Seepage Monitoring in Embankment Dams

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Temperature measurements in the embankment dam at Näs power plant, 1990.

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Sam Johansson

PREFACE

The principal work in this thesis, the measurement and evaluation of temperature and resistivity variation in embankment dams, developed from my previous research concerning heat storage in aquifers (Johansson 1989). The experience gained from the thermohydraulic studies, laboratory experiments and field investigations carried out during my previous research was a major initiating factor for this work concerning the performance of embankment dams.

The thesis is based upon the following publications:

PAPER 1:
Johansson, S., Localization and Quantification of Water Leakage in Ageing Embankment Dams by Regular Temperature Measurements, Q.65, R.54, *Proc. ICOLD 17th Congress in Vienna*, pp991-1005, 1991.

PAPER 2:
Claesson, J., G. Hellström, and S. Johansson, Temperature Analyses for Evaluation of Water Flow in Aquifers and Embankment Dams, Submitted to *Water Resources Res.*, 1996.

PAPER 3:
Johansson, S., J. Claesson, and G. Hellström, Seepage Evaluation in Embankment Dams by Temperature Measurements, Submitted to *Water Resources Res., 1996*.

PAPER 4:
Johansson, B., S. Johansson, and R. Nilsson, Investigations and Repair of the Embankment Dam at Porjus Power Station, *Proceedings from Repair and Upgrading of Dams*, KTH Stockholm, pp218-227, 1996.

PAPER 5:
Johansson, S., Seepage Monitoring in Embankment Dams by Temperature and Resistivity Measurements, *Proceedings from Repair and Upgrading of Dams*, KTH Stockholm, pp288-297, 1996.

PAPER 6:
Johansson, S. and T. Dahlin, Seepage Monitoring in an Earth Embankment Dam by Repeated Resistivity Measurements, *European Journal of Engineering of Environmental Geophysics*, vol 1, no 3, pp229-247, 1996.

PAPER 7:
Carlsten, S., S. Johansson, and A. Wörman, Radar Techniques for Indicating Internal Erosion in Embankment Dams, *Journal of Applied Geophysics 33*, pp143-156, 1995.

These publications, referred to as PAPER 1 to PAPER 7, are appended at the end of the thesis. They are based on several projects involving almost ten years of research and field measurements. Results from these research projects have primarily been published in reports in Swedish. These reports contain more detailed information than PAPER 1 TO

7 as well as additional measurements. They are listed below in chronological order and are available from the author.

- Johansson, S., O. Landin, and P. Ulriksen, Bestämning av tätkärnans krön med georadar, (Location of the core crest with Ground Penetrating Radar), VASO report, Stockholm, 97 p, 1989.
- Johansson, S., Detektering och kvantifiering av vattenläckage i jord- och sten-fyllnadsdammar genom temperaturmätningar (Location and quantification of water leakage in embankment dams by temperature measurements), Royal Institute of Technology, Hydraulic Engineering Report No 45, Stockholm, 53 p, 1990.
- Johansson, S. and S. Berglund, *Utvärdering av temperaturmätningar vid Näs, 1988-1991,* (Temperature measurements in the embankment dam at Näs Hydro Power plant 1988-1991), Royal Institute of Technology, Hydraulic Engineering Report No 54, ISSN 0349-4489, Stockholm, 26 p,1991.
- Johansson, S., Repair of the Porjus dam, *Proc. from the ICOLD 17th Congress in Durban*, Vol 5, pp94-96, 1994.
- Johansson, S., G. Barmen, M. Bartsch, T. Dahlin, O. Landin, och P. Ulriksen, *Nyare metoder för tillståndskontroll av dammar*, VASO Dammkommitté rapport nr 21, Stockholm, ISSN 1400-7827, 71 p, 1995.
- Johansson, S., and T. Dahlin, *Övervakning av tätkärnans funktion genom analys av resistivitetsvariationer,* VASO Dammkommittés rapport nr 24, Stockholm, ISSN 1400-7827, 38 p, 1995.
- Dahlin, T. and S. Johansson, Resistivity Variations in an Earth Embankment Dam in Sweden, *Proc. 1st Meeting Environmental and Engineering Geophysics*, Torino, Italy, September, 25-27, 1995, pp308-311.

Field investigations have been performed on behalf of the following dam owners: BC Hydro, Båkab Energi, Eléctricité de France, Graningeverken AB, Gullspångs Kraft AB, Stora Kraft AB, Water Regulations Enterprises, Sydkraft AB, and Vattenfall AB Vattenkraft.

The first regular temperature measurements started in 1987. All collected data have been evaluated by the author and presented to the dam owners in the form of about 20 internal reports. Some of these reports were written after the papers appended to this thesis. Therefore some of the figures in the thesis have been updated with the most recent results.

ABSTRACT

Internal erosion, which is one of the major reasons for embankment dam failure, causes an increased seepage flow due to loss of fines. A seepage measuring system is therefore a vital part of an embankment dam's monitoring system. Many existing seepage monitoring systems are not however sensitive enough to detect small changes in the seepage flow. Temperature and resistivity measurements represent two methods for seepage monitoring in embankment dams. They are able to detect effects caused by time dependent processes such as internal erosion, where the relative accuracy is more important than the absolute accuracy. Temperature can normally be easily measured in existing standpipes. Resistivity measurements are more complicated; they require a computer-based monitoring system and minor technical installations on the dam.

The temperature in an embankment dam depends mainly on the temperature in the air and the water temperature in the upstream reservoir. These two temperatures vary seasonally and create temperature waves propagating through the dam. The seepage rate, and its change with time, can be evaluated from measurements repeated at regular intervals. The sensitivity of the method depends mainly on the distance between the dam crest and the measurement point, the size of the dam, the location of the standpipes, and the temperature variation in the reservoir at the inflow level. The seepage detection level of the method is about 1 ml/sm^2 for a typical Swedish dam with a height of about 30 m. The detection level depends linearly on the dam height. Results from field measurements show that the method gives reasonable information concerning the condition of the dam. Zones with anomalous seepage rates have been located and seepage flow rates have been quantified. Changes in the seepage flow rate as well as the seepage pathway have also been observed.

The resistivity of the ground depends mainly on the porosity, saturation and clay content. When reservoir water seeps through a dam, the properties of the water in the reservoir will also affect the resistivity in the dam. The resistivity of the reservoir water is temperature dependent, but it is also a function of the total dissolved solids. Both these parameters vary seasonally and this causes variations in the dam. The seepage flow can be evaluated from the resistivity data using methods similar to those employed for seepage evaluation from temperature data. The sensitivity is similar to that of the temperature method but the resolution and accuracy is lower. Zones with anomalous leakage can be located.

Ground penetrating radar and borehole radar methods are based on the measurement of material dependent properties. These are less sensitive to seepage changes than flow dependent parameters. The relatively high accuracy obtained by borehole radar measurements compensates however for their lower sensitivity to porosity changes. Borehole radar based on tomographic analysis can be a valuable method for mapping areas with increased and anomalous porosity formed as a consequence of increased seepage and internal erosion.

Key words: embankment dams, internal erosion, seepage monitoring, temperature, resistivity, ground penetrating radar

CONTENTS

1 INTRODUCTION

1.1 Dams and dam safety

Water storage in dams started early in history and dams are one of the oldest man-made constructions. Nowadays, dams are used to store water for purposes such as human consumption, food production, electricity production, industrial use, and flood protection. Dams are vital elements in modern society and represent large economic values. They also represent a potential risk, something that was recognised early on. In ancient Mesopotamia, for example, the laws of Hamurabi obliged dam owners to keep their dams in order.

Today, there are a large number of dams and many of them are high with large reservoirs. A large dam has a height of more than 15 m according to the definition of the International Commission on Large Dams (ICOLD). There are about 20 000 large dams world-wide, not counting China, where it is estimated that there are a further 20 000. The failure of a large modern dam with a large reservoir would not only be spectacular. It would also cause tremendous damage. This is a well-known risk in society and it entails a recognised responsibility for the dam owner:

> *"A dam failure results in a catastrophe (a break followed by a flood wave), often with a considerable loss of life or property."* (ICOLD 1987)

Considerable attention must therefore be paid to dam safety both at national and international levels. Recommendations on dam safety have therefore been established, for example "Dam Safety Guidelines" published by ICOLD (1987).

Data and experiences from failures and incidents are also important. They have been collected and evaluated in several bulletins by ICOLD and its national committees. The following are especially worthy of mention:

- Deterioration of Dams and Reservoirs (ICOLD 1983)
- Dam Failures, Statistical Analysis (ICOLD 1995)
- Lessons from Dam Incidents, USA (ASCE/USCOLD 1975 and 1988)

ICOLD divide dams into embankment dams (about 70% of the total number), concrete dams (about 28 %) and masonry dams (about 2%). Data from 111 failures show three main reasons for embankment dam failure (ICOLD 1995):

- overtopping at high flood discharge (about 30% of the total failures);
- internal erosion and seepage problems in the embankment (about 20%); and
- internal erosion and seepage problems in the foundation (about 15%).

The majority of these failed dams either did not have a monitoring system or had a system that was out of order. The findings from the ICOLD studies demonstrate therefore the importance of inspection and an appropriate monitoring system for regular observation of dam performance:

"The failure of a dam is, in general, a complex process which normally begins with some abnormality in behaviour (an initial fault) which is not detected. Consequent deterioration, often not observed, then leads to further damage or even disaster. This is why inspection and monitoring of dams, as well as rapid data analyses and interpretation, can play a critical role in the field of dam safety." (ICOLD 1987)

The ICOLD reports also present data from 1105 incidents that did not lead to dam failures. The reports show that the majority of these incidents were detected by "direct observation", that is to say by visual inspection and not by any surveillance system.

Sweden has 143 large dams and 117 of them are embankment dams. Most of the embankment dams were constructed between 1950 and 1980. One large Swedish dam, Noppikoski, has failed and this happened in 1985. The reason was overtopping due to non-functioning spillway gates. Deterioration has occurred in 26 embankment dams (Nilsson 1995a). Damage has mainly been detected by direct observation, and only in a few cases have indications of inadequate performance been given by the surveillance system. Consequently, both international and Swedish experience show a need to further develop and improve surveillance systems for embankment dams.

1.2 Internal erosion in embankment dams

The central part of an embankment dam is called the core (see Figure 1). The core consists of material with a low permeability, such as moraine, that allows a small amount of seepage. A recommended design value in Sweden (Vattenfall 1988) for the permeability of the core is less than $2 \cdot 10^{-14}$ m^2 (or a hydraulic conductivity less than $2 \cdot 10^{-7}$ m/s).

The core is surrounded by filters of more permeable material such as sand or gravel. The main function of the filter is to prevent wash out of the fines from the core but it also acts as a drain for the seepage water. The seepage water is often collected into a drainage system on the downstream side. A proper filter design and filter construction are fundamental for the safety of the dam.

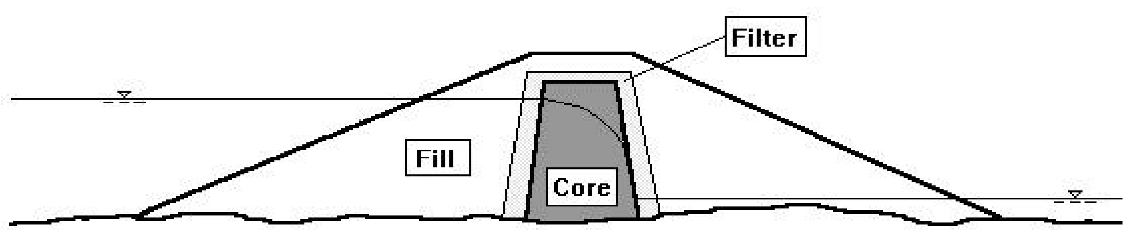

Figure 1 Schematic section through a typical zoned embankment dam.

The purpose of the fill material, which consists of gravel or rock fill, is to support and stabilise the dam by transferring the water load to the ground. Large stones are placed on the upper part of the upstream side for protection against waves. The permeability of the filter and the fill material is more than a thousand times higher than the permeability of the core. The amount of leakage flow through the dam will thus be determined mainly by the permeability of the core.

From studies of failures and incidents, the following primary and secondary causes were found to be the most common (ICOLD 1995):

- **foundation problems**
  deformation, land subsidence, shear strength, seepage, internal erosion and piping
- **improper embankment materials and construction methods**
  compaction and placing of the material
- **unforeseen or exceptional actions**
  overtopping, earthquakes, rupture of a dam upstream, and delay in construction
- **inadequate structural behaviour of the dam.**
  other watertight system than the core, transition zone, slope protection, bonding between concrete structures and adjoining embankments, differential movements (cracking, arching, load transfer, hydraulic fracturing and unexpected settlements), seepage, internal erosion (piping), liquefaction, downstream slidings, and rupture or exceptional flow of conduits inside the body of the dam

Failures are generally due to a combination of several of the above, and it is often difficult to determine a single initial reason for a failure. Most types of damage are related in some way to internal erosion. Internal erosion in the embankment or foundation is therefore the most frequent cause of failures and incidents in embankment dams. These findings are also valid in Sweden as shown by Bartsch (1995).

Internal erosion is a process in which fines are transported away from the core or the foundation. This results in an increasing seepage flow and in an extension of the seepage area. Piping is defined as backward erosion; a seepage pathway starts to grow at the interface between for example the core and the downstream filter, and erosion develops in the opposite direction to the seepage flow.

Internal erosion can severely affect the dam core or the foundation as seen above. A general experience is that loose horizontal zones can be created through the core due to internal erosion and arching in the core. If an erosion channel develops a concentrated leakage takes place within the disturbed area. The flow will increase as a result of the wash out of fines. After some time of continuous material loss, the core material will collapse and be replaced by material from above or upstream. This is known as self-repairing. Eventually this will create a sinkhole at the dam crest as indicated in Figure 2. The flow rate decreases when the material is replaced. This may occur long before the sinkhole appears at the crest of the dam.

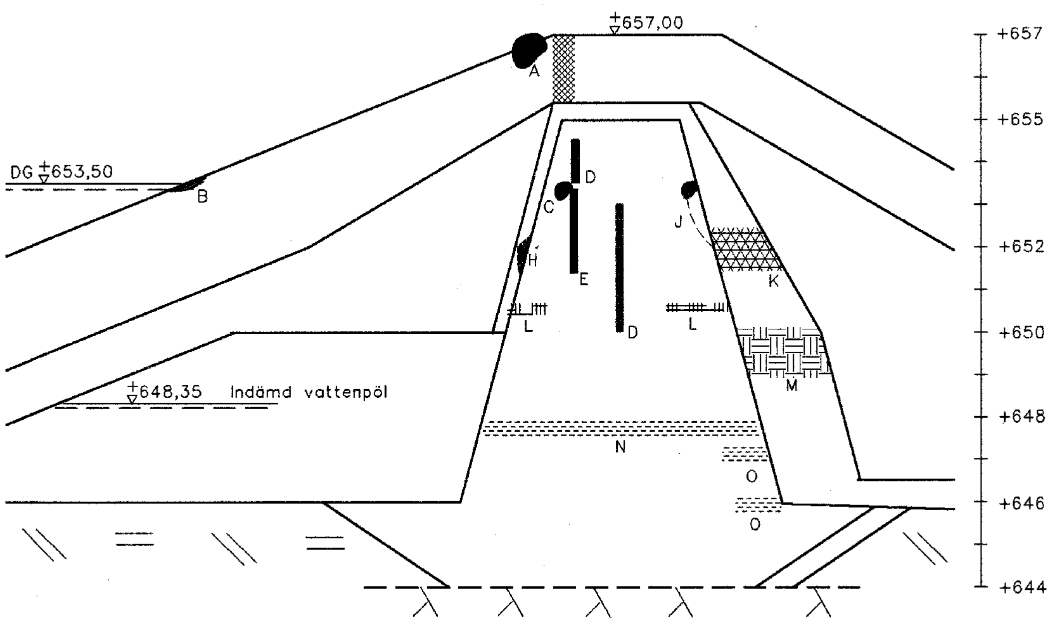

Figure 2 Deterioration and sinkhole in the embankment dam at Grundsjön in the River Ljusnan. Explanations: A) three large stones, B) washed out fine material, C) hard clods of soil, D) loose material (detected through sounding), E) damaged core (detected through infiltration tests), H) core material in the filter, J) cavity, K) wet filter, local wash out of fines, signs of washed out core material, pockets of gravel and stones, L) several small cavities, M) filter without fines, N) pervious material where the fines have been washed out, O) thin wet layers of large horizontal extension, (Eurenius and Sjödin 1991)

The early development of internal erosion in dams is a complex process about which little is known. Traditional methods used for monitoring dam performance can only observe the phenomenon in its final phase. A leakage monitoring system shows for example an increasing leakage, sometimes combined with muddy leakage water, which is followed by a sudden decrease in the leakage. Such changes are often interpreted as internal erosion followed by self-repairing of the core (Vestad 1976 and Sherard 1979). Sometimes a sinkhole develops after some days, months or years. However, a sinkhole may also develop without any clear connection with increased leakage collected in the drainage system.

Design values for the permeability of the core indicate that the measuring range for a seepage monitoring method should be from about 0.1 ml/sm^2 up to about 100 ml/sm^2. The absolute accuracy is however less important than the relative accuracy, because the essential objective for the measurements is to detect changes.

In conclusion internal erosion is a major cause of failures in embankment dams. The seepage flow increases slowly, closely coupled to the induced material transport that can take place over a long time. Methods for seepage monitoring in embankment dams are therefore needed. Of particular importance are methods which are able to register small changes in the seepage rate through a dam, and thus detect internal erosion at an early stage before it starts to affect the safety of the dam.

1.3 Parameters related to internal erosion

Parameters indicating internal erosion have been examined by Johansson et al (1995). Internal erosion initially results in an increased porosity due to the transport and loss of fines. This affects a number of measurable parameters, such as density, seepage flow, hydraulic conductivity, temperature, seismic velocity, dielectricity and resistivity. The relative sensitivity of these parameters to changes in the porosity was studied. Some of them, for example the density, dielectricity and resistivity, can be directly related to the porosity by analytical expressions. For other parameters, such as hydraulic conductivity and seepage flow rate, only empirical expressions or results from laboratory tests are available.

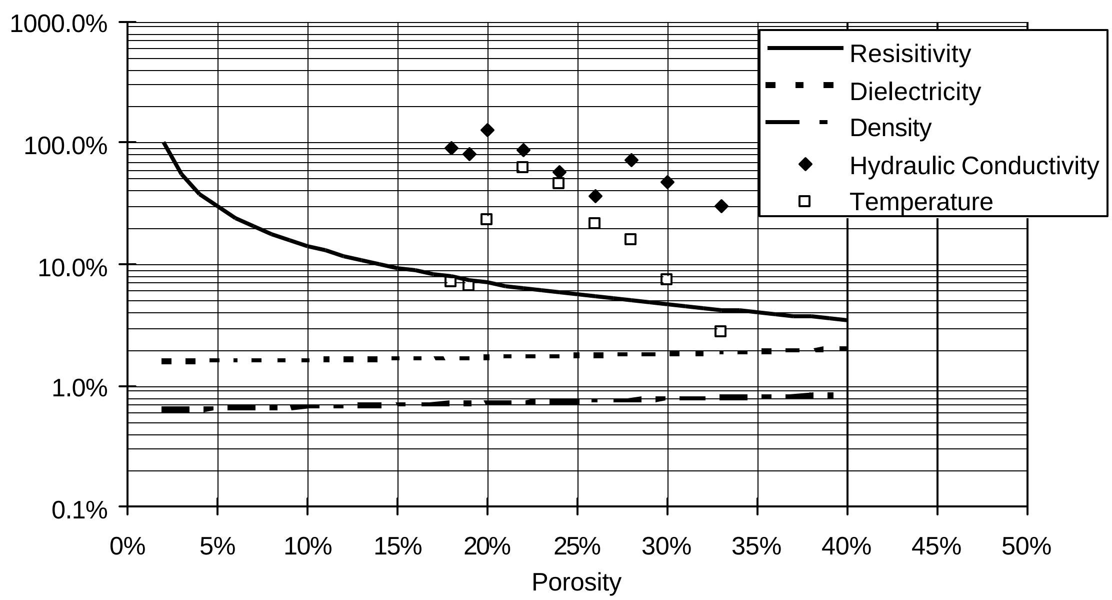

Figure 3 Relative changes of various parameters with changes in porosity in embankment dams, from Johansson et al (1995).

A comparison of the relative change in these parameters caused by changes in the porosity in embankment dams is useful. It shows (see Figure 3) that material dependent parameters (such as density and dielectricity) are less sensitive than flow dependent parameters (such as hydraulic conductivity). Sensitivity alone however is insufficient. Accuracy and resolution must also be considered when evaluating appropriate methods for analysis of internal erosion.

Porosity changes may also have secondary impacts on some parameters. Resistivity for example is affected by both loss of fines and increased seepage. Such secondary effects are not shown in Figure 3.

1.4 Monitoring and examination of dams

Measurements in dams are carried out either for continuous monitoring or for special examinations. Different methods for monitoring and examination of dams in Sweden were studied in two reports as a part of a Swedish dam safety program. “Conventional methods” were studied by Nilsson (1995b) and “New methods” were examined by Johansson et al (1995). Different methods were presented and evaluated in order to find their most appropriate application. A similar report on dam monitoring has been published by Charles et al (1996). These reports represent the “state of the art” concerning dam monitoring.

Some methods can best be applied if the equipment is installed during the construction of the dam. Others can be applied after the dam has begun operation, with or without the need for drilling. Methods are therefore classified as: built-in monitoring, borehole methods, non-destructive testing methods and other methods.

1.4.1 Built-in monitoring

These are the most common monitoring systems and are preferably installed in the dam during construction. They measure:

- crest, slope and internal movements;
- seepage water from the drainage system; and
- pressure (using pore pressure cells).

Movements are measured at points on the dam surface or in vertical tubes with inclinometers. The measurement frequency is normally once a year. Until the final phase of sinkhole development the relation between movements and seepage flow rate is weak due to arching effects.

A seepage water system normally collects seepage water from the entire dam. Dividing the monitoring system into several sections increases the sensitivity of the system. It also improves the possibility of locating a seepage change. During recent years several seepage weirs have been equipped with devices for continuous monitoring.

Pressure is measured at a number of points to provide information about the pressure distribution within the dam. Long term measurement can indicate pressure changes due to deterioration or ageing of the dam. There are different types of pressure cells and their reliability varies. Long term reliability is important since the pressure cells cannot be replaced. Some systems have provided reliable values for a period of 30 years or more.

1.4.2 Borehole methods

Drilling in dams must be done carefully. For example, low pressure drilling methods must be used to avoid damage to the core by hydraulic fracturing. Continuous soil sampling and infiltration tests normally give useful information about the dam condition along the borehole at the time it was drilled.

Standpipes are often installed in boreholes after drilling. They are used for water level measurements but are also suitable for temperature measurements, which can be performed along the entire height of the standpipe. For dam monitoring the best result will be obtained with regular measurements by the method presented in Chapter 2.

Boreholes can also be used for geophysical methods such as borehole radar and sonic cross-hole. Both methods use tomographic analyses to give information on the conditions in the dam between the boreholes. These methods are primarily used for single examinations, but they can also detect changes which have occurred between different measurements. However, neither of these methods is suitable for continuous monitoring.

1.4.3 Non-destructive testing

Ground penetrating radar measures the differences in electrical conductivity or radio wave velocity in the soil. These parameters depend on grain size, degree of saturation and porosity. Measurements are made by moving antennas along the dam. The method is useful as a means of examining dams in order to obtain additional information. Repeated measurements are possible, but the method is not suitable for regular monitoring.

The resistivity in embankment dams depends mainly on water content, water quality and grain size. Measurements are performed by electrodes that are placed along or perpendicular to the dam. Permanent installations allow continuous measurement, as described in Chapter 3.

Different rates of leakage water will cause anomalies in the streaming-potential along the dam. These variations can be used for leakage detection. Measurements of resistivity and streaming-potential can be made with the same equipment and both methods are suitable for regular monitoring. The streaming-potential method is also useful for single examinations of dam performance.

1.4.4 Other methods

Hydrochemical analyses may detect variation of leakage water quality. This is an indication of changes in the conditions within the dam. For example the content of particles in the water, expressed by the turbidity, will increase with ongoing internal erosion. If the leakage or any movements inside the dam cause noise, this can be detected by acoustic measurements. Both these methods are suitable for continuous monitoring, but at present they are not sensitive enough.

1.5 Methods presented in the thesis

This thesis presents three methods which can be applied to detect imperfections that appear in embankment dams and their foundations. The methods are:

1. *The temperature method*
   This method is based on the fact that a change in the permeability leads to a change in the seepage flow. This in turn causes a temperature change, which can be easily measured in existing standpipes.

2. *The resistivity method*
   This method is based on the fact that a change in the porosity leads to changes in water content and fines, which alter the electrical resistivity. A porosity change also leads to a changed permeability, and this affects the seepage flow. The change in seepage flow causes temperature changes that also affect the resistivity. The change in resistivity can be measured with non-destructive techniques.

3. *The radar method*
   This method is based on the measurement of change in the dielectricity, which is affected by the water content and thus by the porosity. Measurements can be made either from the surface or from boreholes.

All of the methods, with the exception of borehole radar measurements, are simple in the sense that they can be carried out with simple means. Hence there is no need for complicated equipment that could interfere with the function of the dam.

All the methods detect a change in permeability or porosity or in both (see Figure 4). If these parameters increase with time it is likely that a deterioration is taking place. Temperature has a clearer and more direct connection to internal erosion than resistivity and dielectricity. This simplifies the interpretation of measurements, especially if we wish to observe changes and do not primarily intend to obtain absolute values of the permeability. Resistivity and dielectricity are affected by several major parameters, and these may either amplify or attenuate the impact of the initial change in porosity or permeability. This complicates the evaluation of observed changes even if it is only relative changes that are being studied.

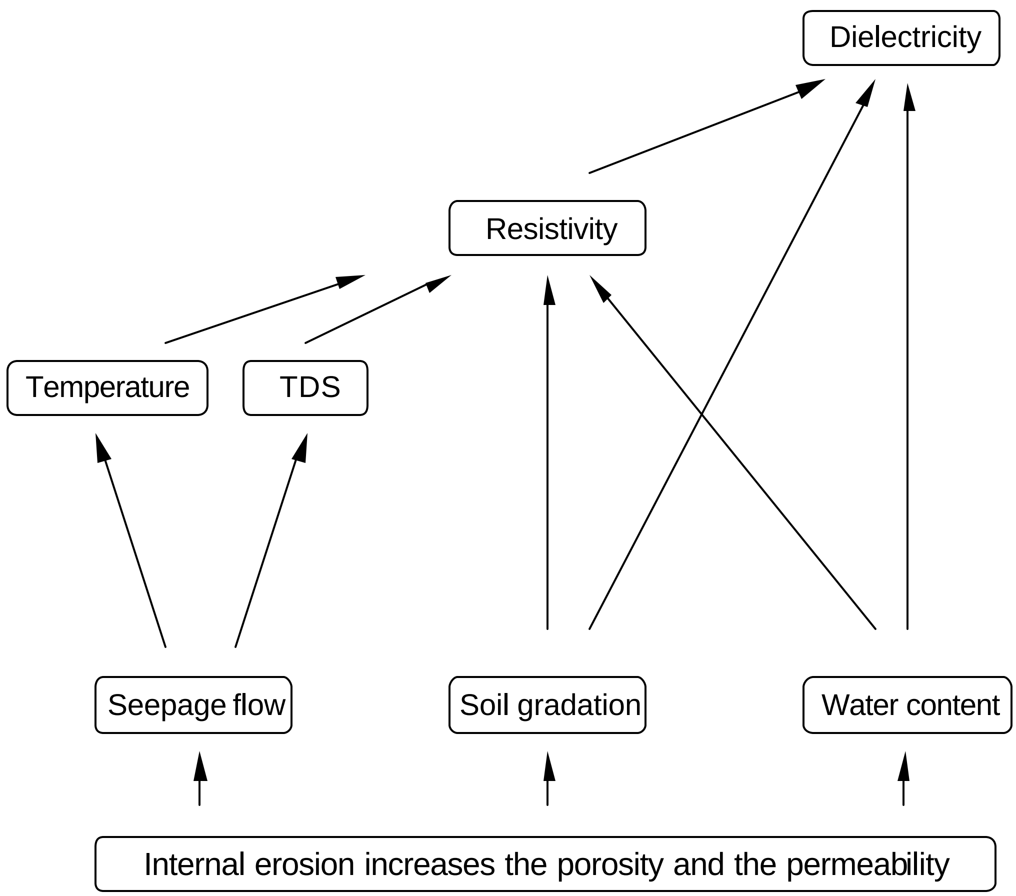

Figure 4 Internal erosion's major influences on selected parameters.

2 TEMPERATURE MEASUREMENTS

This chapter summarises the papers on temperature measurements, PAPERS 1, 2, 3, 4 and parts of PAPER 5. The fundamental principles of the method are first outlined. Important findings are summarized in the conclusions.

2.1 Background

Various authors have proposed temperature measurements or thermographics as a method for investigation of the groundwater flow in aquifers and for leakage detection in embankment dams, Kappelmeyer (1957), Stallman (1960), Bentz (1961), Birman (1968), Cartwright (1968; 1974), and Merkler et al (1985; 1989). Despite the many advantages of temperature measurements, the method was not developed far enough to serve as a general method for examination of embankment dams.

During the 1980's methods for evaluation of thermal processes in soil were developed further by Armbruster and Merkler (1983), Claesson et al (1985) and others. Extensive research projects concerning leakage detection in embankment dams were also carried out in Germany. These studies show that temperature measurements can be a useful tool in field investigations to identify water flow in aquifers, embankment dams and dam foundations.

Measurements started in Sweden in 1987 as part of a research project and the method is now used in a large number of dams in Sweden, France and Canada. Results from these measurements indicate that the method is sensitive and reliable. Most measurements have been performed in existing standpipes but in some cases new standpipes have been installed especially for temperature measurements. Such drilling is expensive and cannot normally be done continuously along the dam. Dornstädter (1996) however presents a drilling method that is suitable for dams with a height less than about 20 m. The method is cost-effective and allows a close spacing between the boreholes so that the dam, or one section of it, can be covered almost continuously.

2.2 Basic concept and assumptions

The temperature in an embankment dam depends mainly on the temperature in the air and in the upstream reservoir. These temperatures vary seasonally and create temperature waves that propagate through the dam. Normally the seepage flow is small in embankment dams and the seasonal temperature variation in the dam depends essentially on the air temperature at the surface. The influence from the air is however less than 1 ^{o}C for depths in the dam body that exceed 10 m. At such depths the influence from the air is therefore negligible.

If larger quantities of water seep through the dam however, the water temperature from the reservoir will influence the temperature inside the dam. At high seepage rates, the temperature variation of the water in the upstream reservoir completely determines the temperature inside the dam. The seasonal temperature variation in the dam is then directly proportional to the seepage rate.

The thermohydraulic behavior of an embankment dam is complex. It includes such basic thermal processes as heat conduction (from the dam crest and from the foundation due to geothermal flow), advection and radiation. The first two processes are partly coupled to each other because viscosity and density are temperature dependent. The problem is further complicated by the variation in material properties in the dam, and the different conditions in the saturated and unsaturated parts of the dam. In order to analyze the problem certain assumptions have to be made.

The influence of radiation, from the sun or to the atmosphere, is restricted to the superficial part of the dam because of the short duration of the heat pulse, mainly day/ night. In the following analyses it is therefore assumed that the temperature inside the dam is independent of radiation. The geothermal flow is also ignored.

The energy flux consists of heat conduction in the solid phase and in the water, heat advection with the average leakage water flow, and dispersion due to variability in the leakage water flow velocities. The energy balance equation can be written:

$$C_0 \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\lambda_0 \frac{\partial T}{\partial x_i} - C_w T q_i - Q_i^{disp} \right) \qquad \text{Eq. (1)}$$

where:

- C_0 = volumetric heat capacity of soil, (J/m^{3}K)
- C_w = volumetric heat capacity of water, (J/m^{3}K)
- Q_i^{disp} = energy flux due to mechanical and thermal dispersion, (J/m^{2}s)
- q_i = leakage flow (Darcy flow), (m/s or m^3/s per m^2 and s)
- T = temperature, (°C)
- t = time, (s)
- x_i = coordinate, (m)
- λ_0 = thermal conductivity of soil, (W/mK)

The advective part of the energy flux is caused by the leakage water flow. From the second term on the right hand side of the Eq. (1) a thermal velocity v_T can be defined (Claesson et al 1985):

$$v_T = \frac{C_w}{C_0} q \qquad \text{Eq. (2)}$$

The thermal velocity describes the velocity of a thermal front through the dam. This velocity is not identical with the velocity of the leakage water in the pore structure v_n, which depends on the porosity n ($v_n = q/n$). The relation between these velocities is:

$$v_T = \frac{C_w}{C_0} n v_n \qquad \text{Eq. (3)}$$

Tracers used in traditional tracer tests are often assumed to be conservative traveling with the pore water velocity. The temperature also acts as a tracer, but it travels with the thermal velocity instead of the pore velocity. The temperature cannot be treated as a conservative tracer, as it also depends on heat conduction.

The mass conservation equation is:

$$\frac{\partial(\rho_f n)}{\partial t} + \frac{\partial}{\partial x_i}(\rho_f q_i) = 0 \qquad \text{Eq. (4)}$$

where ρ_f is the density of the fluid, (kg/m^3).

The seepage water velocity is often described by a general form of Darcy's law:

$$q_i = -\frac{k_{ij}}{\mu}\left(\frac{\partial p}{\partial x_j} + \rho_f g_i\right) \qquad \text{Eq. (5)}$$

where:

k_{ij} = permeability, (m^2)
μ = dynamic viscosity, (kg/ms)
p = pressure, (N/m^2)
g_i = gravity, (m/s^2)

The equation of motion for the leakage water flow and for steady state conditions can then be written as:

$$\frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial p}{\partial x_j} + \rho_f k_{ij} g_j\right) = 0 \qquad \text{Eq. (6)}$$

This equation, with initial and boundary conditions, describes the leakage water flow induced by differences in pressure and by differences in density of the water. As both the density and viscosity of the water are dependent on the temperature, we must distinguish between hydraulic conductivity K (m/s) and permeability k (m^2), where k is independent of the fluid properties. The relation between K and k is:

$$K_{ij} = \frac{g\rho_f}{\mu} k_{ij} \qquad \text{Eq. (7)}$$

A general solution of heat and water flow in a dam is based on Eqs. (1) and (6) in combination with initial and boundary conditions. The equations are coupled since Eq. (6) depends on the temperature field while the second and third terms in Eq. (1) depend on the flow field.

2.3 River temperatures in Sweden

The Swedish Meteorological and Hydrological Institute regularly observes water temperature at 74 measuring stations situated in the principal rivers of Sweden. A brief study of the temperature variations in five rivers was made by Johansson (1990) and a general study was published later by Koucheki (1995). The water temperature in the rivers in the south of Sweden exhibits an almost sinusoidal annual variation, while the temperature is more like a triangular pulse over a few months in the northern rivers (see Figure 5).

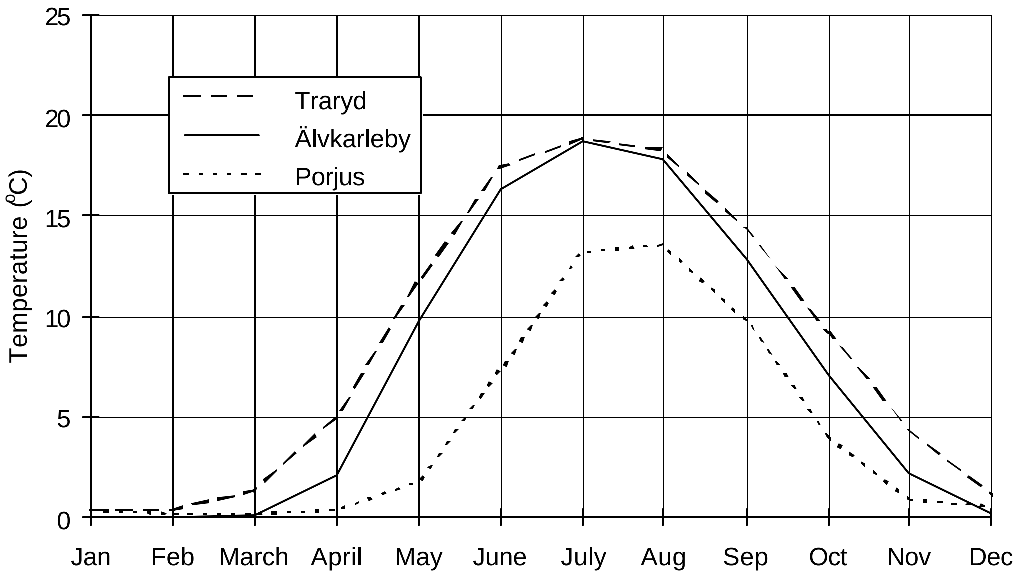

Figure 5 *Average water temperature in three rivers in Sweden. Measurements are from Traryd in the south in the River Lagan, Älvkarleby in central Sweden in the River Dalälven and Porjus in the north in the River Luleälven.*

The lowest monthly mean temperatures are about 0^{o}C with a yearly variation of less than 0.5^{o}C. The highest temperatures during summer, which are about 15 to 20^{o}C, show a larger variation, about 1 to 2^{o}C. All these measurements are made in rivers where thermal stratification can be ignored. This will not be the case for dams larger than those presented in the following sections, where the stratification of the water in the reservoir is significant and cannot be neglected.

2.4 Measurement method and data presentation

The first temperature measurements were performed manually with a temperature probe that is easy to handle. The probe is lowered to different levels in the standpipes and a vertical temperature profile is obtained for each standpipe. The cost of such equipment is low and this is now the general method. Measurements are normally carried out once a month.

An automatic measuring system was installed in January 1990 in the embankment dam at Näs power plant in the River Dalälven. Sixty PT-100 temperature sensors were installed in fourteen standpipes. Unfortunately the sensors only remained watertight for three to nine months. They were therefore removed and the automatic system was replaced with manual measurements.

The temperature data are presented in three types of diagram, as shown in Section 2.6. The first type illustrates the temperature variation with time, from which the lagtime can be obtained. The second type of diagram presents vertical profiles at different dates. It can be used to detect zones with increased seepage. A third type shows the annual temperature variation.

2.5 Seepage evaluation methods

The first models used for evaluation of temperature variations were based on an analysis of the phase-delay of the wave (the lagtime method) and numerical modelling, as described in PAPER 1. Later, as described in PAPERS 2 and 3, further methods were developed based on analysis of the amplitude. These later methods were developed from a method used to model heat storage in aquifers.

2.5.1 Lagtime method

The lagtime method is a simplified one-dimensional method. The lagtime t_d is the time between the temperature pulse at the boundary at x=0 and the measured temperature variation at a point x. The velocity of the temperature wave is the thermal velocity, if the heat conduction is ignored. The thermal velocity is then obtained directly from the lagtime and the length of the seepage path, which is assumed to be equal with the distance between the boundary and the measuring point x:

$$v_T = \frac{x}{t_d} \qquad \text{Eq. (8)}$$

The assumption of no heat conduction is valid for large seepage flows or for large seepage zone thicknesses where the vertical heat exchange is negligible, particularly in the central part of the zone. By inserting Eq. (2) we get an expression for the relation between the seepage flow and the lagtime:

$$q = \frac{C_0 x}{C_w t_d} \qquad \text{Eq. (9)}$$

The seepage flow can now be calculated for known values of the volumetric heat capacity, which is assumed to be constant along the seepage path. Normal values for the volumetric heat capacity can be found in Sundberg et al (1985).

2.5.2 Amplitude methods

The analytical model is based on the attenuation of the wave and a consideration of the principal heat processes. The most important assumptions in the model are that:

- the temperature varies sinusoidally at the upstream boundary;
- the seepage is limited to a zone of constant height H;
- one-dimensional advection and vertical heat conduction occur in the central layer;
- only vertical heat conduction occurs in the upper and lower layer; and
- thermal properties are constant in the layers.

These assumptions have generally been found to be valid for applications in embankment dams. In order to simplify seepage evaluation the solution is presented in dimensionless form in diagrams of the temperature variation and the seepage flow rate. The main parameters are the dimensionless temperature T' and the dimensionless distance x'. They are defined as:

$$T' = \frac{T_{\max,0} - T_{\min,0}}{T_{\max,1} - T_{\min,1}} \qquad \text{Eq. (10)}$$

and

$$x' = \frac{l_0 x}{C_0 v_T H^2} \qquad \text{Eq. (11)}$$

It is often convenient to rewrite the expression for x' by replacing v_T with the seepage flow q using Eq. (2). This gives an expression which shows the governing parameters of seepage flow:

$$q = \frac{l_0 x}{C_w x' H^2} \qquad \text{Eq. (12)}$$

The dimensionless temperature T' is obtained from the extreme values in the yearly temperature cycle in the reservoir ($T_{max,1}$ and $T_{min,1}$) and at the measuring point ($T_{max,0}$ and $T_{min,0}$). If the temperature profiles indicate anomalies, the height H is obtained. The length of the seepage pathway from the boundary to the measuring point is expressed by the distance x. Only the heat conductivity of the soil has to be known because the heat capacity of water is a constant. The seepage flow is obtained from the x'-value given by the dimensionless diagram for x' (T').

The evaluation method can be further simplified to express the total seepage flow within the zone, $Q=qH$, if the vertical heat losses from the seepage zone are assumed not to influence the maximum temperature in the centre of the zone. This is called the simplified amplitude method. An approximate relationship can be formulated between seepage flow and temperature variation (expressed by T') for assumed values of l_0 and C_w and various values for the distance x (see Figure 6). The figure is based on the assumptions listed above, and can only be used as a first approximate evaluation of seepage from measured temperatures. The increasing temperature variation for larger flows is clearly shown in the figure.

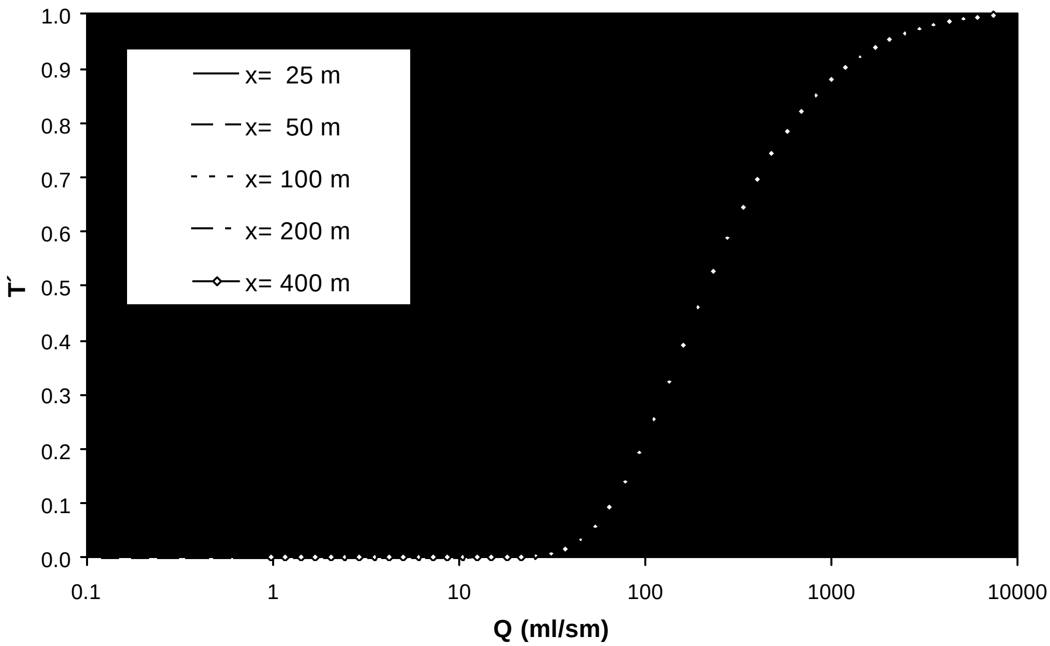

Figure 6 Approximate relation between dimensionless temperature and seepage flow for λ_0*=2.5 W/mK and* C_w*=4.18 MJ/m*^{3}*K.*

2.5.3 Numerical methods

A computer program called SUTRA, Saturated-Unsaturated TRAnsport (Voss 1984), was used to simulate the energy flux in a dam. The program simulates transport of energy or solutes in saturated or unsaturated soil. It employs a two-dimensional hybrid finite-element and integrated finite-difference method to approximate the governing equations, Eqs. (1) and (6). Simulations are made assuming a two-dimensional region with time dependent boundary conditions in the form of pressure, flow or temperature. Temperature variations with time can be studied for each node. Temperature dependent fluid properties can also be simulated.

About 60 simulations were performed, most of them assuming a dam with a central homogeneous core. Different values of core permeability and dam height (10 to 25 m) were assumed. The permeabilities of the filter and earthfill were constant. All simulations were carried out in three steps.

1. The pressure distribution in the dam was calculated by iteration.
2. Ten years of temperature variations were simulated with a time step of one week to establish true initial temperature conditions.
3. The subsequent year was simulated with a time step of two days to achieve a high accuracy.

The simulations showed that almost constant temperature pulses were reached within less than 3 or 4 years. The time taken depended on the estimate of the initial conditions of the temperature field.

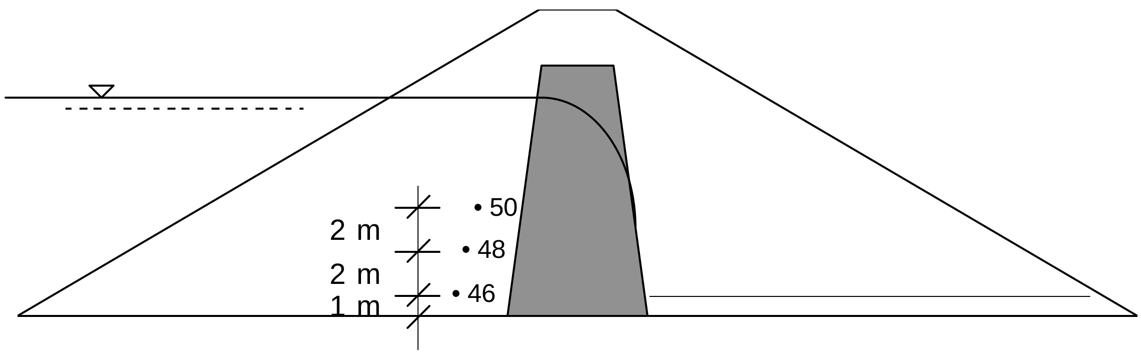

Figure 7 Dam geometry and sample nodes for SUTRA calculations showing the nodes studied on the upstream side.

The result from the simulations (Figure 8) clearly shows that at seepage flows larger than 1 ml/sm the temperature variations increase with increasing seepage, due to increasing permeability of the core. As the flow increases the advective thermal process begins to dominate. A leakage flow of less than 1 ml/sm seems not to influence the temperatures. The temperature variations must therefore be a result of heat conduction from the boundary. The variations are also larger closer to the boundary (see the calculated temperatures for nodes 48 and 50 in the figure).

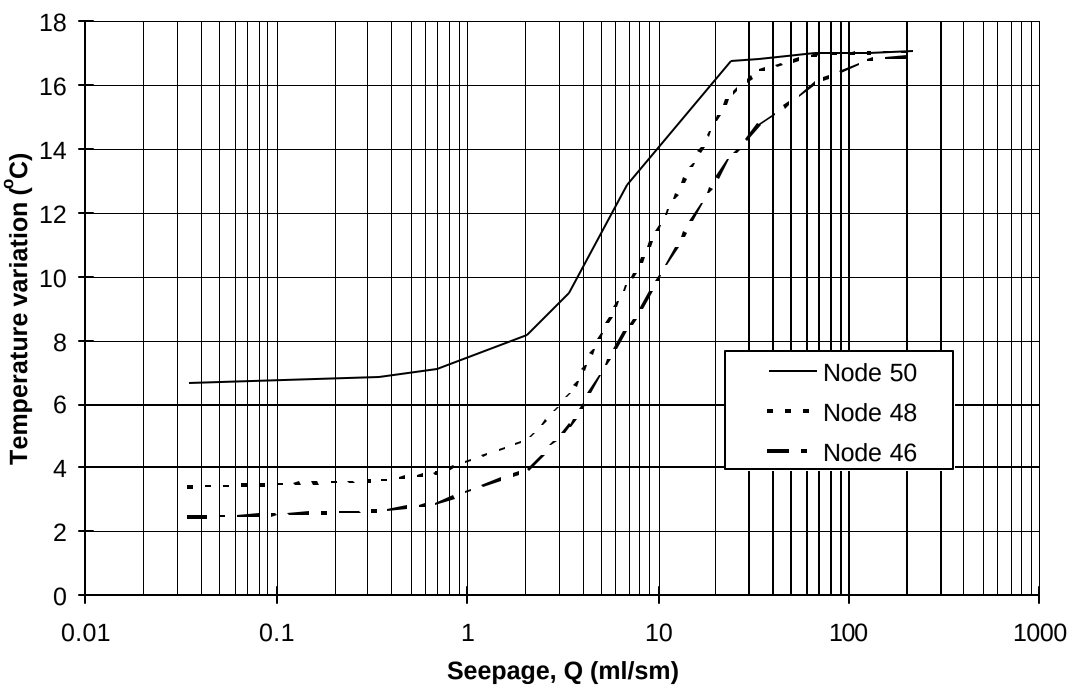

Figure 8 Temperature variation in nodes 46, 48 and 50 in the upstream part of a 10 m high dam for various seepage flows.

The result of the simulations indicates that the temperature pulses are almost constant when the permeability of the core is less than about 2 to $6 \cdot 10^{-14}$ m^2 (which corresponds to a hydraulic conductivity of approximately 2 to $6 \cdot 10^{-7}$ m/s).

2.5.4 Evaluation of methods

The temperature variations calculated by SUTRA as a function of seepage flow (see Figure 8) can be compared with those given in dimensionless form by the simplified amplitude method. The following table compares the two methods.

SUTRA	**Simplified amplitude method**
2D seepage in the dam (x, y)	1D seepage in the seepage zone (x)
2D heat conduction in the unsaturated part of the dam (x, y)	1D heat conduction in the upper layer (y)
2D heat conduction in the foundation of the dam (x, y)	1D heat conduction in the lower layer (y)
Real dam geometry	Simplified geometry with a constant seepage zone height
Real temperature variations at the boundaries	Sinusoidal temperature variations at the upstream boundary

The temperatures calculated by SUTRA are first transformed into dimensionless temperatures using Eq. (10). The distances from the nodes to the upstream boundary are then determined from dam data. Together with thermal data used by SUTRA, this gives the input values for x', see Eq (11). In the next step, x'-values are calculated for different seepage flow rates from the SUTRA calculations. These x'-values and their corresponding T'-values are then plotted together with the result from the simplified amplitude method (see Figure 9).

The agreement between the two methods is satisfactory at large seepage flows where the advective transport predominates. Heat conduction in both the x- and y-directions must however be considered at lower seepage rates, especially in this case where the height of the dam is relatively small. As this is ignored in the amplitude method, the results from the two methods do not agree at low seepage rates. The largest difference is obtained in node 50, which has the shortest distance to the upstream boundary of the dam.

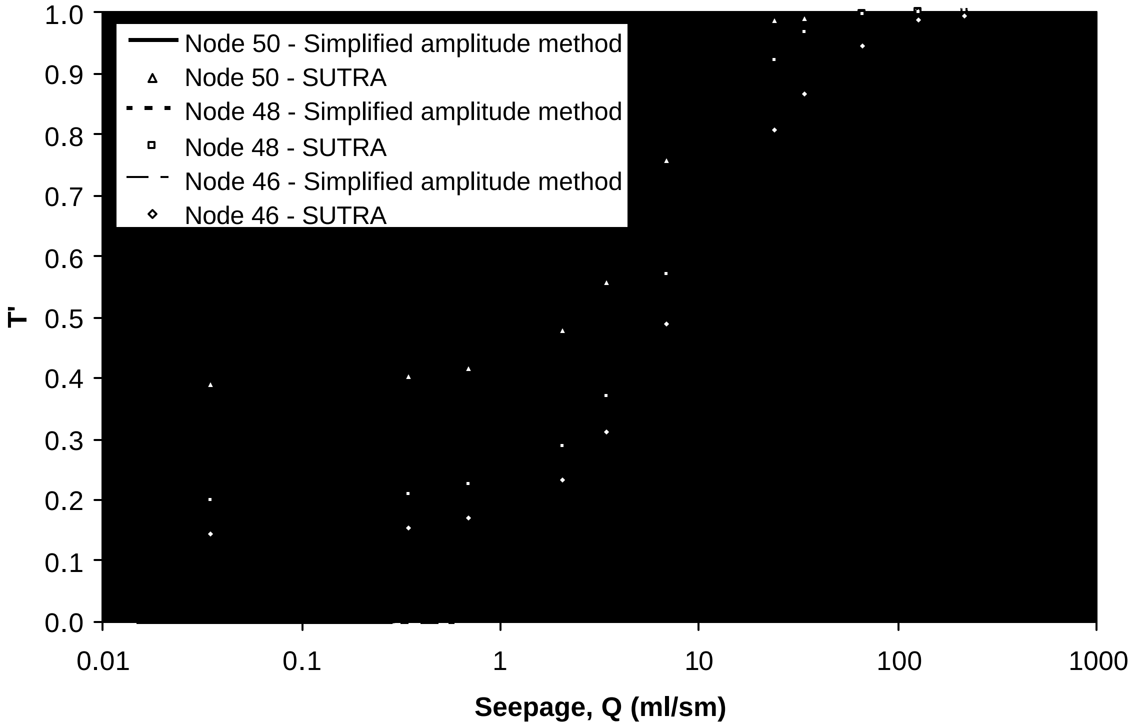

Figure 9 *Dimensionless temperature obtained from numerical simulations with SUTRA and analytical calculations with the simplified amplitude method for various seepage flows in a 10 m high dam.*

2.6 Examples from field measurements

2.6.1 Uniform low seepage flow

Small seepage flows will not affect the seasonal temperature variation in the dam. Seasonal variation of the ambient air temperature therefore dominates. This results in decreasing variations with depth, as illustrated by the example from Näs power plant in the River Dalälven (see Figure 10). These temperature variations decrease with depth and the temperature is almost constant at level +51.2 m, situated almost 18 m below the dam crest. The variations have been approximately constant since the measurements started, which indicates that the seepage flow rate is also approximately constant. The flow rate can be estimated to be less than about 1 ml/sm since no significant signs of advection can be found.

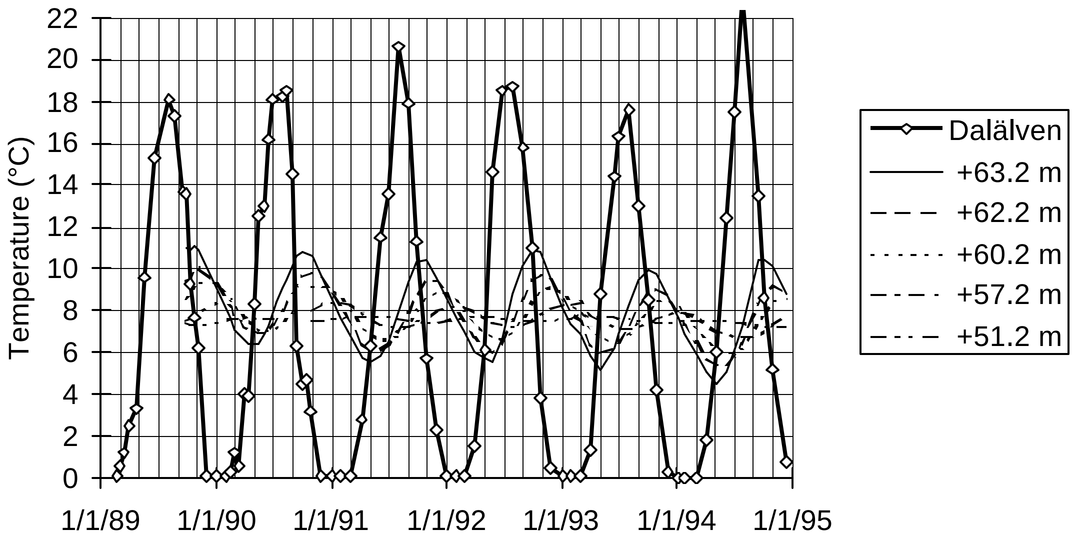

Figure 10 Temperature measurements in the River Dalälven and at different levels in standpipe V55 in the embankment dam at Näs power plant. The dam crest is located at +69 m.

2.6.2 Concentrated seepage flow

A zone with increased seepage was detected in standpipe V67 in the embankment dam at Näs power plant during the first year of measurements. The standpipe is located in the downstream filter. The zone was situated between elevation +53 m and +55 m in the foundation of the dam as shown by the temperature profiles in Figure 11.

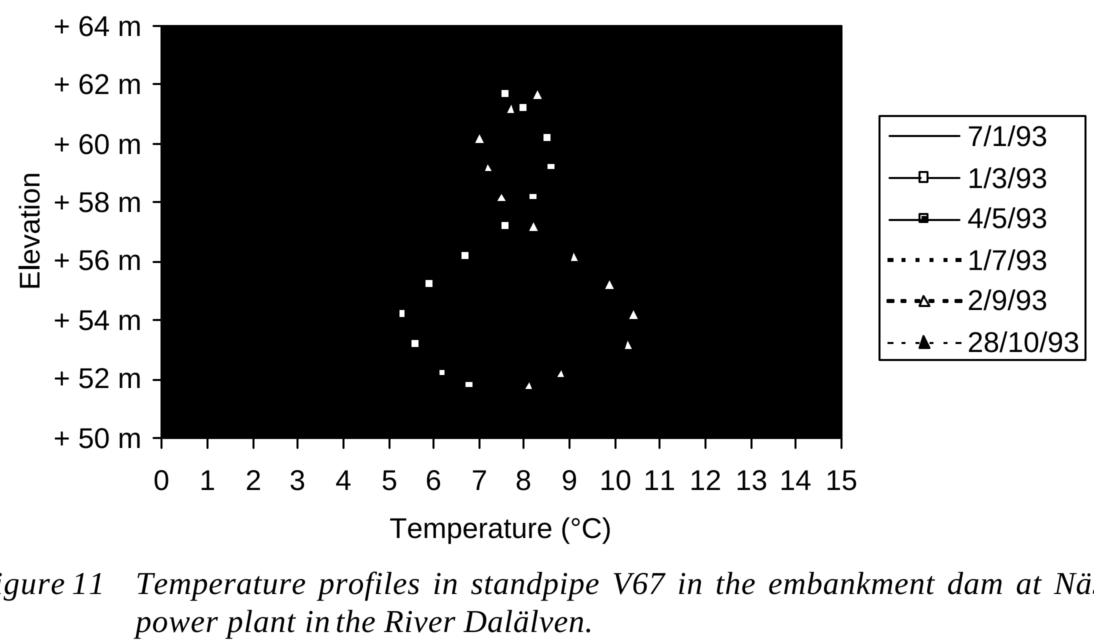

Figure 11 Temperature profiles in standpipe V67 in the embankment dam at Näs power plant in the River Dalälven.

The location of the leakage zone is even more evident from Figure 12, which shows the annual temperature variation. The variation between different years depends mainly on the various annual maximum temperatures. Hence the use of dimensionless temperature is recommended. The general shape of the temperature profile has not changed during the measuring period, and no significant seepage changes have been found.

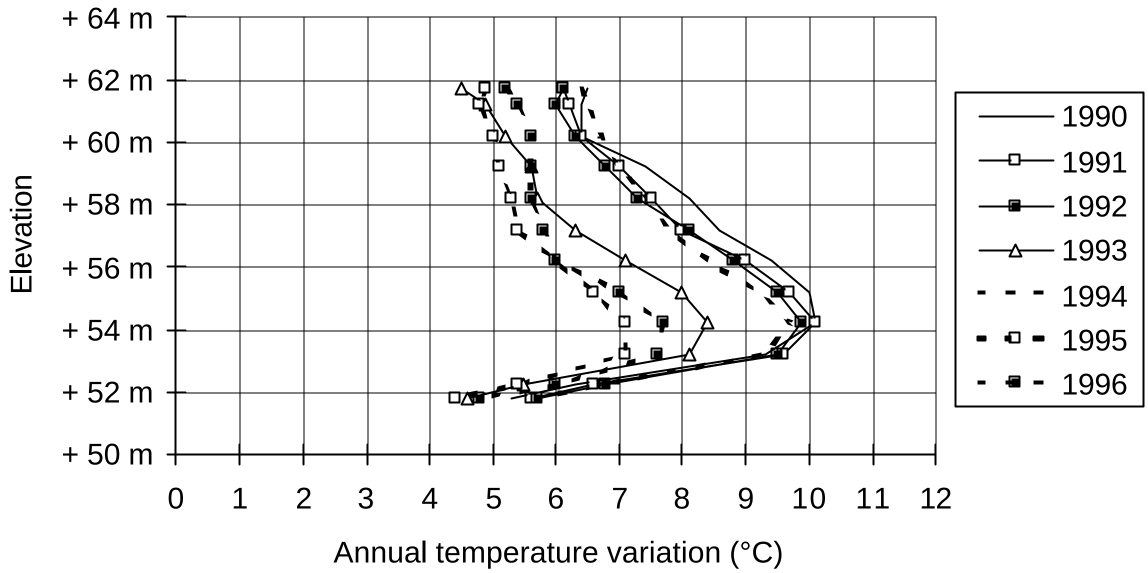

Figure 12 Annual temperature variation in standpipe V67 in the embankment dam at Näs power plant in the River Dalälven.

2.6.3 Slowly increasing and decreasing seepage flow

Significant zones with increased seepage have been found in the embankment dam at Lövön power plant in the River Faxälven. The dam has a maximum height of 25 m. It is founded on moraine, except in the area where it connects to the water intake where it is founded on rock. A sinkhole was detected in this area in 1992 and the bedrock was grouted during the same year.

Two zones with increased seepage flow were detected by temperature measurements in standpipe B10, located just outside the grouted area. One zone is in the core at elevation +267 m, one meter above the bedrock. The second one is in the rock.

The dimensionless temperatures for different years, shown in Figure 13, indicate a slow seepage decrease at elevation +267 m and a significant seepage increase in the bedrock, especially between the years 1993 and 1994. A larger seepage flow may be occurring below the standpipe. The small decrease in the dimensionless temperature above elevation +270 m may be a result of increased seepage flow.

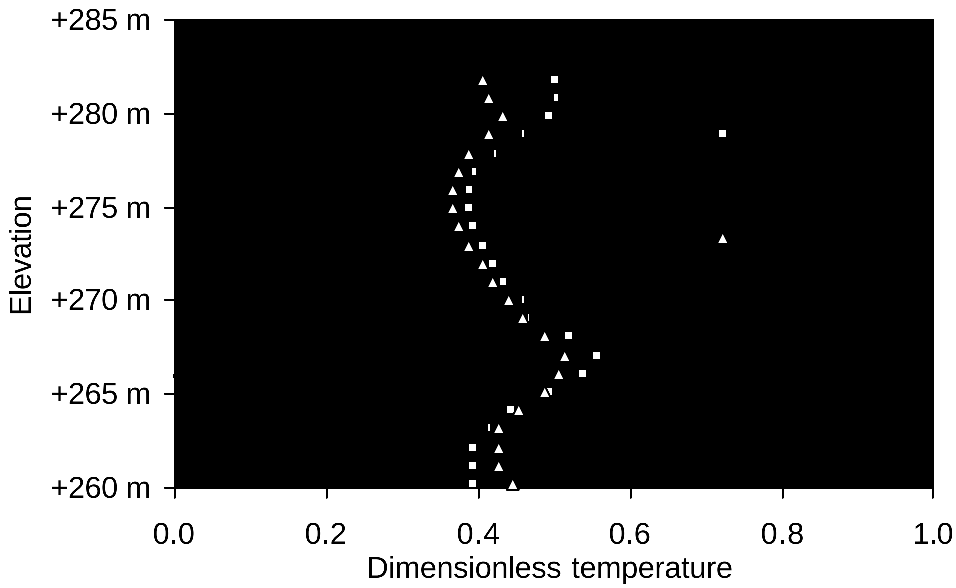

Figure 13 Dimensionless temperatures for standpipe B10 in the embankment dam at Lövön power plant in the River Faxälven between 1993 and 1996.

2.6.4 Decreasing seepage flow due to repair

A sinkhole developed in July 1993 on the upstream side of the crest of the embankment dam at Porjus power plant in the River Luleälven. Field investigations started immediately, including temperature measurements in new standpipes installed in the damaged area of the dam. Monthly temperature measurements started in December 1993 in eleven standpipes. The dam was repaired in the summer of 1994 by extensive grouting using sand-bentonite materials as described in PAPER 4.

Analysis of regular temperature measurements from 1994 and 1995 shows that the seasonal temperature variations have decreased in the repaired area. An example is standpipe BH 93/11, where the maximum temperature difference has decreased from about 8 to 4^{o}C (see Figure 14). The thickness of the seepage zone has reduced and the location of the largest temperature difference has moved from elevation +363 m to +360 m. The conclusion is that there is still an increased seepage, but that the flow is smaller than before and at a different level.

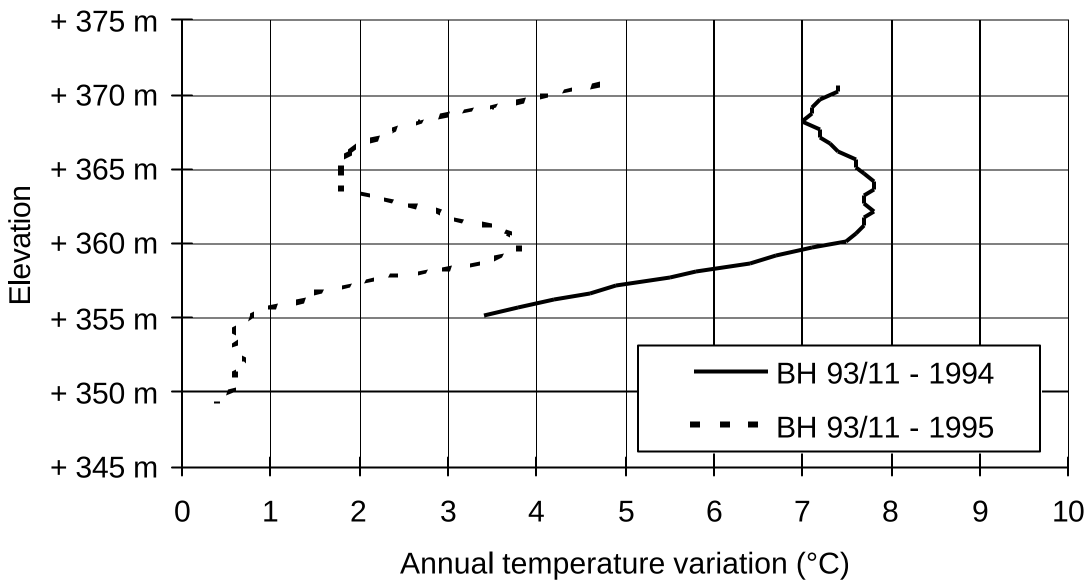

Figure 14 Annual temperature differences in standpipe BH 93/11 in the embankment dam at Porjus power plant in the River Luleälven.

2.7 Evaluation of field measurements

Temperature measurements in several standpipes normally give useful information on the condition of a dam. A single set of measurements from standpipes in a similar location can be compared with each other to indicate if advection or heat conduction predominates. Results from the embankment dam at Porjus demonstrate the information which can be obtained from a small number of measurements. However, regular monitoring provides the best input for seepage evaluation, as is illustrated by the example from the Lövön embankment dam.

The seepage flows at the standpipes in the Porjus dam have been evaluated three times. A first preliminary evaluation was made in 1994 (Preliminary 1994), based on only a few soundings before the repair work started. A second evaluation was made after the measurements in October 1994 (Modified 1994). The third evaluation was made after the measurements in September 1995. The differences between the flow rates calculated from the first two evaluations are sometimes large (see Figure 15). This is due to the difficulties in making a correct estimation of the annual temperature variation based on only a few sets of measurements.

The temperature variations in the standpipes have generally decreased after the repair work and the evaluated seepage flows have significantly decreased in all standpipes except for BH 93/6. The seepage has decreased by about 90% of its former value in the damaged part of the dam, and by about 75% some distance away from the damaged area.

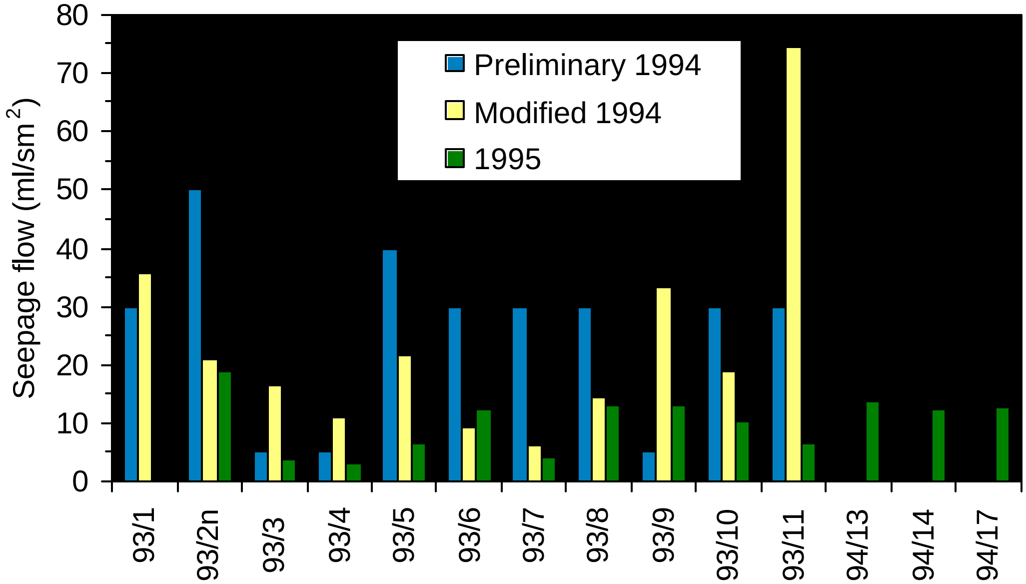

Figure 15 Evaluated seepage flow rates in14 standpipes in the embankment dam at Porjus power plant in the River Luleälven.

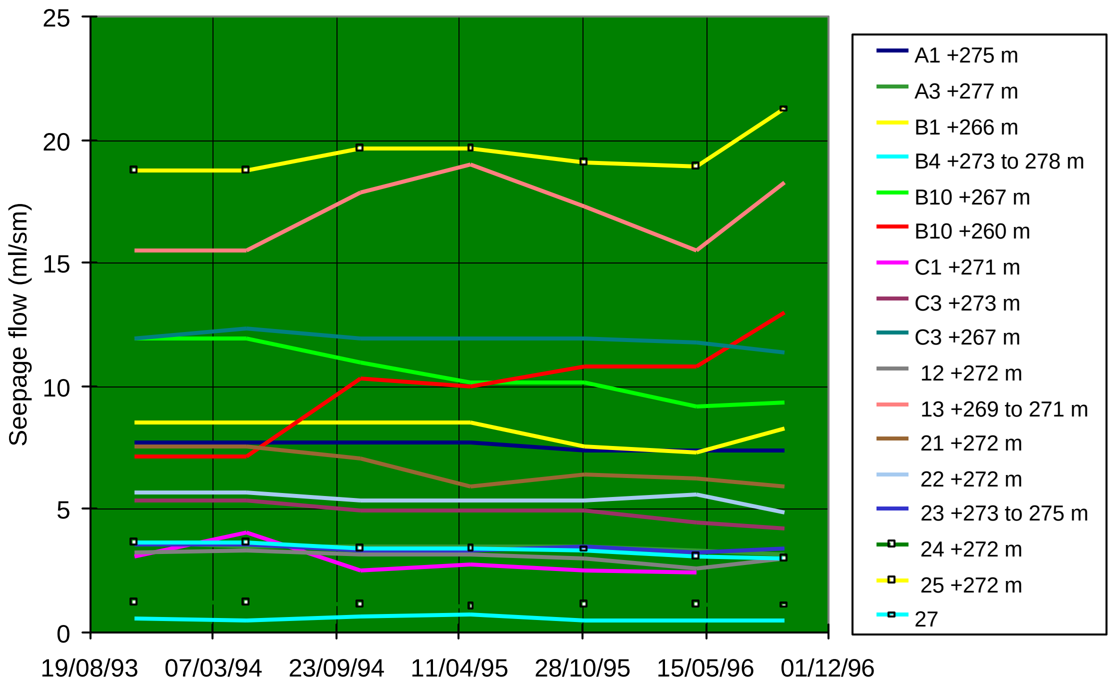

Figure 16 Evaluation of seepage flow in the embankment dam at Lövön power plant in the River Faxälven.

Regular measurements over a period of several years, such as those performed in the embankment dam at Lövön power plant in the River Faxälven, provide a better means of evaluating the seepage flow. Evaluations can be made twice a year with the methods described above and small changes in the seepage flow can be detected (see Figure 16). The small variations around a mean value may be an indication of the accuracy of the method.

2.8 Conclusions

Theoretical calculations and field measurements presented in PAPER 1 show that the temperature variation in an embankment dam primarily depends on the seepage flow rate in combination with the seasonal temperature variation in the reservoir. Zones with anomalous seepage and changes in the seepage flow rate can therefore be detected by evaluation of regular temperature measurements. Such measurements should be performed approximately once a month. Compared to single temperature measurements, regular measurements improve the possibility of interpreting the result correctly.

Seasonal variation of air temperature will cause temperature variations in the upper, superficial part of the dam. This heat conduction from the surface can be ignored for large dams, where the distance between the measuring point and the surface exceeds 20 m. It must however be considered for small dams. In larger dams the geothermal flow may be important.

Regular temperature measurements enable both the phase delay of the temperature pulse and the maximum temperature difference over the year to be determined. The two independent seepage flow evaluation methods presented in PAPER 2 can therefore be used if both these parameters are known.

The lagtime between the temperature variation at the upstream boundary and at the measuring point can be determined for the maximum and minimum temperatures. This allows seepage evaluation twice a year using the thermal velocity as a measure of temperature wave propagation.

Internal erosion in embankment dams often creates horizontal zones in which the main seepage flow is concentrated. The propagation of the thermal wave will thus primarily depend on the seepage flow rate and the vertical heat conduction. Simulations with a mathematical model based on these assumptions show that the temperature variation along the seepage zone mainly depends on the seepage flow rate, the thickness of the seepage zone, and the distance from the inflow section to the measuring point. The thermal properties of the soil have a relatively small influence. The accuracy depends mainly on the quality of the estimate of the leakage zone's vertical extension. The natural variation of the thermal properties is usually well known and of little significance for the required accuracy of the method.

Numerical simulations with SUTRA for dams lower than 25 m indicate that the temperature pulse in the dam is almost constant and independent of the seepage at flow rates of less than about 0.2 ml/sm^2 (which corresponds to a hydraulic conductivity of approximately $4 \cdot 10^{-7}$ m/s). Heat conduction from the surface is the main cause of the temperature variation in the dam at such low seepage flows. The temperature variation above this value is proportional to the seepage for seepage flows up to 20 ml/sm^2. At this level of seepage the entire temperature variation at the upstream boundary is obtained in the dam; the seepage flow is so large that no attenuation of the pulse can be observed. A homogeneous core was assumed for all calculations. However, SUTRA can also simulate permeable channels or horizontal layers in the core, as well as geothermal flow and thermal stratification in the reservoir.

Regular temperature measurements have proved that they are useful for monitoring seepage, see PAPERS 3, 4 and 5. The method can also be used for examination to some extent. The temperature can normally be measured in existing standpipes and additional drilling can thus be avoided. The only cost therefore relates to the monthly temperature observations, which can be carried out by the dam engineering staff.

The seepage detection level depends mainly on the distance between the dam crest and the measurement point, the size of the dam, the location of the standpipes, and the temperature variation in the reservoir at the inflow level. It is important that the standpipes extend over the full height of the dam. Seepage flows as low as 1 ml/sm can be detected in a typical Swedish dam with a height of about 30 m, if regular measurements are carried out over a number of years. The detection level depends linearly on the dam height and for a 300 m high dam it will be about 10 ml/sm^2.

The presented results from the measurements show that the method gives a useful picture of a dam's condition. Zones with increased seepage have been located and seepage flow rates have been quantified. Differences between different years, and sometimes also within a year, have been observed. Temperature measurements can be used to assess the efficiency of dam grouting by comparing measurements before and after the repair work. The result presented in PAPER 4 indicates a significant seepage decrease, although some zones with higher seepage rates still remain. If internal erosion starts to develop again, this will affect the seepage flow rate and the temperature. Regular temperature measurements are therefore being carried out in order to detect such seepage changes at an early stage.

3 RESISTIVITY MEASUREMENTS

3.1 Background

It is well known that resistivity in soils depends on material properties, such as clay content, porosity and saturation. This is the fundamental base for soil investigations with resistivity measurements (see for example Palacky 1987, Ward 1990, and Parasnis 1986). However, resistivity also depends on pore water properties, such as temperature and the concentration of total dissolved solids (TDS). This is normally neglected in resistivity measurements, but it cannot be ignored in the case of resistivity measurements in embankment dams.

Temperature measurements in embankment dams have shown a seasonal variation due to the seasonal temperature variation in the reservoir and the seepage water. Since the resistivity in the dam depends partly on the temperature it will also exhibit seasonal variations. The resistivity also depends on the TDS in the water and this too varies seasonally. The combination of these parameters, temperature and TDS, is expressed by the absolute resistivity of the reservoir water (see Figure 17), which will create a seasonal variation in the resistivity in the dam due to the seepage through the dam. This variation is similar to the temperature variation and methods similar to those described in Chapter 2 can therefore be used for seepage evaluation.

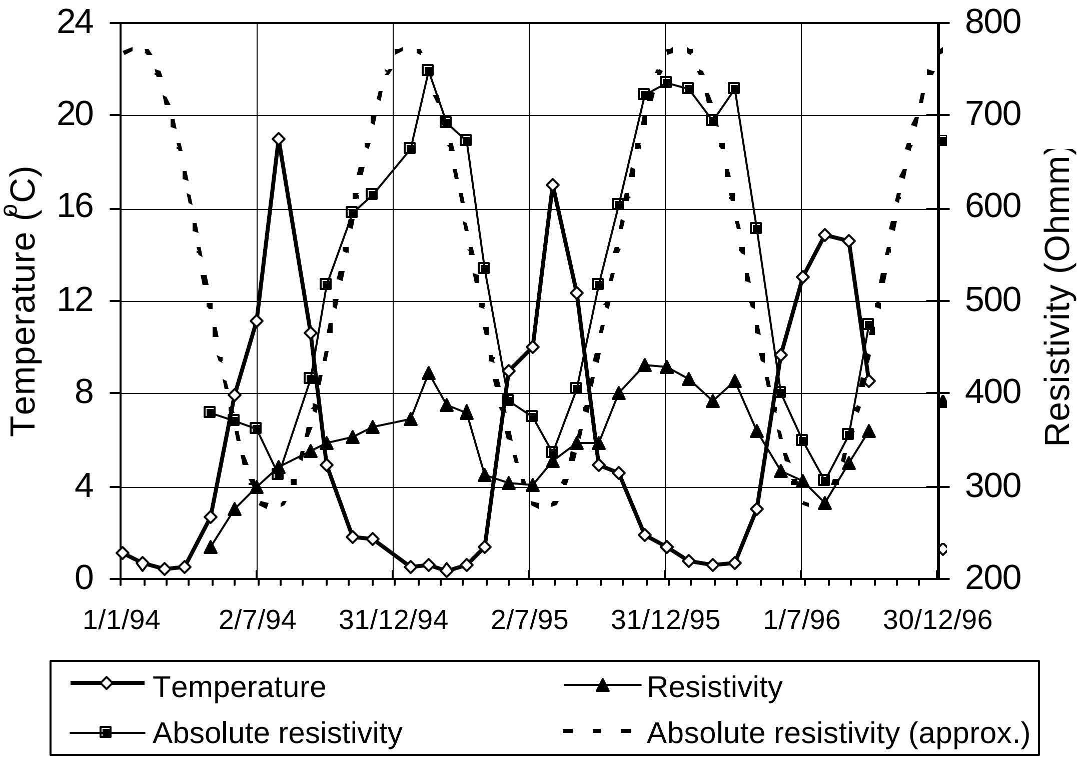

Figure 17 Temperature and resistivity variation in the reservoir at the Lövön power plant in the River Faxälven.

Embankment dams with normal dam performance have material properties that are essentially constant over long periods of time. In such cases the resistivity variation is a function of seepage alone. If internal erosion occurs, however, it also affects the material properties due to increased porosity and loss of fines. Unfortunately, an increasing porosity decreases the resistivity while a loss of fines increases it, and this makes seepage evaluation more difficult.

Regular resistivity measurements in two embankment dams started in 1993, after model calculations had indicated that seasonal resistivity variations could be detected using resistivity measurements. The objectives of this pilot research project were to measure the resistivity variations in the dams and, if possible, to quantify the seepage from the measured resistivities. The aim was primarily to extend the methodology developed for the evaluation of temperature measurements to the evaluation of resistivity measurements, rather than to develop a complete description of the transport theory.

3.2 Basic concept and assumptions

Solute transport within a dam is an advective process related to the seepage flow. The seepage flow is coupled to the temperature field, which is formed as a result of advective flow and heat conduction. It is necessary therefore to consider a set of coupled transport processes for heat and solute. Heat conduction, mainly through the unsaturated parts of a dam, may also be important for low seepage flow rates and small dams. Geothermal flow may be important for large dams.

The seasonal variation of the absolute resistivity in the reservoir water is separated into two parts when the seepage water passes through the dam, see Figure 18. The solutes penetrate into the dam with the pore velocity v_n while the temperature travels with the thermal velocity v_T. The resistivity variation in the dam is therefore a combined result of these two transport processes.

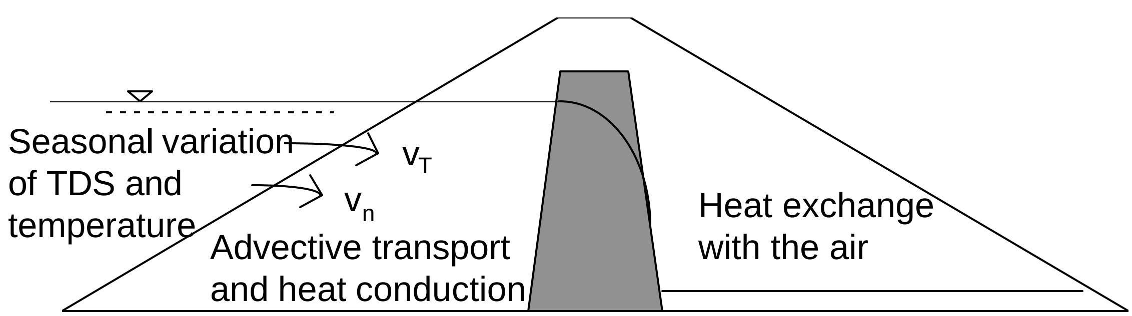

Figure 18 Important transport processes that affect the resistivity variation in an embankment dam.

3.3 Measurement method and resistivity evaluation

The resistivity was measured with a system which gave accuracy and high resolution (Dahlin 1993). Electrodes were permanently installed at five meter intervals on the dam crest at Lövön embankment dam. The measurements were performed with Wenner configurations (see Figure 19) on eight occasions over a period of 18 months.

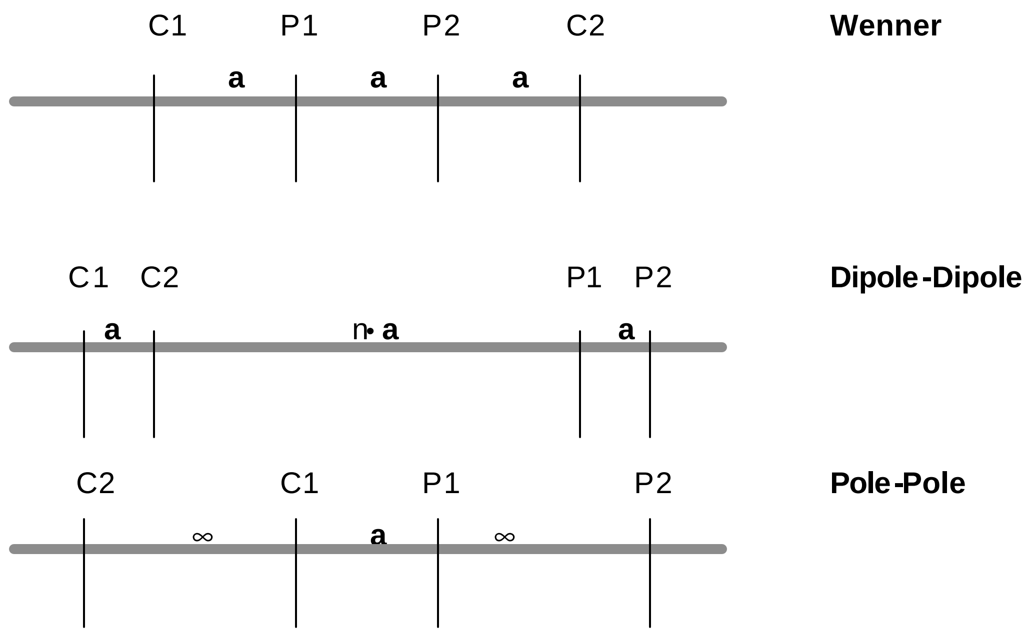

Figure 19 *Examples of some common electrode arrays for resistivity measurements. C1 and C2 represent current electrodes and P1 and P2 potential electrodes. The distance between the electrodes is denoted by* **a**.

The result was plotted in pseudosections for data quality control and a qualitative interpretation of the data. The true resistivity in the dam was calculated by inversion. This was done using two-dimensional finite difference models, in which the interpreted model resistivities are adjusted to fit the field data (Loke and Barker 1996). The pseudosections and inverted sections were processed statistically to provide an annual mean resistivity section and a normalised variation section.

3.4 Seepage evaluation methods

3.4.1 Lagtime method

The quantitative interpretation of water flow through the dam is based on the fact that a variation in resistivity in the reservoir water will propagate into the dam with the seepage water. The variation due to variations in TDS will travel with the pore velocity, whereas the variation due to temperature will move with the thermal velocity.

The simplest method of seepage evaluation consists of comparing extreme values for the absolute resistivity in the reservoir and the interpreted resistivity in the embankment dam. This is the lagtime method described in Section 2.5.1. This method is one-dimensional and neglects both heat loss and dispersion effects. It requires the lagtime t_d and the length of the seepage pathway x as input data. The assumptions concerning heat transport are not valid for small leakage zones where the heat losses around the leakage zone can be large. The approximations are more valid for larger zones, with cross sections of some 10 m^2 or more. This size corresponds to the cell size used for inversion of the resistivity data.

If the temperature is constant at the boundary the seepage flow only depends on the TDS transport, and this travels with the pore velocity. The evaluated seepage flow from these assumptions q_{TDS} will thus be a function of the porosity:

$$q_{TDS} = \frac{nx}{t_d} \qquad \text{Eq. (13)}$$

On the other hand, if the TDS in the reservoir is constant it is the temperature changes that cause the main resistivity variation in the dam. Seepage evaluation can then be performed with the lagtime method developed for temperature measurements, and Eq. (9) can be used directly. The evaluated seepage flow q_T depends on the volumetric heat capacity.

These two estimated values of the seepage flow (q_{TDS} and q_T) can be interpreted as limits for the real seepage flow q since it can be proved that the pore velocity is larger than the thermal velocity:

$$\frac{nx}{t_d} < q < \frac{C_0 x}{C_w t_d} \qquad \text{Eq. (14)}$$

Normal values of n, C and C_w inserted in the equation above give the limits:

$$0.2 < \frac{q t_d}{x} < 0.6 \qquad \text{Eq. (15)}$$

These limits do not include the entire range of uncertainty values. It is in many cases difficult to estimate the length of the real seepage pathway as well as the lagtime. The dispersion will not influence the lagtime, but it strongly affects the temporal variations of the resistivity and complicates the evaluation of the lagtime. However, in the absence of more accurate methods, such limits may sometimes be good enough to estimate the seepage flow in dams.

3.4.2 Simplified amplitude method

The amplitude method employed for seepage evaluation using temperature variation can be modified to serve also for resistivity measurements. The general solution is given in dimensionless form for the dimensionless temperature T', defined as the thermal response within the dam divided by the initial variation at the boundary. The simplified amplitude method is the most appropriate one because resistivity measurements cannot give as fine a vertical resolution as temperature measurements. The finest vertical resolution which can be obtained from resistivity measurements is the height of the cells in the resistivity evaluation model.

If the TDS is constant T' can be replaced by a dimensionless resistivity, defined as the normalised variation R':

$$R' = \frac{r_{\text{max,dam}} - r_{\text{min,dam}}}{r_{\text{mean, dam}}} \Bigg/ \frac{r_{\text{max, reservoir}} - r_{\text{min,reservoir}}}{r_{\text{mean, reservoir}}} \qquad \text{Eq. (16)}$$

where r is the resistivity in Ωm. By calculating R' from evaluated resistivity data and estimating the length of the seepage pathway, Figure 6 can be used to obtain the seepage through the dam.

3.5 Field measurements

Field measurements at Lövön power plant in the River Faxälven show that the temperature in the reservoir is normally about 0°C during the winter and about 18°C in the summer (see Figure 17). The absolute resistivity of the water varies seasonally between 300 and 750 Ωm. Both variables can be approximated with ordinary sine functions. The lowest absolute resistivity occurs during the summer, when the temperature is highest. The TDS, described by the resistivity at 25°C, has its maximum during the winter. The relative change in the absolute resistivity is about $\pm$50%, compared with about $\pm$15% for the resistivity at 25°C. Hence the effect of the seasonal temperature variation on the resistivity is about three times larger than that due to the TDS variation. It is therefore acceptable to ignore the TDS variation and assess the seepage flow using thermal methods.

The variation within the dam (see Figure 20) exhibits seasonal variations similar to those which occur at the boundary. Unfortunately the measuring intervals are large, which complicates the evaluation. The results are generally similar at all measured depths, except for some minor deviations in the upper part of the dam. The minima are in the beginning of October, which gives a lagtime of two months. The lagtimes for the maxima are more difficult to evaluate, but again two months seems to be a reasonable estimate.

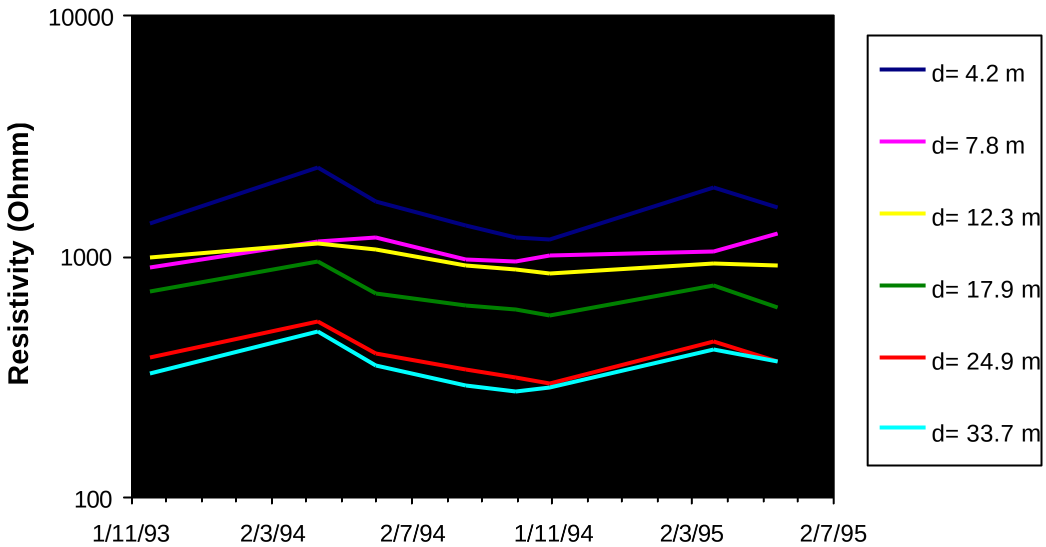

Figure 20 *Resistivity variation in section 0/100 in the embankment dam at Lövön power plant at various depths d to the midpoint of the evaluation cell.*

The normalised variation in the dam is between 20 and 80 % as shown in Figure 21. The large variation in the upper part of the dam (where no seepage occurs) is due to seasonal soil moisture and temperature variations and freezing.

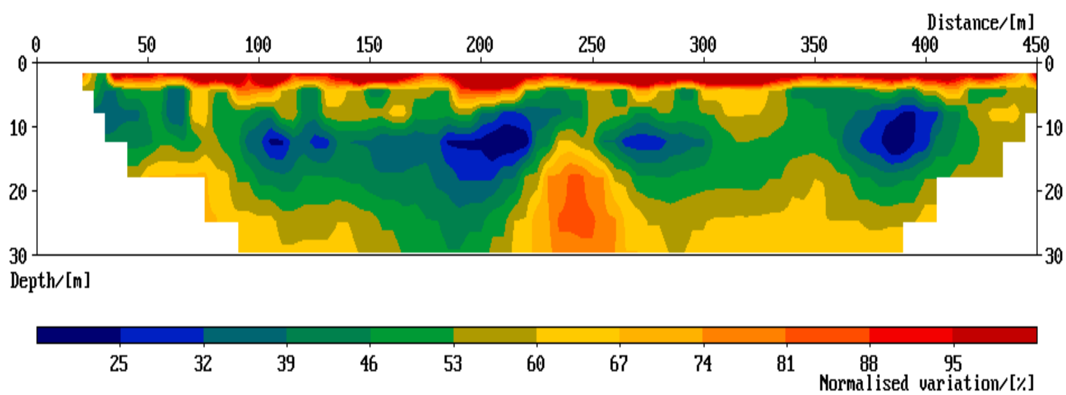

Figure 21 *Normalised variations of evaluated resistivities in the embankment dam at Lövön power plant in the River Faxälven.*

The largest observed resistivity variation is between section 0/230 and 0/250 at a depth of about 25 m. Seepage evaluations in this area give 20 to 40 ml/sm with the lagtime method and 40 ml/sm with the simplified amplitude method. Thus the total seepage flow between section 0/230 and 0/250 can be estimated to be about 0.8 l/s. This flow is rather small in such a dam. Since the resistivity variations are smaller in the rest of the dam the seepage flow will also be smaller.

3.6 Comparison of the temperature and resistivity methods

Two standpipes, B10 located at section 0/043 in the core and 13 at section 0/097 in the downstream part of the dam, are within the resistivity profile. These standpipes are also used for temperature measurements. The seepage flows evaluated from the temperature measurements are similar to the seepage flows evaluated from the resistivity measurements. There are however some important differences as discussed below.

It is generally difficult to determine the depth in resistivity measurements. In the calculation below it is assumed that the depth to the midpoint of the evaluation cells *d* is equal to the depth below the dam crest. It is further assumed that *x*, the distance from the inflow section to the evaluation cell, is equal to *d*, due to the slope of the upstream dam side. The largest absolute resistivity variation in this case is caused by the temperature variation in the reservoir and therefore the TDS is assumed constant in the following evaluations.

The seepage flow q around B10, as given by the lagtime method, is estimated to be between 1.7 and 3.5 ml/sm^2 in the three cells between 14.8 and 38.6 m depth (approximately between elevation +275 m and +251 m). The estimated total seepage flow Q in the section is therefore between 40 and 83 ml/sm.

A comparison between the variation with depth of the normalised resistivity and the dimensionless temperature shows clearly the higher vertical resolution achieved by the temperature measurements. The maximum values are similar but do not occur at the same elevations (Figure 22).

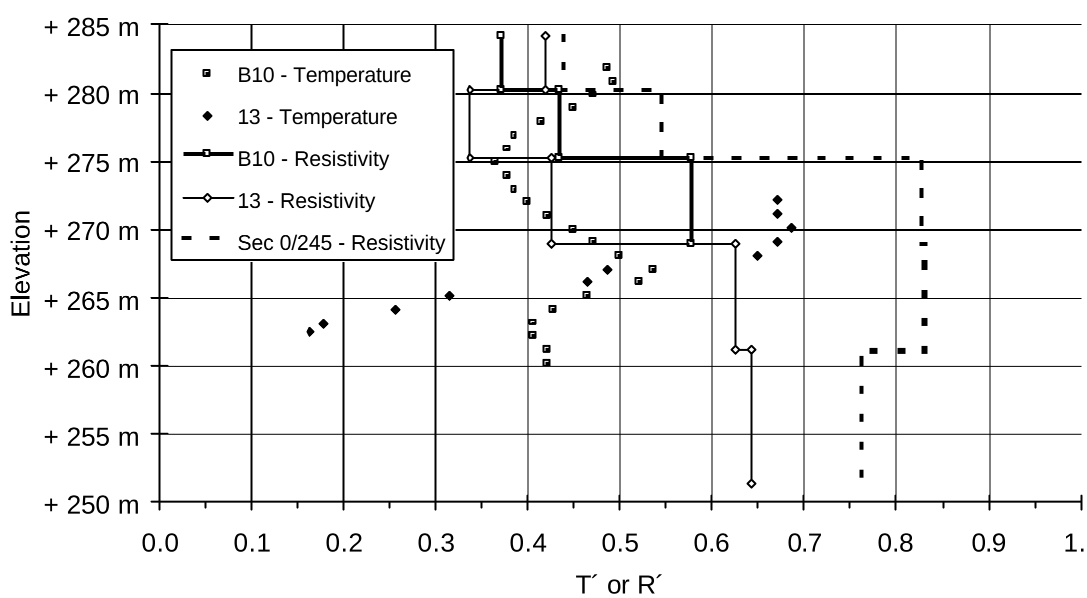

Figure 22 T' and R' at different levels in standpipes B10 and 13 and R' in section 0/245 in the embankment dam at Lövön power plant.

The lagtime for standpipe 13 is about two months for the maximum value and about three months for the minimum value (see Figures 17 and 20). The lagtime method gives a seepage flow of between 14 and 20 ml/sm. Evaluation using the simplified amplitude method gives an approximate seepage flow of 22 ml/sm for R´=0.63. These values are similar to those given by the temperature analyses: about 18 ml/sm using the amplitude method and larger than about 9 ml/sm using the lagtime method.

The temperature measurements in standpipe B10 indicate the highest seepage around +268 m. The resistivity measurements on the other hand show an increasing flow with depth, since the same lagtime is estimated for all depths. The normalised resistivity is calculated as $R'=0.58$, which with Figure 6 gives a seepage flow of about 13 ml/sm. The temperature measurements also give a seepage flow of about 13 ml/sm using the amplitude method with $T'=0.56$ and x=20 m, and a value larger than 9 ml/sm using the lagtime method.

It can be concluded that these results are in good agreement with each other although some of the evaluation methods are based on significant assumptions. It would seem reasonable to estimate the seepage flow in this section to be between 10 and 20 ml/sm, even if the lagtime method gives a higher value. These flow rates are about half of the highest evaluated seepage flow obtained between section 0/230 and 0/250.

3.7 Conclusions

Resistivity measurements have been carried out in two embankment dams. The result indicates a seasonal resistivity variation due to the seepage flow through the dam. This is mainly a result of the combined influence of the variation in temperature and TDS in the reservoir. These variations can be used to monitor seepage flow and locate zones of anomalous leakage. Analyses of resistivity variation can provide a good overview of embankment dams. The technique is non-destructive apart from electrode installation, which is a minor intrusion on the crest of the dam.

Data of good quality were obtained and this is crucial for analyses of temporal variation. The true resistivity in the dam was calculated by inversion. This was done using two-dimensional finite difference models, in which the interpreted model resistivities are adjusted to fit the field data. The normalised resistivity variation obtained from the inverted sections can be used for seepage evaluation.

The 2D data acquisition and interpretation technique used is however a simplification of the 3D reality. The reservoir water could be expected to have a smoothing effect on the resistivity variation along the dam. On the other hand, the dam core may have a channelling effect on the current due to its higher fine particle content. This would tend to emphasise the variation. A variation in the condition of the embankment dam on the downstream side may also affect the results. A further complication for resistivity measurements may be the presence of conductive objects, such as metal borehole casings and ground cable, in the dam. The influence from such objects is normally difficult to assess. Since the objective is to analyse time variations in resistivities, however, the problem is less significant than it would normally be.

Other factors which affect the resistivity in the upper part of the dam may also influence the measurements. Examples of such factors are soil moisture variation due to climatic variation, air temperature variation and seasonal freezing of the ground. The measured resistivity is generally also influenced by the water level in the reservoir, but this is not considered to have a major influence in the studied dams.

The seepage flow can be evaluated from the resistivity data using methods similar to those employed for seepage evaluation from temperature data. For seepage flows larger than about 1 ml/sm^2 the resistivity variation inside the dam is mainly caused by the seepage flow and the seasonal variations of the resistivity in the reservoir. The seepage flow limit depends on the dam height, and the value of about 1 ml/sm^2 is valid for typical Swedish dams with a height of about 30 m. Zones where seepage changes occur or zones with anomalous leakage can therefore be located in such dams with a detection level of about 1 ml/sm^2.

Seepage flows evaluated from resistivity and temperature measurements are generally in good agreement. A few boreholes for temperature measurements at selected points can provide good reference data for interpretation. In combination therefore, resistivity and temperature measurements can be used for identifying and quantifying anomalous leakage.

In conclusion, the seasonal resistivity variation can be significant in embankment dams and cannot be assumed to be constant. If resistivity measurement is performed in a dam on a single occasion the result must be interpreted carefully; the result is incomplete without the time variation and may even be misleading. The resistivity variation depends mainly on the seepage through the dam. Seepage can therefore be quantified along the entire dam. Further development of evaluation methods is possible and is recommended once a system for continuous surveillance and monitoring has been installed.

4 RADAR MEASUREMENTS

4.1 Background

Ground penetrating radar (GPR) and borehole radar have been used in studies of embankment dams aimed at detecting anomalous zones and the leve l of the core crest. The work summarized in PAPER 7 was carried out within two different projects. My co-authors, Dr Anders Wörman and Seje Carlsten, were responsible for the borehole radar measurements. The author carried out the GPR measurements for detection of the core crest in co-operation with Dr Peter Ulriksen and Ola Landin.

Although seepage flow cannot be measured directly with GPR or borehole radar, the results and experiences gained in the projects can be usefully compared with the results from the previously presented methods. Temperature, GPR and borehole radar examinations have also been used jointly in some dam studies. One example is the Porjus dam study which is briefly described in PAPER 4.

4.2 Basic concept and assumptions

Electromagnetic waves within a certain frequency range can propagate through rock, soil or water. The wave velocity depends on soil properties such as the dielectricity, electrical conductivity and magnetic permeability. Porosity and water content affect the soil properties significantly. The resulting differences in electrical conductivity (or radio wave velocity) in the soil are detected by radar measurements. This is the fundamental principle of both GPR and borehole radar. The main difference between the methods is that a tomographic analysis can be performed between two boreholes.

The penetration depth depends on soil properties but also on the emitted frequency. Different antennas are therefore used for various applications. A long frequency gives a high penetration depth but a low resolution due to the low wavelength.

Internal erosion affects the porosity of material in the core and increases the water content. Radar measurements can detect these changes since they influence the radio wave velocity.

Core crest detection by GPR is based on an assumed difference in saturation between the core and the filter above the core. The core has a higher degree of saturation than the filter material due to the higher capillarity of the core material. The porosity in the core is normally also lower. Both these differences will affect the wave velocity.

4.3 Measuring methods

GPR applied from the dam crest is a non-destructive method that can quickly give information about the status of the dam. Normally two antennas are used, one for transmitting and the other for receiving signals. They are moved slowly along the dam. Antennas with different frequencies are used in order to get an optimal result with respect to penetration and resolution.

The objective of the GPR measurements presented in PAPER 7 was to detect the level of the core. In Swedish dams the core is normally located less than five meters below the dam crest. High frequency antennas were therefore chosen. The system allows measurements with five antennas, and this gives five parallel profiles in one measurement. Different set-ups of sending and receiving antennas can be combined. These were also tested at some measurements.

Measurements with borehole radar must be performed from boreholes with plastic casing and with a diameter larger than 56 mm (the diameter of the antennas). The system consists of two borehole probes to transmit and receive the radar pulses. There is no direct connection between the transmitter and receiver. This permits the two antennas to be used in the same borehole (single-hole reflection) as well as in separate boreholes (cross-hole tomography). One antenna is then kept in a fixed position in one borehole while the other is moved at fixed intervals in the other borehole. After measurements have been made at all levels in the second borehole the antenna in the first borehole is moved and the measurements are repeated at all levels in the second borehole. Each ray between the antennas represents the average of a measured property of the soil along the ray path.

In tomographic analysis, the plane between the boreholes is divided into a number of cells. Several rays pass through each cell. This gives an overdetermined system, which can be solved. The cells are normally 2x2 m in size.

4.4 Results and evaluation

Six dams were examined and the core crest was located by GPR measurements in four of them. A satisfactory result was not obtained from the measurements at the first two dams, and the method was therefore improved. In two of the dams the result could be verified. The accuracy was estimated to be about ±0.1 m, or about 5% of the measured depth to the core crest.

An important observation was made at the embankment dam at Grundsjön in the River Ljusnan close to Långå power plant. A sinkhole on the dam crest was observed visually at the time the GPR measurements were carried out. The result of the measurements on this dam was of good quality along the entire dam, except at the location of the sinkhole where the signal from the core crest was poor. Repair revealed that internal erosion had occurred below the penetration depth obtained by the 500 MHz antennas. Loose areas consisting of coarse sand and gravel were found below the core crest. Such material may act as a capillary barrier and this would mean that the basic assumption of a saturated core was not fulfilled. This may explain the poor signal from the core crest in the sinkhole area.

The borehole radar measurements in the embankment dam at Suorva in the River Luleälven showed areas of increased water content (see Figure 23). Based on this and other examinations it was decided to grout the dam. Grouting was performed by injecting a silicate compound. Data from the grouting program agreed well with the radar model obtained.

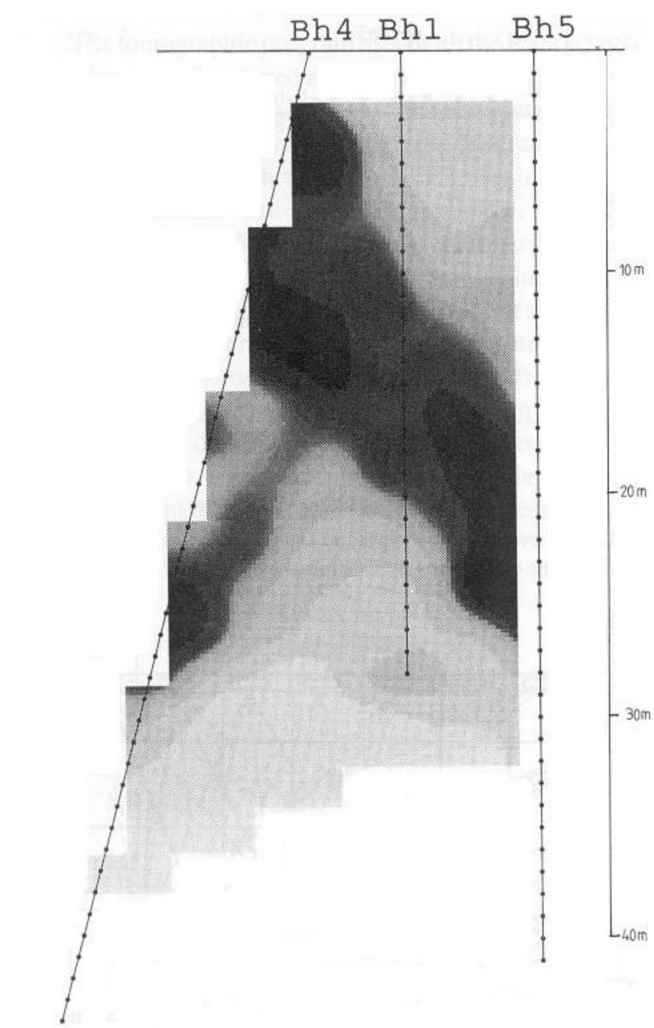

Figure 23 Tomographic image from boreholes Bh4 and Bh5 in the embankment dam at Sourva in the River Luleälven, showing variations in radar velocity. Dark colours represent increased dielectric permittivity, which is interpreted as increased water content.

4.5 Conclusions

Ground penetrating radar and borehole radar methods are based on the measurement of material dependent properties. These are less sensitive to seepage changes than flow dependent parameters. The relatively high accuracy obtained by borehole radar measurements compensates however for their lower sensitivity to porosity changes. Borehole radar based on tomographic analysis can be a valuable method for mapping areas with increased and anomalous porosity formed as a consequence of increased seepage and internal erosion. Repeated measurements with identical measurement parameters may also show temporal variations.

GPR measurements can detect large zones with anomalous properties that may be interpreted as zones with internal erosion or increased seepage. Such results may serve as guidance for additional investigations as in the case of the Porjus dam described in PAPER 4. The level of the core crest can also be detected by GPR measurements.

5 CONCLUSIONS AND RECOMMENDATIONS

Internal erosion, which is one of the major reasons for embankment dam failure, causes an increased seepage flow due to loss of fines. Methods that are able to register small changes in the seepage flow rate along the entire dam are therefore important, because they can detect internal erosion at an early stage before it starts to affect the safety of the dam.

The seasonal temperature and resistivity variations in the reservoir upstream of an embankment dam offer two possibilities of measuring the seepage flow in the dam. This is because both temperature and resistivity affect the seepage water that slowly passes through the dam. Measurements in the dam of either of these parameters will therefore show a similar seasonal variation, which will depend on the seepage flow rate. The seepage flow can thus be quantified. The application of the two methods is mainly for monitoring of time dependent processes such as internal erosion, where the relative accuracy is more important than the absolute accuracy.

Temperature can normally be easily measured in existing standpipes and additional drilling can therefore be avoided. The only cost relates to the monthly temperature observations, which can be carried out by the dam engineering staff. Resistivity measurements are more complicated; they require a computer-based monitoring system and minor technical installations at the dam.

Temperature measurements

Theoretically, the temperature variation in an embankment dam depends primarily on the seepage flow rate and the seasonal temperature variation in the reservoir. Seasonal variation of air temperature will cause temperature variations in the upper part of the dam. These can be ignored in larger dams where the distance between the measuring point and the surface exceeds 20 m. Geothermal flow and thermal stratification in the reservoir must however be considered in such dams. The opposite is the case for small dams; heat conduction from the surface must be considered but both geothermal flow and thermal stratification in the reservoir can normally be ignored.

Both the lagtime and the annual maximum temperature difference are obtained from regular temperature measurements. The seepage rate can then be evaluated with two independent methods, using either the lagtime or the attenuation of the pulse.

Internal erosion in embankment dams often creates horizontal zones in which the heat transport occurs mainly due to advection and vertical heat conduction. A mathematical model based on this assumption shows that the temperature variation depends mainly on the seepage flow rate, the seepage zone thickness, and the distance from the inflow section to the measuring point. The thermal properties of the soil have a relatively small influence. This method, where the seepage flow is given in dimensionless form, is suitable for evaluation using the annual temperature variation. The result shows good agreement with numerical simulations that have been performed for dams lower than 25 m.

Results from field measurements show that the method gives reasonable information on dam's condition. Zones with anomalous seepage rates have been located and seepage flow rates have been quantified. Changes in the seepage flow rate as well as the seepage pathway have also been observed.

The sensitivity of the method depends mainly on the distance between the dam crest and the measurement point, the size of the dam, the location of the standpipes, and the temperature variation in the reservoir at the inflow level. The seepage detection level of the method is about 1 ml/sm^2 for a typical Swedish dam with a height of about 30 m. The detection level depends linearly on the dam height. The sensitivity is decreased if the temperature variations in the dam are affected by both air temperature variations and seepage.

Resistivity measurements

Seasonal resistivity variation in embankment dams has been detected by regular resistivity measurements in the dams. This variation is mainly a result of the combined influence of the seasonal variation in temperature and TDS in the reservoir. The seasonal resistivity variation can be significant in embankment dams and cannot be assumed to be constant. If resistivity measurement is performed in a dam on a single occasion the result must be interpreted carefully; the result is incomplete without the time variation.

Other factors which affect the resistivity, especially in the superficial part of the dam, may also influence the measurements. Examples of such factors are soil moisture variation due to climatic variation, air temperature variation and seasonal freezing of the ground. The measured resistivity is in principle also influenced by the water level in the reservoir, but this effect is not considered to be significant for the studied dams.

Data of good quality were obtained in the measurements and the true resistivity in the dam was calculated by inversion. This was done using two-dimensional finite difference models. The normalised resistivity variation obtained from the inverted sections can be used for seepage evaluation.

However, the 2D data acquisition and interpretation technique used is a simplification of the 3D reality. The reservoir water could be expected to have a smoothing effect on the resistivity variation along the dam. On the other hand, the dam core may have a channelling effect on the emitted electrical current due to the higher fine particle content in the core compared to other parts of the dam. This would tend to emphasise the variation. A variation in the properties of the embankment dam on the downstream side may also affect the result.

The seepage flow can be evaluated from the resistivity data using methods similar to those employed for seepage evaluation from temperature data. For seepage flows larger than about 1 ml/sm^2 the resistivity variation inside the dam is mainly caused by the seepage flow and the seasonal variations of the resistivity in the reservoir. The seepage flow limit depends on the dam height and the value of about 1 ml/sm^2 is valid for typical Swedish dams with a height of about 30 m. Zones where seepage changes occur or zones with anomalous leakage can therefore be located with a detection level of about 1 ml/sm^2.

Analysis of resistivity variation provides a good overview of the state of an embankment dam. The monitoring is non-destructive, apart from the electrode installation, and provides a possibility of observing the effects of time dependent processes such as internal erosion.

A few boreholes for temperature measurements at selected points can provide good reference data for interpretation. In combination therefore resistivity and temperature measurements can be used successfully for locating and quantifying anomalous leakage. Seepage flow patterns evaluated from resistivity and temperature measurements are in good agreement, although the evaluation methods are based on significant assumptions.

Radar measurements

Ground penetrating radar and borehole radar methods are based on the measurement of material dependent properties. These are less sensitive to seepage changes than flow dependent parameters. The relatively high accuracy obtained by borehole radar measurements compensates however for their lower sensitivity to porosity changes. Borehole radar based on tomographic analysis can be a valuable method for mapping areas with increased and anomalous porosity formed as a consequence of increased seepage and internal erosion. Repeated measurements with identical measurement parameters may also show temporal variations.

GPR measurements can detect large zones with anomalous properties that may be interpreted as zones with internal erosion or increased seepage. Such results may serve as guidance for additional investigations as in the case of the Porjus dam described in PAPER 4. The level of the core crest can also be detected by GPR measurements.

Recommendations

An effective computerized system for monitoring temperatures in embankment dams should be developed. A system based on optical fibre sensors would provide the desired high level of accuracy and is therefore recommended. Such a system has many advantages compared to more conventional thermal probes; it is less sensitive to damage by lightning and generally more durable.

Resistivity measurement is a promising technique but there is a need for improvement in measurement strategies such as the choice of electrode arrays, as well as data processing and interpretation techniques. There is a particular need to determine depths more accurately. Techniques for inversion and interpretation should be developed for operating directly on the differences between data from time series of measurements, instead of calculating differences from inverted sections. In many cases 3D measuring and data processing strategies may be needed, especially for short dams.

There is furthermore a significant ambiguity in resistivity data interpretation, due for example to the equivalence principle. This will be studied further in the ongoing project at the embankment dam at Hällby power plant in the River Ångermanälven, where a permanent resistivity system has been installed. This system will improve the quality of the data and provide an increased measuring frequency. It will thus enable improved evaluation models to be developed.

Laboratory experiments to study the resistivity change caused by internal erosion are also recommended. These will enable the relative effects of the porosity increase and the loss of fines to be analyzed. The experiments could be carried out using soil samples from the cores of several dams. Supplementary field studies should also be carried out.

Both temperature and resistivity methods can be further developed for application in the following fields, where time dependent processes occur:

- induced infiltration (as described in PAPER 2);
- artificial aquifer recharge;
- monitoring of waste deposits in soil or rock;
- monitoring of soil remediation;
- tracer tests in soil or rock; and
- heat storage in aquifers.

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