LEAKAGE DETECTION
TEMPERATURE AS A TRACER

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ABSTRACT

Internal erosion and piping are frequent reasons of failure and deterioration of dams and foundations e.g. breach of dams and collapse of excavation pits. Internal erosion and piping is controlled by material and construction properties (e.g. filters and drainage, grain and pore sizes) and hydrodynamic conditions. While construction properties are usually known, poor information is available on the local hydrodynamic situation inside dams and foundations. Hydrodynamic parameters may vary strongly due to local inhomogeneities and the most critical hydrodynamic parameter inducing internal erosion and piping (material transportation phenomena) is the pore velocity of the seeping water. The onset of 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.

The existence of reliable methods for the detection of erosion is indispensable to anticipate the failure of dams and foundations.

Using the temperature of seepage water as a tracer, applied to dams since 1953 [1] and to deep excavation pits and shafts since 1997, has demonstrated to be a reliable method to detect and monitor in-situ the seepage flow conditions, even at extremely low velocities, i.e. detecting erosion at an early stage of development. Nowadays it is even used to estimate the leakage rate. The paper demonstrates how to measure in-situ ground temperatures along an array of temperature probes and alternatively along optical fibres – passive and active method. Examples from a dam in Germany and a deep building pit in Italy are given.

1. Introduction

There are different approaches to detect seepage. The first approach, a passive approach – using temperature probes or simple fibre optic sensing cables - is based on absolute temperature changes in the subsurface caused by seepage water. This method is limited to cases with a temperature gradient between the seepage water and ground material. Nevertheless, the method is often an invaluable seepage indicator.

Many phenomena in soil can be investigated by ground temperature measurements. In all cases the temperature is used as a tracer for flow. Ground temperature measurements below 1m depth are an excellent tool for the detection of leaks in dams and dikes and their foundation, for the investigation of pollutant plumes downstream of waste deposits and landfill sites with organic content and for the detection of leaks in cement-sealed deep building pits. Uprising zones of thermal or karstic water in sediment basins can be investigated as well as leaks in sewers, district heating and other buried pipeline systems.

In 1991 GTC Kappelmeyer GmbH developed a patented temperature sounding method - temperature measurement by direct push - for economic measuring the temperature depth profiles. A chain of conventional temperature sensors is inserted a hollow pipe with a small diameter. This hollow pipe has to be rammed into the ground by a vibrating hammer before. Depending on grain size distribution and degree of compression 40 to 45 meter depth have been reached in the past. These depths are only reachable because special metal pipes are used and due to the low mantle friction of the small diameter pipes. More than 70 000 temperature soundings have been realised in the last 25 years.

To surpass the limitation to temperature gradients the second approach was developed – the heat-pulse method. It is also referred to as an active method. In praxis this method is mostly used in combination with fibre optic hybrid sensing cables. By heating the fibre optic sensing cable, cable sections within zones of higher water saturation or even flow zones appear as sections with increased heat transport, i.e. they heat up less. By calculating the effective thermal conductivities along the cable even the distribution of flow velocities in the subsurface can be estimated.

Both, the temperature difference and the effective thermal conductivity are sensitive methods to measure seepage or changes in the saturation of the ground.

The first technique, especially with the use of temperature probes, has been developed to measure in-situ temperatures at different depths within existing embankment dams [2] and deep building pits [3]. The second approach - 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 or rehabilitation.

2. In-situ temperature measurement techniques

The ground temperature is mainly determined by the temperature on the surface. Climatic influences lead to temperature highs in summer and temperature lows in winter. Due to the low thermal conductivity of the soil increasing phase differences develop between the temperature development on the surface and the temperature development in the soil with increasing depth. Further, due to the heat capacity of the ground, the amplitude of the temperature variations in the ground is decreasing with depth. The soil has therefore different temperature developments over time for different depths. Diurnal temperature changes on the surface have an impact in the soil down to few decimetres below ground level. Seasonal temperature variations can be measured as deep as 10 to 20m below surface. And the temperature of the region below is reflecting the long-term annual average temperature. In even bigger depths the temperature field is dominated by the heat flow from within the earth.

Anthropogenic influences such as sewerage, basements, underground railways etc. are influencing the ground temperature within urban areas, i.e. they lead to an increase of the soil temperature. These effects spread through ground water flows far beyond the immediate surrounding of the heat source. Through infiltration of surface water ground temperatures in the near field are adapting to the surface water temperature.

2.1 Temperature probes

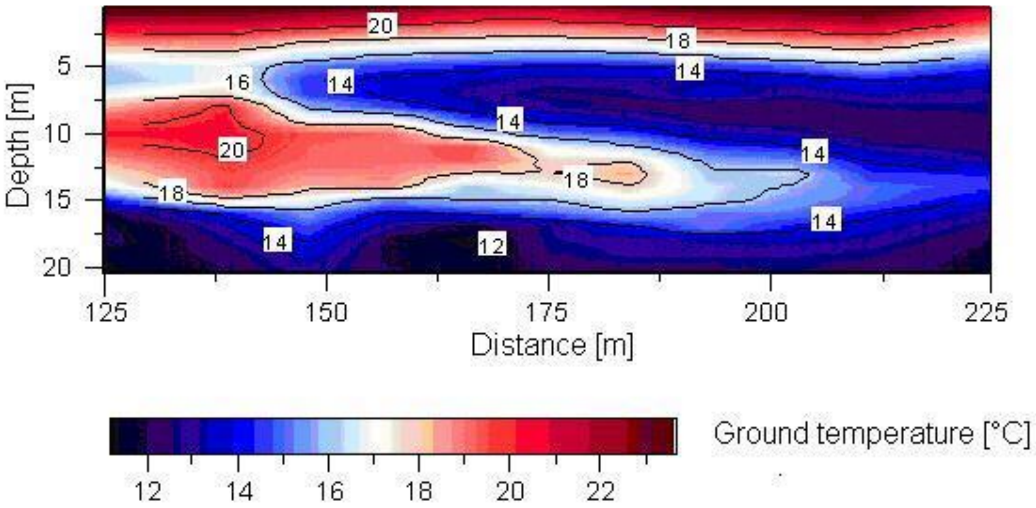
This technique provides temperature measurements in sediments and embankments down to depths in excess of 40-45 m. Metallic tubes, consisting of several threaded sections, are rammed into the ground along a profile to result in an array of temperature probes as shown in Picture 2.1.1. Chains of temperature sensors generally placed at 1 m interval are inserted in the tubes. The in-situ ground temperatures at different depths are taken after the tube's temperature has adapted to ground temperature. As the measured temperatures are immediately mapped on the field-computer as a 2 dimensional cross-section, the initial spacing of the temperature probes can be reduced where temperature anomalies are detected. Thus, vertical and horizontal boundaries of seepage zones, are localised on site.

Application in Dams

Picture 2.1.2 shows the 2D temperature distribution of a 100 m long vertical cross-section along dam's axis starting from 1m below crest level down to 20m depth. This example was taken from a 7m high embankment dam along the river Rhine in Germany. The temperature probes were rammed to 20m depth, through the dam into the foundation, to investigate potential seepage flow through the dam and/or through its foundation. The first few meters of the dam show high temperatures close to the surface fading away at greater depth as a result of the climatic situation in summer (see right hand site of graphic). In the centre and the left hand side high temperatures a clearly visible at greater depths, starting from 7m depth down to 16m. The water temperature of the river at the time of the investigation was 20°C. Between 130m and 140m length of the dam section in 10m depth the ground temperature was equivalent to the actual water temperature proofing a strong seepage flow through the dam's foundation at that part of the foundation. A new sheet pile wall was locally built and the leakage flow was terminated, avoiding the risk of internal erosion and piping.

To date, temperature probes have been applied to embankments of about 500 km length in all and to other hydraulic structures, e.g. ship locks, 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 in dams.

Picture 2.1.1 Installation of an array of temperature probes



Picture 2.1.2 Temperature distribution resulting from a survey of an array of temperature probes

Application in Deep Building Pits

In most cases, performing construction work below ground water level requires a dry excavation. For economic, structural and ecological reasons, it is usually necessary to isolate the pit hydraulically from its surroundings. Therefore in most cases, the excavation is sealed artificially. The sealing system typically consists of vertical elements (walls), and in the absence of an impermeable embedment layer, a horizontal element as well. A most common method for the realisation of these horizontal sealing elements is jet grouting and gel injection.

During the curing of the cement, the release of heat from hydration leads to an increase in ground temperatures in the areas surrounding the sealing elements. A combination of low thermal conductivity and high heat capacity in both the ground and building materials causes a low decay of the increased temperatures. However, if water flows from the ground into the excavation via a leak during dewatering, this will change the temperature profile in the ground around the affected area. The ground temperature therefore adjusts to the temperature of the inflowing water due to the advective heat transport of the flowing water. The cooled area extends to the area affected by leakage, and after some time to the close surroundings as well, through conductive heat transport. Temperature measurements in sealed excavation pits therefore enable the location of leaks in the sealing system.

Close to the surface the ground temperature in a building pit is influenced by solar radiation, the air temperature and the reflux of the jet grouting liquid. Normally the top few meters of the ground are anomalous warmed. With increasing depth then, the ground temperature is decreasing clearly – since there, as a rule, only a small amount of hydration heat is released – until the immediate vicinity of the jet grouting layer, where it starts increasing significantly. The temperature maximum is reached directly above the top of the grouting layer (respectively in the middle of the grouting layer). The propagation distance of the heat front, caused by the hydration process, into the ground of the building pit, depends on the age of the grouting layer. At the same time the grouting layer is cooling slightly. I.e., the older the grouting layer is, the more it will have cooled down and the further the heat front will have travelled. Since this heat transport is very slow, the grouting layer and the surrounding ground will be clearly warmed even months after the jet grouting process.

During dewatering the ground of the building pit is drained. As a rule the wells are equipped over their entire length with filter pipes, and therefore the influx occurs at first essentially from the top ground layers, according to the hydraulic gradient. If a building pit is leak-proof no significant flow from the deeper layers underneath the well will occur. Only in the case of a leak in the sealing system a hydraulic gradient - and the herewith connected water flow - will develop from the leak to the well. This flow will lead to an additional heat transport. First, there will be a brief warming, since the temperatures in the grouting layer (bottom or wall) are higher as directly above or nearby. After that, cooler water from outside the building pit flows inside. The temperature depth profile of the temperature soundings reflects this process. In the perfused depths of the pit it will become briefly warmer, before temperatures are dropping clearly and after some time reaching values, which are distinctively below the ones within the building pit.

Because the measurements are depths dependent - given the case of a leak - it can normally be distinguished between a leak in the vertical or the horizontal sealing element. Only if the leak is in the immediate vicinity of the intersection of the horizontal and vertical sealing element, an accurate classification can't be established.

Parts of the pit where ground water from outside the pit is entering through a leak during dewatering or has been entering during previous dewatering, are, respectively were, cooled down by the comparably cold ground water. At the completion of dewatering, no significant circulation occurs within the pit. The advective heat transport, linked to the leakage, will have stopped. From this point on, further temperature changes are only caused by heat conduction. The temperature front propagates in saturated and unsaturated materials at a velocity of approximately 10^{-6} to 10^{-7} m/s, equivalent to a few centimetres to decimetres per day. Therefore, temperature anomalies in the ground will only fade very slowly, allowing the temperature profile in the vicinity of a leak to show clearly, for a considerable time after dewatering (known as a memory effect) past flow processes. The temperature arrays in the surrounding of the leakage zones and in the influx zone of the respective well are showing therefore, long after the dewatering, significant temperature anomalies.

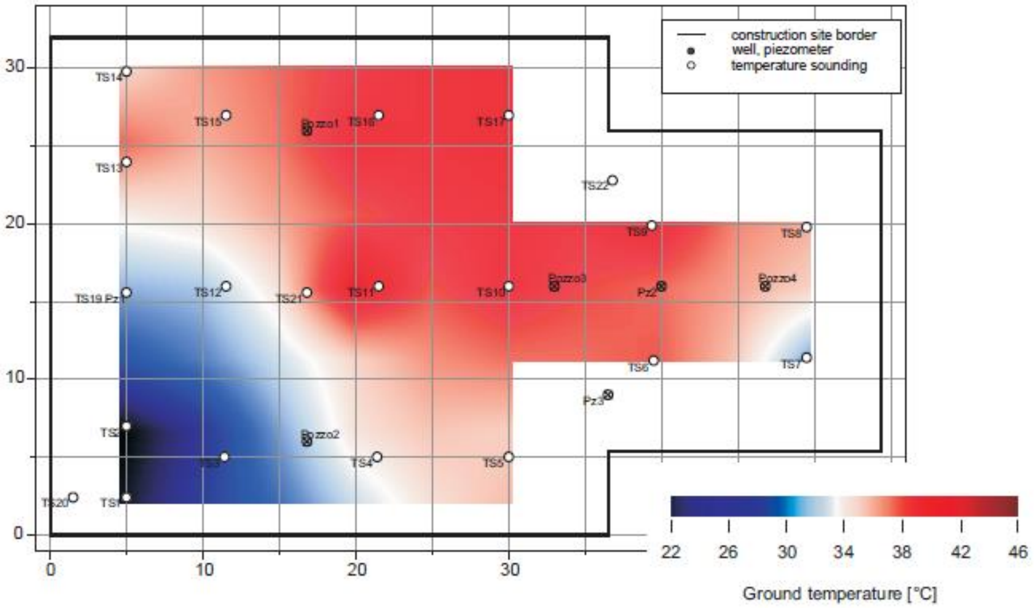
The temperature measurements inside the pit are carried out in a similar way as described for the dam application above. If the ground of the building pit is not penetrable by ramming, due to its compactness and soil composition, or if greater sounding depths are to be achieved, corresponding holes for the hollow pipes have to be predrilled.

The hollow pipes are inserted then in these predrilled holes and the thus created annulus in between pipe and (bore-)hole has to be backfilled. The backfill material needs to match the hydraulic properties of the surrounding soil, i.e., the hydraulic conductivity of the backfill should be in the range, or if need be, lower as the one of the one of the surrounding soil. It could mislead the interpretation if neglected vertical flow paths would arise.

The data obtained are used to compile temperature-depth profiles, as well as horizontal and vertical isothermal sections for the excavation pit. The temperature-depth profiles allow for an exact determination of the depth of the failure in the sealing system, whereas the isotherms allow for an overview in the lateral extent of the leakage zone.

Picture 2.1.3 shows a horizontal 2D temperature distribution above the jet grouting layer after 3 days pumping test inside a sealed excavation pit. At the bottom of the left hand side of the graphic the soil inside the pit has cooled strongly due to a leak in the sealing element. Cold ground water flow from outside into the pit cooled the soil temperatures. A pinpointed repair work sealed the leak at that place and the pit was excavated without any risk of piping induced heave.

Since 1995 the leakage detection method was applied in more than 170 excavation pits. Existing leaks have been localised exactly and the necessary rehabilitation works could be directed carefully. As an evidence for the spatial and temporal spreading behaviour of injection material the ground temperature measuring method has been used successfully on several occasions of silica-gel and micro-cement injections. At all application named above the temperature of the water, respectively the temperature of the injecting material, is used as a tracer for the to be detected flow.



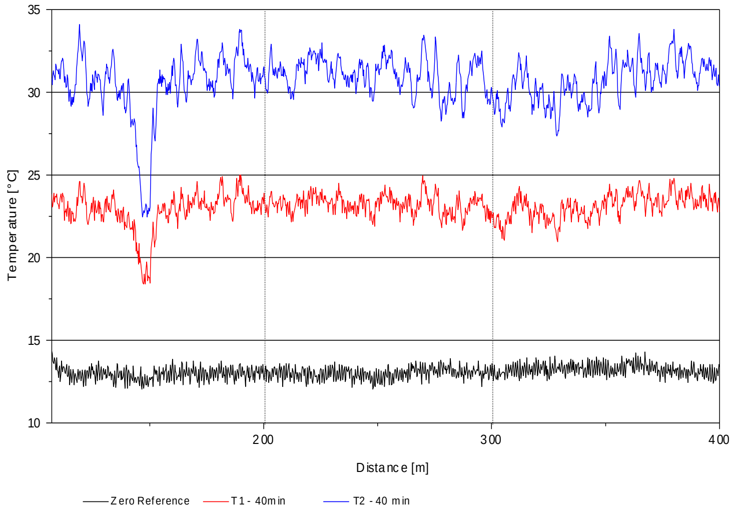
Picture 2.1.3 Temperature distribution resulting from a survey of an array of temperature probes

2.2 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 30 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 provides the exact localisation of emerging leaks by temperature monitoring along the inexpensive fibre optic cable.

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 a heat pulse in the vicinity of the cable. If both, the optical fibres and the electrical wires, are combined within the same cable, the cable is referred to as a hybrid cable. The installation of hybrid cables provides fibre optic temperature measurements while the cable is heated (see heat pulse method, HPM, next paragraph). The electrically induced heat is dissipated at locations of seepage or increased flow and the temperature along the fibre does not increase as much as at places where no flow exists (see Picture 2.2.1). Leakage detection using HPM is thus independent of the temperature gradient between retaining water temperature and the dam temperature.



Picture 2.2.1 Temperature measurements along optical fibres at different times of heating, showing distinct seepage zones

The fibre optic sensing method was first applied in 1996 [4]. Since then, worldwide more than 180 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[5].

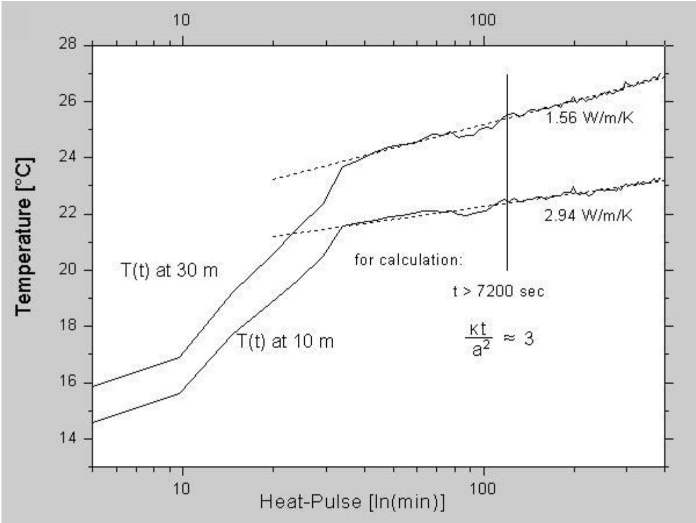
Furthermore, a more elaborate analysis of HPM reveals an estimation of pore velocities.

2.3 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 [4].

As soon as the heat source has been switched on, the temperatures within the measuring device rise quickly and in the case of pure thermal conduction they will increase constantly on a logarithmic time scale (see Picture 2.3.1). In the case of convection, provided by a seepage flow, the temperatures tend towards some asymptotic value – the final temperature. According to its thermal conductivity, the material surrounding the temperature measuring device dissipates the induced heat. 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.



Picture 2.3.1 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 4.5Wm^{-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 [6].

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 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.

3. Summary

In situ temperatures measurements, in the form of temperature probing or distributed fibre optic temperature sensing constitute a powerful tool for seepage detection and seepage monitoring. The method and its enhancements, such as the Heat Pulse Method, have served successfully as a leakage investigation and seepage monitoring tool for more than 100 dams and 500 km of embankments throughout the world. More than 170 deep building pits have been investigated upon leakage by using temperature as a tracer for seepage flow.

4. References

[1] Kappelmeyer, O. (1957). The use of near surface temperature measurements for discovering anomalies due to causes at depth. Geophysical Prospecting, The Hague, Vol. 3, pp. 239-258.

[2] [Dornstädter, J. (1997). Detection of internal erosion in embankment dams. ICOLD, Florence.Q.73R.7. 2: 87-101, International Commission on Large Dams, Paris.

[3] Dornstädter J., Dr. Huppert F. (1998) Thermische Leckortung an Trogbaugruben mit tiefliegenden Sohlen, pp 179-187, Vorträge der Baugrundtagung 1998 in Stuttgart, Deutsche Gesellschaft für Geotechnik e.V.

[4] Aufleger, M., Dornstädter, J., Fabritius, A., Strobl, Th. (1998). Fibre optic temperature measurements for leakage detection - applications in the reconstruction of dams. 66th ICOLD annual meeting, New Delhi, pp. 181-189, International Commission on Large Dams, Paris.

[5] Aufleger, M., Dornstädter, J., Strobl, Th., Conrad, M., Perzlmaier, S., Goltz, M. (2007). 10 Jahre verteilte faseroptische Temperaturmessungen im Wasserbau. 14. Deutsches Talsperrensymposium/ 7th ICOLD European Club Dam Symposium, pp. 8 14, Freising.

[6] Carslaw H.S., Jaeger I.C. (1959): Conduction of heat in solids. Oxford University Press, London, 2nd ed.