earth fill dams and in the foundation. This method is based on generating a well defined heat disturbance of the ground represented by a line heat source. The line heat source is most easily realised with electrical wires.

In 1991 the line heat source was combined with temperature probes, i.e. electrical wires were inserted into the hollow tubes in addition to the chain of temperature sensors. In combination with optical fibres, HPM was first applied in 1998 [3].

As soon as the heat source has been switched on, the temperatures within the measuring device rise quickly and then tend towards some asymptotic value – the final temperature (see Figure 5). 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 theoretically will 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.
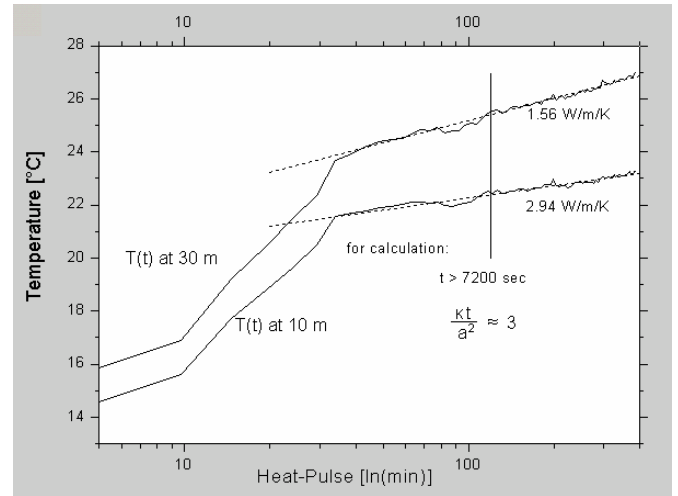

Figure 5: Temperatures versus time at different depths within a vertical probe as a result of HPM

Both temperature adaptation processes (heating and relaxation) are used for the determination of thermal conductivities of the material at the temperature measuring point. Thermal conductivities of soil and construction material range between 0.8 and 4.5 $W\,m^{-1}\,K^{-1}$. Thermal conductivities exceed by far these values when fluid flow occurs and they are then proportional to flow velocities. The heat pulse method offers thus the facility to estimate qualitatively pore velocities from ground temperature surveys.

The theoretical interpretation of temperature surveys undertaken with the heat pulse method is described in [5]. The present study focuses on the equation of heat transport for a line heat source (simplified assumptions). Equation (1) describes the evolution of the temperature $T(t)$ of the source for the heating phase which is:

$$T(t) = (q_L / 4\pi\lambda) \times \ln(t/t_0) + const. \qquad (1)$$

where

q_L: source strength $[W\,m^{-1}]$
λ :   thermal conductivity of material $[W\,m^{-1}\,K^{-1}]$
t :   time [s] from beginning of heating
t_0 :   time [s], total duration of heating

The source strength q_L is defined by the electrical current and the characteristics of the wire (electrical resistance) constituting the heat source. Equation (1) presents the solution of heat transport in a homogeneous and isotropic volume. It is valid for large times t. When the t-coordinate has a logarithmic graduation, equation (1) displays a straight line with a slope G inversely proportional to the thermal conductivity:

$$G = \Delta T(t) / \Delta \ln(t/t_0) = q_L / 4\pi\lambda \qquad (2)$$

Solving equation (2) for the thermal conductivity results in equation (3):

$$\lambda = q_L / 4\pi G \qquad (3)$$

Similarly, the thermal conductivity is deducible from the relaxation phase.

As stated before, equation (3) provides thermal conductivities of a homogeneous volume, not influenced by convection phenomena. Because the measured temperatures are locally influenced by seepage zones, the HPM provides apparent thermal conductivities with a conductive contribution and a convective contribution. Knowing from laboratory experiments the range of thermal conductivities of different dry and saturated soils (without flow movement), anomalous thermal conductivities calculated with equation (3) suggest convective contributions, i.e. seepage zones. The identified convective contributions provide an estimation of the corresponding pore velocities [6], as seen in Figure 6.
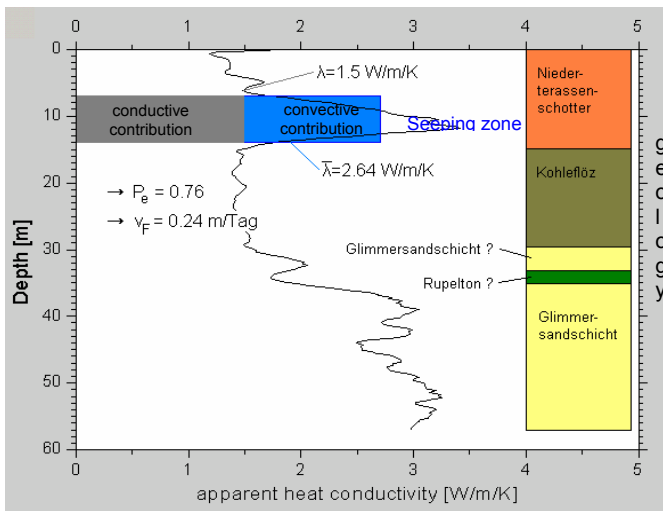

Figure 6: Thermal conductivities resulting from a HPM application

The penetration into the soil or construction material of the temperatures induced with HPM depends on the duration of heating, the strength of the heat source and on the flow velocity. The ongoing development of HPM envisages a more accurate estimation of pore velocities. The approach of pore velocities as described above has been applied in temperature probes in embankment dams and along a hybrid cables.

The opposite method of HPM is the frost pulse method. On sites without electrical supply, velocity estimations are technically feasible by cooling the tubings of temperature probes instead of heating them. Temperature surveys are monitored while cooling the tubes with liquid CO_2. Similar to HPM, the evaluation of data obtained with the frost pulse method reveals a qualitative estimation of the pore velocities.

Pore velocities from temperature probes

To date, critical pore velocities at which transportation of material (internal erosion) is initiated have theoretically been determined from grain size distributions and hydraulic gradients. Grain size distributions and hydraulic gradients are generally specified for a large volume, i.e. local heterogeneities are ignored by this determination of pore velocities. Caution is thus advised for the implementation of theoretically determined flow velocities.

Considering temperature probes, reiterative surveys allow the evaluation of pore velocities at the probe's location. Figure 7 shows for a water retaining embankment perturbations of ground temperatures versus time at different depths induced by seepage flow at depth. For depths within the seeping zone, trajectories of ground temperatures approach the temperatures of the retained water. The temperatures of the water reveal seasonal, weekly and even daily variations which reappear in the trajectories measured within the seepage zone, more or less attenuated in dependency of the flow velocity (see Figure 7 at 4 m, 6 m and 8 m depth). The time shift (labelled dt [s]) between evident variations detected in the graph of water temperatures and in trajectories of ground temperatures, is the time the seeping water needs to get from the entry point (into the embankment dam) to the measuring point (temperature sensor). Suggesting a length l [m] for this seepage path, the pore velocity at the considered measuring point is

$$v_{pore} = l/(dt). \qquad (4)$$

The capture of an evident temporal variation is necessary for the evaluation of pore velocities within seepage zones. Significant for the analysis and the determination of critical pore velocities at which internal erosion is initiated is the position of the temperature probe within the maximum ground temperature anomaly suggesting being the zone of maximum flow.

Consequently, for the application of this methodology, it is suggested to narrow down the position of the maximum ground temperature anomaly to 1 m interval (detection of the centre of the seeping zone) and to monitor evolutions of ground temperatures within the percolated soil and the temperatures of the retained water during seasonal variations. Applying this method, pore velocities of the order between 10^{-2} m/s (daily variations showing time shifts < 20 min) and 10^{-6} m/s (seasonal variations showing time shifts of 2-3 months) have been determined with satisfying accuracy.
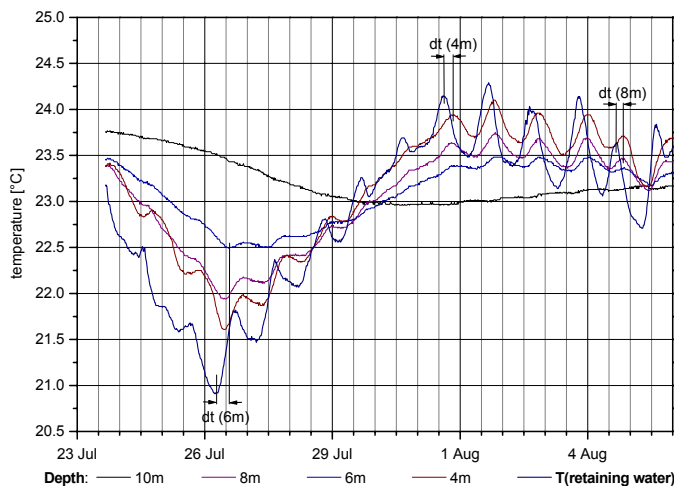
Figure 7: Temperature versus time at different depths for seasonal and, in this case, daily variations

Conclusion

The best confirmations of any phenomena are in-situ measurements. In-situ temperature measurements are a reliable method for the detection of seepage zones. Temperature differences (anomalies) indicate directly and clearly where seeping water exists in the ground (embankment dam and/or foundation). The heat pulse method is an in-situ temperature monitoring method independent of environmental temperatures, thus applicable at any season. In addition to the localisation of leaks, HPM is used for estimating pore velocities. HPM in combination with optical fibres is often applied to hybrid cables implemented in hydraulic structures and provides an estimate of pore velocities along the optic fibre (one line). The reiterative monitoring of temperature surveys along an array of temperature probes reveals reliable orders of pore velocities for a 2-dimensional section of the subsurface along that array. In theory, the integration of these pore velocities provide a measure of the total seepage flow. Repeated measurements of in-situ pore velocities allow conclusions to be drawn on the occurrence of erosion or clogging.

All described methods have proven practical applicability, reliability and cost effectiveness.

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