Is internal erosion detectable?

J. DORNSTÄDTER, GTC Kappelmeyer GmbH, Karlsruhe, Germany
D. DUTTON, British Waterways, Watford, UK
A. FABRITIUS, GTC Kappelmeyer GmbH, Karlsruhe, Germany
P. HEIDINGER, GTC Kappelmeyer GmbH, Karlsruhe, Germany

SYNOPSIS. Three possible methods of estimating seepage flow velocity, using the well-proven ground temperature sensing technique, are presented for use as a means of detecting and monitoring the progress of internal erosion within an embankment dam.

INTRODUCTION

Embankment dams account for nearly 80% of the dams in the UK and, of these, about 75% were built before 1940, thus predating modern geotechnical engineering. There have been a number of catastrophic failures in which lives have been lost; the best known being Bilberry (which failed in 1852 with the loss of 81 lives) and Dale Dyke (which failed in 1864 with the loss of 245 lives). Overtopping and internal erosion have been the two main causes of embankment dam failure in the past; the risk of catastrophic overtopping during floods has now largely been eliminated with improvements that have been made in the methods of hydrological analysis over the last 75 years, leaving internal erosion as the most likely cause of dam failure in this country in the future.

INTERNAL EROSION

The processes of initiation and progression of internal erosion are not, as yet, well understood. Modern dam design practice includes the use of zoned fills and filters to combat internal erosion but, for existing, old dams, the emphasis has to be on surveillance and monitoring for the early detection of progressive internal erosion.

The following case study, involving the embanked River Rhine, demonstrates a possible way to detect internal erosion. Over a period of

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several years, ground temperatures at different depths in the river embankment were measured, together with the temperature of the river water. Initially, there was almost no phase shift between the water temperature and the ground temperature (Fig. 1) as would normally have been expected *(Armbruster et al 1992)*. After a slurry trench wall had been built, a phase shift and a difference in amplitude of the temperatures occurred and increased over time, indicating that Darcy-velocities had decreased in the embankment. As a consequence of constructing the slurry trench, all indications of seepage - and therefore internal erosion - ceased. Inverting the argument, one can conclude that a reduction in phase shift between water and ground temperatures is caused by increased seepage, itself the consequence of internal erosion. Therefore, ground temperature measurements can help to detect internal erosion.

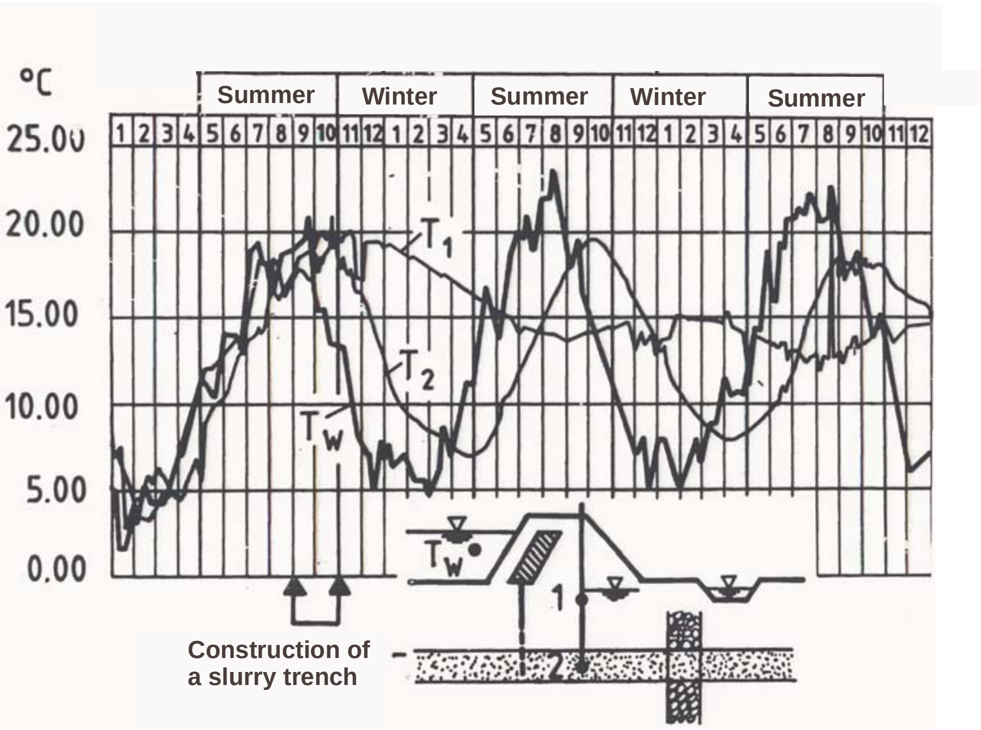

Figure 1. The building of a slurry trench in an embankment leads to a phase shift in the temperature between the water and the ground at the positions T1 and T2.

GROUND TEMPERATURE MEASUREMENT

The technique exploits the differing seasonal variations in temperature which occur within the ground and within surface water bodies. In non-percolated ground, the temperature at any depth is a function of the temporal variation in surface temperature and the thermal conductivity of the soil.

The flow of fluid from a surface water source through the soil will alter the non-percolated ground temperature distribution, creating temperature anomalies. Measurable temperature disturbances will be created by Darcy-velocities as low as 10^{-7} m/s to 10^{-6} m/s.

To measure ground temperatures at depth, a series of small-diameter, thread-coupled hollow steel tubes are installed vertically at intervals along the line of the embankment; in the case of homogeneous dams, and those with a watertight element within the embankment, the probes are sited close to the downstream edge of the crest. The tubes are driven by hand-portable rammers; depending on the nature of the ground, the distance between probes is generally 10m or 20m, but may be reduced to 5m for particular investigations, and probe depths of 20-30m can be achieved. For short-term or limited-extent investigations, ground temperatures are measured by lowering a string of temperature sensors into each tube; the tubes are withdrawn from the ground at the end of the investigation. For long-term monitoring, temperature sensors can be permanently installed within the tubes, and the cables run to a nearby data-reader unit for remote interrogation.

Because of the hand-portable nature of all the equipment, access is not normally a problem and no heavy vehicles are required on the embankment. It is quite possible to carry out all site operations at a 150m long, 15m high dam in one working day.

METHODS OF COMPUTATION OF DARCY-VELOCITY

To detect internal erosion (and the corresponding Darcy-velocity) with ground temperature measurements over short time periods, or with only one set of measurements, the following methods have been used: the phase shift approach, the determination of Darcy-velocities by scaling and the use of apparent thermal conductivity.

A. Phase shift approach

This approach has two essential requirements. The first is a period of frequent measurements of the reservoir water temperature and the ground temperatures within the dam; the second requirement is that the monitoring takes place at a time of year when the water temperature is not static and, during the period of monitoring, there must be a clear temperature turning point, either a maximum or a minimum.

The method of analysis requires first that a leakage investigation is undertaken to locate the percolated and non-percolated sections of the dam, using the ground temperature sensing technique developed and patented by GTC Kappelmeyer GmbH (Dornstädter 1997). Knowledge of the ground temperatures at the non-percolated sections of the dam allows the temperature changes due to seepage to be identified.

At the percolated sections, variations in the reservoir water temperature will, after a time interval, be reflected in the ground temperatures. Establishing this phase shift between the reservoir water temperature and the ground temperature at each point of leakage, and knowing the length of the flow path from the water/dam interface to the position of the ground temperature sounding, enables the Darcy-velocities to be calculated. For leakage at shallow depth below the crest of the dam, the assumption of a horizontal flow path may provide a sufficiently accurate estimate of the flow velocity but for leakage at greater depth, or for a more accurate estimate of the flow velocity, it would be necessary to install, and monitor, a second temperature probe on the percolated section, at a known distance from the initial leakage investigation probe. Under these circumstances the frequency of temperature monitoring may have to be increased to ensure that the phase shift is accurately measured.

B. Temperature and Spacial Difference Scaling approach

Under certain circumstances, this method offers a fast and easy estimation of the Darcy-velocity distribution within a dam. The approach is based on a single measurement of the ground temperature distribution in the dam and the flow rates of all issues from the dam, together with a knowledge of the geometry of the dam. The measurement of ground temperatures in the dam must show at least one non-percolated section in order that the temperature anomalies due to seepage can be identified. The method of analysis also assumes that:

- the water temperature is constant throughout the full depth of the reservoir and that it has not varied significantly for a period of time (~ 14 days) prior to the ground temperature investigation,
- the dam foundation is impermeable and the measured issue flows represent the total leakage through the dam

The leakage potential at every point (node) in the dam where the ground temperature is measured, and the Darcy-velocity at these nodes can then be determined by scaling.

The average Darcy-velocity through the dam is by definition:

$$v_{\bar{d}} = \frac{Q}{A} \qquad (1)$$

where

$v_{\bar{d}}$: average Darcy-velocity [m/s]

Q: total leakage flow rate [m^3/s]

A: longitudinal profile area of dam [m^2]

This average Darcy-velocity represents an evenly distributed seepage velocity, as if through an isotropic and homogenous dam. In practice the water will flow in some places more than in others. Where there is little or no leakage, the ground temperatures in the dam will approach, or be identical to, those at the non-percolated sections of the dam but, at places with a high seepage flow, the ground temperatures will be closer to the temperature of the reservoir water.
An area of flow is assigned to every measured temperature node. This assigned area covers, both vertically and horizontally, the half distance to the next temperature node. Thus, if all the temperature nodes except one display a non-percolated ground temperature, then all seepage water is assumed to flow through the assigned area of that one particular node. If more nodes with disturbed temperatures exist, the flow must be distributed to the areas assigned to them. This flow distribution has to be done in accordance with the scale of the temperature disturbance at each node. The sum of all flows leads to the total leakage flow:

$$Q = \sum_{n=1}^{m} v_n \cdot A_n \qquad (2)$$

where

m: number of nodes

v_n: Darcy-velocity at node n [m/s]

A_n: assigned area of node n [m²]

A scaling factor can be implemented in the following way:

$$v_n = f_n \cdot v_{ref} \qquad (3)$$

where

f_n: scaling factor for node n

v_{ref}: reference Darcy-velocity [m/s]

The reference Darcy-velocity is not necessarily a physical value; it is more a calibration value, which can directly be determined out of equations (2) and (3):

$$v_{ref} = \frac{Q}{\sum_{n=1}^{m} f_n \cdot A_n} \qquad (4)$$

With the assumptions shown above, the mathematical description of the temperature field inside the dam can be simplified from the unsteady (Bear 1972, Huyakorn and Pinder 1983) to the general steady heat conduction and convection equation of an isotropic and homogenous porous media. The steady state equation has the following form:

$$0 = A' + b \cdot v_d \cdot grad\ T \qquad (5)$$

where

A' : conductive heat transport [W/m³]

b : constant factor [J/K/m³]

v_d : Darcy-velocity [m/s]

Neglecting the conductive heat transport[1], a scaling of the Darcy-velocities must be done according to $grad\ T$. The gradient of the temperature is defined as the quotient of the temperature difference and the spatial difference. Therefore, to fully implement the gradient of the temperature, we have to split the scaling factor f_n into two sub-scaling factors:

$$f_n = f_{\Delta T} \cdot f_{\Delta X} \qquad (6)$$

where

$f_{\Delta T}$: scaling factor for temperature difference

$f_{\Delta X}$: scaling factor for spatial difference (geometry factor)

The scaling factor for the temperature difference can be found by comparing the water/ground temperature variance. A leakage potential at any depth d below the dam crest level is represented by:

$$\Delta T_{(NW)d} = T_W - T_{Nd} \qquad (7)$$

where

T_W : reservoir water temperature [°C]

T_{Nd} : non-percolated ground temperature at depth d [°C]

[1] This can be done at first order, because the amount of heat transported by conduction is generally far less than the amount transported by convection. The amount is the same at a Darcy velocity of about 1.E-7m/s.

The measured ground temperature anomaly of a node is represented by:

$$\Delta T_{(Gd)n} = T_n - T_{Nd} \qquad (8)$$

where
T_n: ground temperature at node n [°C]

Then, the ratio of the measured ground temperature anomaly to the leakage potential is the scaling factor for the temperature difference:

$$f_{\Delta T} = \frac{\Delta T_{(Gd)n}}{\Delta T_{(NW)d}} = \frac{T_n - T_{Nd}}{T_W - T_{Nd}} \qquad (9)$$

This scaling factor $f_{\Delta T}$ ranges from 0 (the measured temperature equals the non-percolated ground temperature - no leakage) to 1 (the measured temperature equals the water temperature - maximum leakage). Where, due to inherent physical limitations of the method of investigation, $f_{\Delta T}$ is found to be less than 0 or greater than 1, its value is limited to 0 or 1 respectively.

The scaling factor for the spatial difference can be found by consideration of the geometry of the dam; the longer the seepage flow path, the greater the significance of the measured ground temperature anomaly. The scaling factor again ranges from 0 to 1 and is calculated from:

$$f_{\Delta X} = \frac{d_n}{d_{\max}} \qquad (10)$$

where
d_n: flow path length to node n [m]
$d_{\max}$: maximum flow path length to any node [m]

Now all the necessary equations are established. For an analysis, first all scaling factors of the nodes are calculated and added, weighted by their assigned area (Equation 4). Thereby, the calibration Darcy-velocity v_{ref} is determined. Then, the Darcy-velocity for each node can be specified, according to equation 3.

C. Flow velocity determination by the use of heat conduction

C.1. Approximate solution for the determination of thermal conductivity

It is possible to establish the differential equation describing unsteady conductive heat flow from a long, cylindrical, ideal heat source embedded within a homogenous matrix. (*Blackwell, 1954* and *Jaeger, 1956*), but the complexity of the equation makes it of limited practical use. A simpler form of the equation, requiring only the direct determination of the thermal conductivity provides an approximate solution, although this is only valid for a certain time frame. The error involved is no more than ± 10% (*Sattel, 1982*).

for $\frac{\kappa t}{a^2} >> 1$ follows:

$$T_i(t) = A \ln\left(\frac{t}{t_0}\right) + B \qquad (1)$$

where

$$A = \frac{q_L}{4\pi\lambda}$$

and

$$B = \text{constant}$$

with:

$T_i(t)$: temperature of the heat source after time t [°C]
λ: thermal conductivity of the homogenous matrix [W/m/K]
q_L: heat capacity per unit length of the cylindrical heat source [W/m]
κ: thermal diffusivity of the homogenous matrix [m^2/s]
t: time since the start of the heat-pulses [s]
t_0: time unit (1 sec.)
a: radius of the cylindrical heat source [m]

In equation (1) – for a semi-logarithmic display of the temperature – the gradient of the curve is inversely proportional to the thermal conductivity of the surrounding matrix and this simple relationship is used to determine the conductive heat flow. The constant shift B depends on the heat transfer coefficient at the heat source/matrix interface and is not taken into account in the evaluation of the conductive heat flow *(Dornstädter 1987)*.

To use this method to investigate seepage through an earth dam, a linear heat source is installed at locations within the embankment. Where seepage is occurring, heat will be transported away from the heat source by convection as well as conduction, and the assumptions which underlie equation (1) are no longer valid. The heat flow is no longer solely dependent on the material surrounding the heat source, but is also influenced by the seepage flow; the value of λ derived under these circumstances using the approximate solution is referred to as the apparent thermal conductivity.

The apparent thermal conductivity can also be determined by numerical modelling although, unfortunately, there is no exact analytical solution because the cylindrical symmetry of the purely conductive heat flow is corrupted by the seepage flow and complicates the heat flow equation. In practice there are two different approaches which enable the influence and the quantitative value of the seepage flow velocity (Darcy velocity) to be determined.

C.1.1. Péclet number analysis

The Péclet number analysis is a one dimensional approach to determine the Darcy velocity. The Péclet number P_e describes the ratio between the convective and conductive heat flow. This ratio must be determined by using the approximation solution (equation (1)). Sections with high apparent thermal conductivity can be identified as percolated layers (convective and conductive heat transport) and sections with low apparent thermal conductivity as layers without seepage flow (pure conductive heat flow). If the same thermal conduction is assumed for the ground matrix in all the layers, the thermal conductivity λ_{cond} in the layer without seepage flow is proportional to the conductive heat transport, and in the layer with seepage flow the apparent thermal conductivity $\lambda_{cond+conv}$ is proportional to the sum of the convective and conductive heat transport. Therefore, the Péclet number can be determined by:

$$P_e = \frac{\lambda_{cond+conv.} - \lambda_{cond.}}{\lambda_{cond}} = \frac{\lambda_{cond+conv}}{\lambda_{cond}} - 1 \qquad (2)$$

and the Darcy velocity can be calculated by using the definition of the Péclet number (*Zschocke, 2003*):

$$P_e = \frac{q_a}{q_c} = \frac{\rho\, c_p\, v_f\, \Delta T}{\lambda \left(\frac{\Delta T}{l} \right)} \qquad (3)$$

$$v_f = \frac{P_e\, \lambda}{l\ \rho\ c_p} \qquad (4)$$

$$v_f = \frac{\lambda_{cond+conv} - \lambda_{cond}}{l\,\rho\,c_p} \qquad (5)$$

with:

q_a:	convective (advective) heat flow [W/m^2]
q_c:	conductive heat flow [W/m^2]
ρ:	density of the fluid [kg/m^3]
c_p:	specific heat capacity of the fluid at constant pressure [J/kg/K]
v_f:	flow velocity of the fluid [m/s]
ΔT:	temperature difference [K]
$\lambda = \lambda_{cond}$:	thermal conductivity of the ground [W/m/K]
l:	characteristic length [m]

The Péclet number analysis is a fast and direct method of determining the seepage velocity by the use of the heat pulse method. The accuracy of the results, though, is strongly dependent on the thermal conductivity of the ground material. Using incorrect thermal conductivities for the ground material may mean that the conductive part of the heat flow is not determined correctly, with errors of up to 100% or more. Nevertheless the method can be used for a quick assessment of a change in the seepage flow velocity with respect to previous measurements, thus helping to determine the onset of internal erosion.

C.1.2 FD Modelling

The second method of determining the Darcy velocity uses FD- (or FE-) modelling, involving the following steps:

- measuring the heat-up curve
- simulation of the heat-up curve with a finite difference (or finite element) program for various seepage velocities
- comparison of the simulated curves with the measured ones from which conclusions about the Darcy velocity can be drawn..

This approach enables a fairly exact determination of the Darcy velocity in the ground, even if the parameters necessary for the modelling (permeability, porosity, thermal conductivity and specific heat capacity) are not known exactly. The accuracy which can be achieved with this method is ± 25% (*Heidinger, 1998*). The disadvantage of this method lies in the considerable effort needed, and power required, to provide all the data and conditions for the model.

CASE STUDIES

Cam Loch

Cam Loch is at the head of a cascade of reservoirs feeding the Crinan Canal in Scotland. The loch is retained by two dams, the more westerly one of which is about 60m long and has a maximum height of 7.5m. A small issue of water has been known to occur at the toe for many years. A ground investigation carried out at the dam in 1989 did not locate a clay core but showed that the embankment consists mainly of peat on a rock foundation; a rockfill berm, with a drain at its toe, was constructed on the downstream face during remedial works undertaken in 1990.

A temperature sounding leakage investigation was carried out in March 2005 when the reservoir water was still at a typical winter temperature of 3.5 °C. The measured temperatures are shown on the longitudinal profile of the dam in Figure 2. Issue flows at the dam toe totalled 0.6 l/s and the investigation indicated temperature anomalies partway along the dam, down to a depth of 2 m below crest (1 m below TWL), and also adjacent to the left abutment.

Analysing the temperature data by means of the Temperature and Spatial Difference Scaling method outlined above gave a Darcy-velocity distribution shown on the longitudinal profile of the dam in Figure 3.

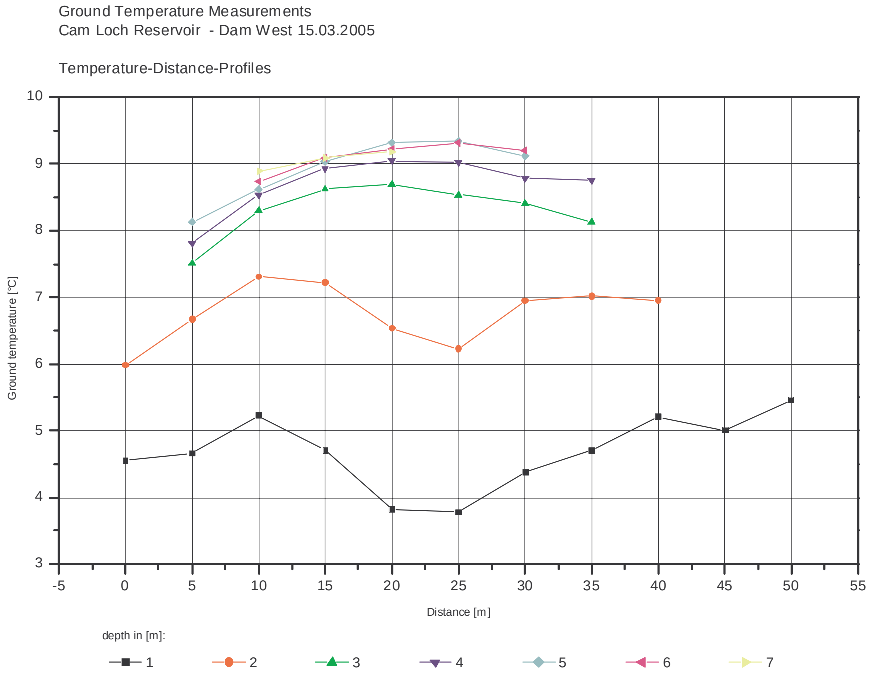

Figure 2 The temperature-distance profile recorded during the temperature sounding leakage investigation.

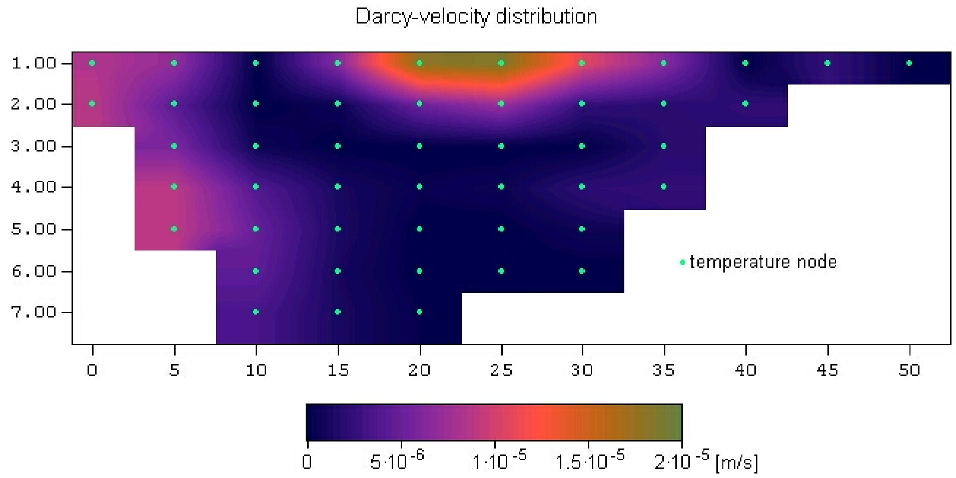

Figure 3. Darcy-velocity distribution. The maximum flow velocity was calculated to be $1.87*10^{-5}$ m/s.

River Rhine embankment

This investigation was conducted to check the impermeability of a newly installed sealing wall. Temperature measurements using the Heat-Pulse method were conducted along a several hundred metre long section of the river embankment. These results, combined with the Peclet number analysis, enabled Darcy-velocities of a possible seepage flow through the embankment to be determined.

At three points within the investigated section, temperature soundings were performed on the upstream and the downstream side of the sealing element. The soundings were positioned at 1m distance from the sealing element and reached 1m below it.

At one of the soundings, the results showed a slight seepage flow – in the range of 10^{-6} m/s. The results are displayed in Figures 4, 5 and 6.

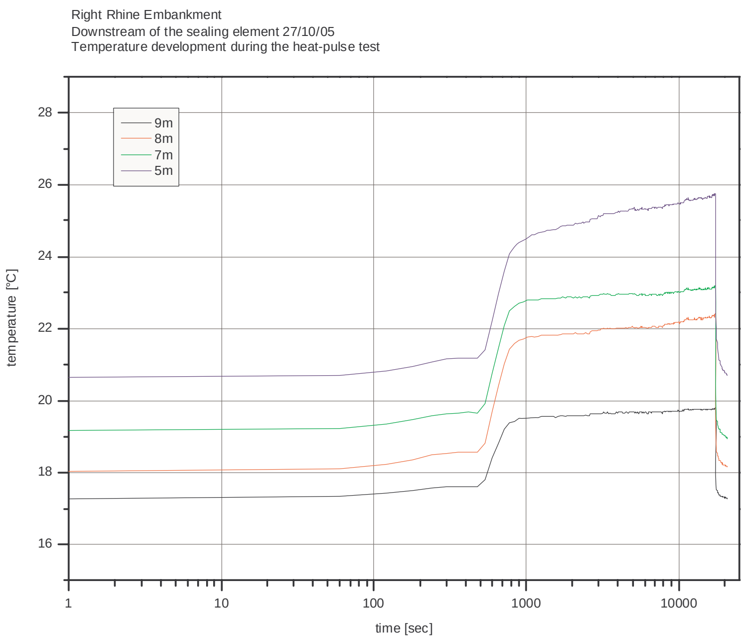

Figure 4 Temperature development during the heat-pulse test shown on a logarithmic time scale.

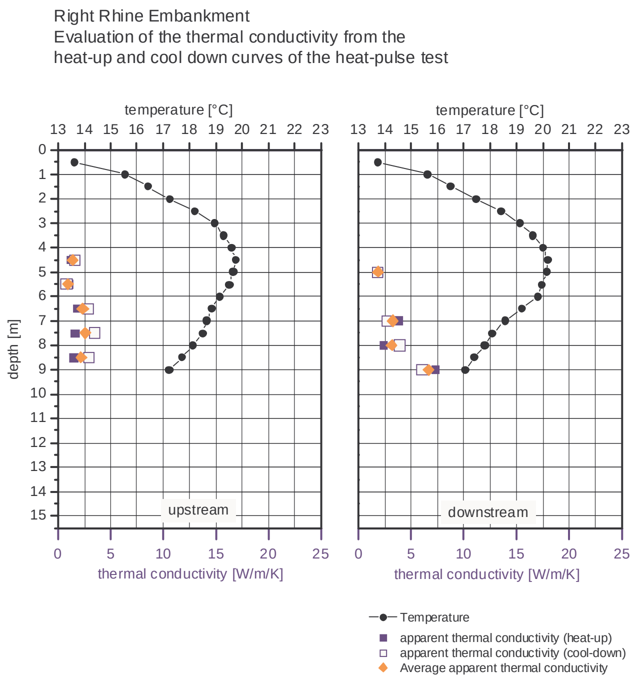

Figure 5 Thermal conductivity upstream and downstream of the sealing element.

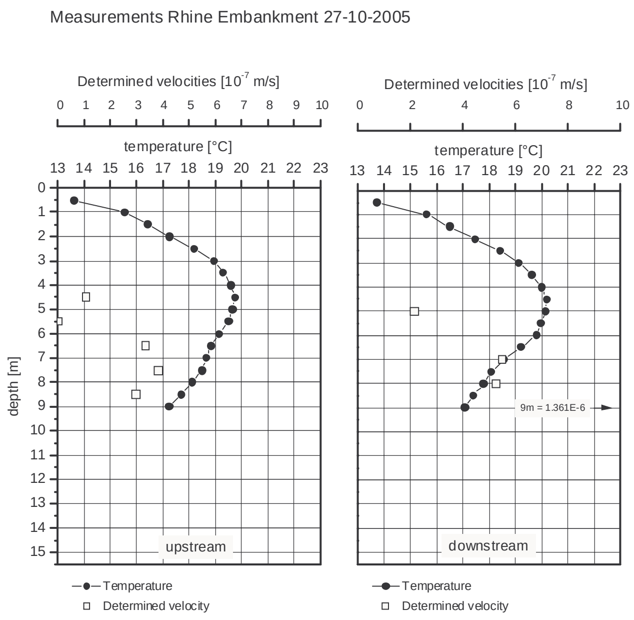

Figure 6 Darcy velocities on both sides of the sealing element.

CONCLUSIONS

Seepage through embankment dams can be detected by means of ground temperature measurements. Ground temperature measurements taken over a period of time or, under certain conditions, during a single investigation, can provide an initial estimate of the Darcy-velocity of the seepage flow. This allows an early diagnosis of internal erosion, to be confirmed if necessary by further investigation. If, during a second investigation, an increase in the Darcy-velocity is detected with the same hydraulic loading conditions, progression of internal erosion is indicated.

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