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SEEPAGE MONITORING IN AN EARTH EMBANKMENT DAM BY REPEATED RESISTIVITY MEASUREMENTS

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ABSTRACT

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Resistivity measurements have been carried out in two embankment dams in order to develop non-destructive methods for seepage monitoring. 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 concentration of total dissolved solids in the reservoir. Data of good quality were obtained, which is crucial for analyses of temporal variation. However, the 2-D data acquisition and interpretation technique used is a simplification of the 3-D reality. The seepage flow can be evaluated from the resistivity data using methods similar to those employed for seepage evaluation from temperature data. At seepage flows larger than around 10^{-6} m^3/sm^2,the resistivity variation inside the dam is mainly caused by the seasonal variations of the resistivity in the reservoir. Seepage flows evaluated from resistivity and temperature measurements show good agreement. Resistivity monitoring is non-destructive apart from the electrode installation and can provide measurements of time-dependent processes such as internal erosion.

KEY WORDS: Embankment dams, internal erosion, monitoring, non-destructive, resistivity, seepage, temperature.

INTRODUCTION

Internal erosion is one of the major causes of embankment dam failure. The seepage flow increases as a result of the material transport and a sinkhole may develop at the dam crest. Methods for seepage monitoring in embankment

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dams are therefore important. Of particular importance are methods able to register small changes in the rate of seepage through a dam, and thereby allow of detection of internal erosion at an early stage before it starts to affect the safety of the dam. It is also desirable to develop methods which can examine the total length of a dam, in order to complement single point measurements. The presented method satisfies some of these criteria.

The resistivity of a soil depends on its porosity, water content and clay content, among other factors. The same factors also apply to embankment dams. However, the resistivity of the water in the reservoir varies seasonally, depending on the seasonal temperature variation and the seasonal variation of the concentration of total dissolved solids (TDS) in the water. Hence, when reservoir water seeps through the dam, the properties of the seepage water in the dam will also affect the resistivity in the dam.

Temperature measurements in embankment dams, repeated at regular intervals, also provide a sensitive method for detecting seepage through the dam (Johansson, 1991). However, the measurements must be performed in standpipes which have to be drilled from the dam crest. Such drilling is expensive and may sometimes negatively influence the dam. Moreover, drilling cannot be done continuously along the dam, hence non-destructive methods are needed for localising zones of anomalous leakage and assessing the total seepage through the dam.

This paper summarises the theory of seepage monitoring by resistivity measurements and discusses its application to two dams. Results are presented from eight measurements in the Lövön embankment dam, but experience gained from six measurements at Moforsen embankment dam is also presented to supplement the study. A full report (in Swedish) of the project has been published elsewhere by Johansson and Dahlin (1995).

OBJECTIVES

The basic hypothesis for the measurements is that the seasonal resistivity variation can be used to detect anomalous seepage. Model calculations showed that these variations could be detected using resistivity measurements, hence repeated measurements were started in two embankment dams in 1993. The aim of this pilot project was to measure the resistivity variations in the dams, and if possible, to quantify the seepage from the measured resistivities. The idea was primarily to extend the methodology developed for the evaluation of temperature measurements to the evaluation of resistivity measurements. Since the long intervals between the measurements meant that only one approximate evaluation could be made, it was decided that a complete description of the transport theory would not be appropriate within the project.

TEMPERATURE VARIATIONS IN EMBANKMENT DAMS

The temperature in an embankment dam depends mainly on the temperature in the air and in the temperature of the upstream reservoir. These temperatures vary seasonally and create temperature "waves" in the dam. Normally, the seepage flow is small in embankment dams and the seasonal temperature variation therein depends mainly on the seasonal temperature variation at the surface of the dam. The influence from the air is less than 1 °C if the distance to the dam surface exceeds 10 m. Therefore, at such depths the influence from the air is negligible. If water seeps through the dam, 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 determines the temperature inside the dam. The seasonal temperature variation in the dam is then directly proportional to the flow rate.

The heat transfer in dams consists of heat conduction and advection. The advective part is temperature dependent because both the density and the viscosity are functions of the temperature. Hence, there is a coupled function between the temperature field and the seepage flow rate.

The seepage rate, and its change with time, can be evaluated from measurements repeated at regular intervals. The seepage detection level of the method is about 10^{-6} m^3/s per m^2 (or 1 ml/sm^2) for typical Swedish dams with a height of about 30 m. The detection level depends linearly on the dam height and for a 300 metre high dam, the detection level will be about 10 ml/sm^2.

From the foregoing discussion, the temperature inside an embankment dam is related to the advective thermal flow due to water seepage through the dam, and to heat conduction resulting from temperature variations on the dam surface. If internal erosion creates a more permeable zone, the seepage concentrates in this zone and the advective heat flow will dominate the total thermal flow in the zone.

The models first 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 by Johansson (1991). An analytical model based on the attenuation of the wave (the amplitude method) is presented by Johansson (1997). The most important assumptions in this model are that:

- the temperature varies sinusoidally at the boundary;
- the seepage takes place only in a zone of constant height;
- one-dimensional advection and vertical heat conduction occur in the seepage zone;
- only vertical heat conduction occurs in the layers above and below the seepage zone; and

- thermal properties are assumed constant along the direction of the seepage flow.

The solution is presented in terms of dimensionless parameters, representing the temperature variation and the seepage flow rate.

ORIGIN OF RESISTIVITY VARIATIONS IN EMBANKMENT DAMS

The resistivity in a dam depends on material properties (such as clay content and porosity) and on liquid properties (temperature and content of Total Dissolved Solids). For embankment dams (without internal erosion) the material properties are essentially constant over long periods of time. However, the liquid properties are not constant with time because both the temperature and TDS depend on the water that seeps through the dam. The combination of these parameters is expressed by the absolute resistivity.

If material properties are constant with time, the measured resistivity variation is only a function of the seepage, similar to the basic concept of temperature variations. If internal erosion occurs, it also affects the material properties due to increased porosity which changes the resistivity.

The solute transport is an advective process with the seepage flow, which is coupled to the temperature field as described above. Thus, it is necessary to consider a set of coupled transport processes for heat and solute transport with the seepage flow (see Fig. 1). Heat conduction, mainly through the unsaturated parts, may also be important at low seepage flow rates. The advective transport process is briefly described below.

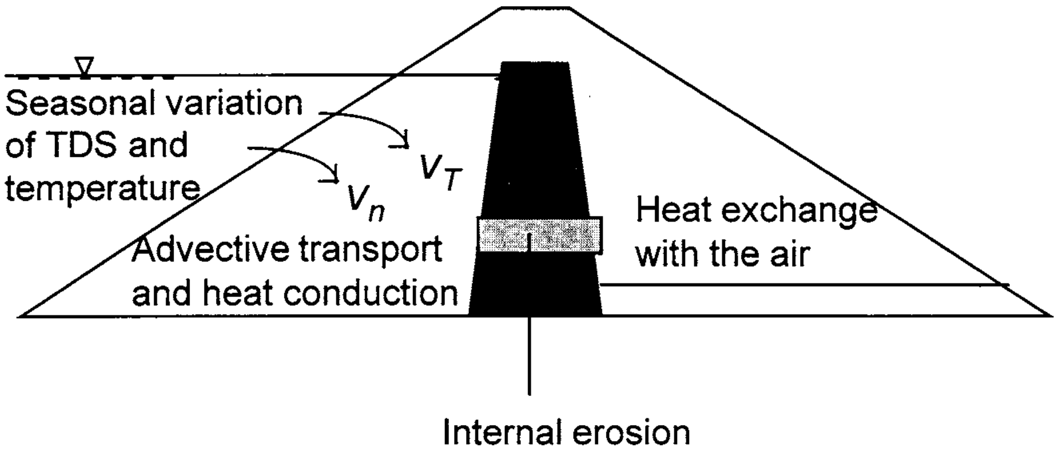

Fig. 1. Important transport processes that affect the resistivity in an embankment dam.

The TDS will penetrate into the dam with the advective seepage flow q as a tracer. Assuming a conservative tracer, i.e., no exchange with the soil matrix, the pore velocity v_n is a function of the effective porosity, n:

$$v_n = q/n \quad . \tag{1}$$

The effective porosity in the core of embankment dams is normally between 15 and 25%, and somewhat higher in the filling material.

The velocity of the heat flux is given by the thermal velocity v_T defined as:

$$v_T = (C_w/C)q \quad , \tag{2}$$

where the volumetric heat capacity is C for the soil and C_w for the water. For most minerals the volumetric heat capacity varies between 1.9 and 2.1 MJ/m^{3}K (Sundberg et al., 1985). With 20% porosity, the heat capacity of saturated soil is normally between 2.3 and 2.5 MJ/m^{3}K. The volumetric heat capacity of the water is 4.18 MJ/m^{3}K.

SEEPAGE EVALUATION FROM RESISTIVITY MEASUREMENTS

Lagtime method

The combined influence of the two transport velocities gives the temporal variation of the resistivity of the soil in the dam which results from the effective resistivity variation in the reservoir. A comparison between extreme values in the reservoir and the dam gives the lagtime, t_d. If the travel length from the boundary to the measuring point x is known, the velocity ($v = x/t_d$) and the seepage flow can then be calculated.

The seepage flow q_n depends only on the porosity if the temperature is constant (Eq. (1)), and can be written as:

$$q_n = (n \cdot x)/t_d \quad . \tag{3}$$

If, on the other hand, the TDS variation is constant in the reservoir, the temperature variation causes the major part of the resistivity variation. The seepage flow q_T is then obtained from equation (2):

$$q_T = (C/C_w)(x/t_d) \quad . \tag{4}$$

The assumptions in the equations above, such as a conservative tracer and negligible heat losses, are not generally fulfilled in small leakage zones where the heat losses around the leakage zone are large. For larger zones (with cross-sections of some 10 m^2 or larger) the approximations are more valid, and the two seepage flows can be interpreted as limits for the real seepage flow. Typical values of n, C and C_w give:

$$0.2 < (q \cdot t_d)/x < 0.6 \quad . \tag{5}$$

These limits are, in general, acceptable for seepage measurements in embankment dams, due to the low detection level for this application. However, the interval above does not include the entire range of uncertainty values. In many cases, both the distance and the lagtime are difficult to estimate. The dispersion will not influence the lagtime, but it strongly affects the temporal variations of the resistivity and complicates the evaluation of the lagtime.

Amplitude method

The method employed for seepage evaluation using temperature variation can be modified to serve also for resistivity. 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 seepage flow, q, is primarily a function of the thickness H of the seepage zone, thermal properties, and the distance from the boundary to the measuring point, x. However, resistivity measurements cannot give as fine a vertical resolution as temperature measurements; the finest vertical resolution which can be obtained is the height of the cells in the resistivity evaluation model. Johansson (1997) shows that the solution of q(T′,H) can be further simplified to an approximate function of Q(T′), where Q is defined as the total seepage per

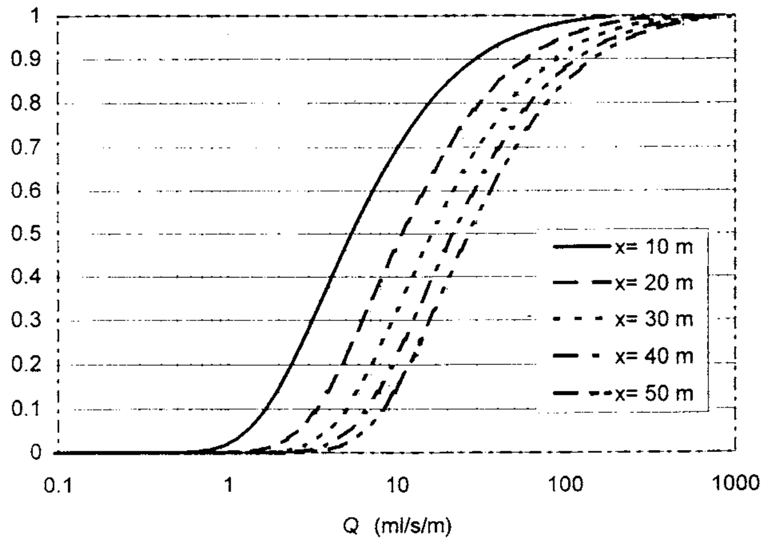

Fig. 2. Approximate relation between dimensionless temperature and seepage flow for the thermal conductivity $\lambda = 2.5$ W/mK and $C_w = 4.18$ MJ/m^{3}K.

length of the dam within a zone which has the thickness H, (Q = qH). For a set of thermal data, the result will be as shown in Fig. 2.

If the TDS variation is constant, T′ can be replaced by a dimensionless resistivity defined as the normalised variation R′:

$$R' = [(\rho_{max,dam} - \rho_{min,dam})/\rho_{mean,dam}]/[(\rho_{max,reservoir} - \rho_{min,reservoir})/\rho_{mean,reservoir}] \quad . \qquad (6)$$

By calculating R′ from evaluated resistivity data (ρ), Fig. 2 can be used to obtain the seepage through the dam for each evaluation cell.

MEASUREMENTS

Data acquisition

A multi-electrode data acquisition system developed at Lund University was used to obtain the resistivity data (Dahlin, 1993; Dahlin, 1996). The system consists of a standard resistivity meter with booster, a 4×64 channel relay-matrix switching unit, four electrode cables with 21 take-outs each, a portable IBM PC-type computer, various connectors, etc. Four cables with 5-metre spacing between the electrodes were used, linked together giving a maximum examination length of 400 metres. The system has been further developed into what is now called the ABEM Lund Imaging System.

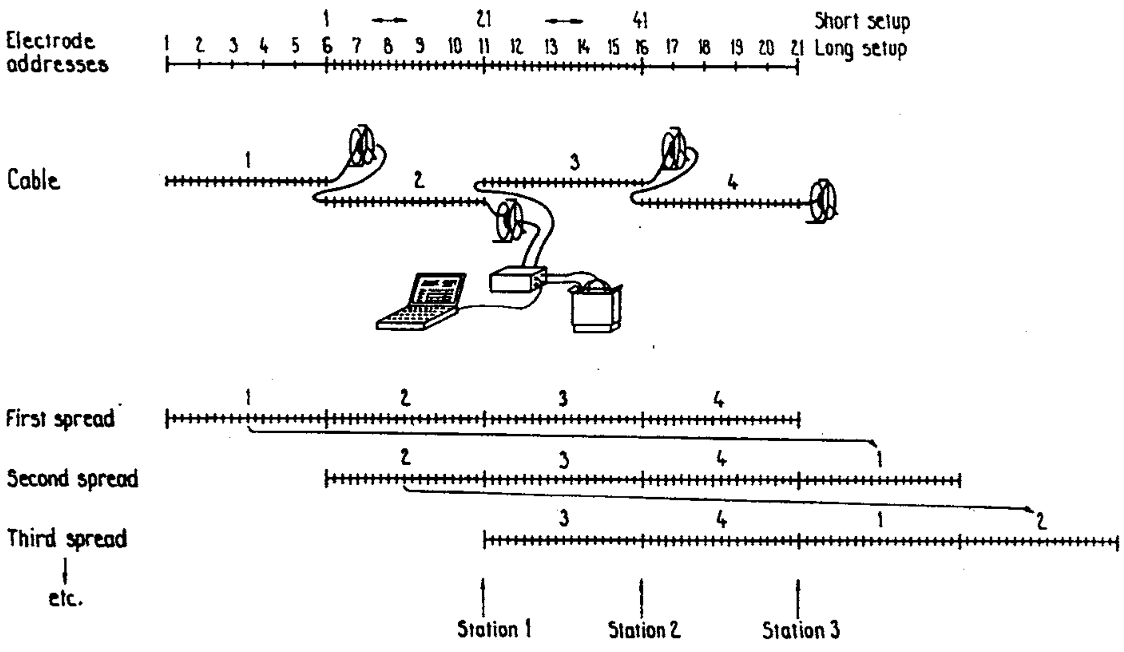

Fig. 3. Sketch layout of the resistivity data acquisition system (modified from van Overmeeren and Ritsema, 1988).

The data acquisition process is completely controlled by software. After the electrode cables have been hooked up to the electrodes, the program checks that all electrodes are connected and properly grounded before actual measuring starts. After adequate grounding is attained, the software scans through the measurement protocol selected by the user. Protocol files for Wenner CVES were used for the data presented here, with the measurements at each instrument station being divided into two parts. The first part involves all four electrode cables, using every second or fourth electrode take-out, depending on the version of the system, while the second part uses only the two central cables but with every take-out active. The measurement protocol used here gives Wenner measurements with 10 different electrode spacings ranging from 5 to 120 metres.

Data processing and presentation

Pseudosection plotting was used during the measurements for data quality control and a qualitative interpretation of the data. The measured apparent resistivities were contoured as a function of the distance along the profile and the electrode separation. If linear interpolation is used for the pseudosection plotting, no smoothing of the data is done, so that the image obtained reflects the quality of the data correctly.

The true resistivity structure was interpreted using 2-D smoothness-constrained inversion. In the inversion 2-D structures are assumed, i.e., the ground properties are assumed constant perpendicular to the line of the profile, while the current electrodes are modelled as 3-D sources. A finite-difference model of the resistivity distribution in the ground is generated, which is adjusted iteratively to fit the data by means of a least-squares technique. The smoothness constraint prevents unstable and extreme solutions. The program used employs a quasi-Newton technique to reduce the numerical calculations (Loke and Barker, 1996). In the inversion of the data presented here, the default damping factor was used throughout, with the vertical-to-horizontal flatness filter ratio set to unity.

The pseudosections and inverted sections were processed statistically to provide an annual mean resistivity section and a normalised variation section. The real variation may be larger than the measured because the extreme values may have occurred between the measurement times. This is also true in the reservoir, where monthly measurements are performed. This would not be a problem if daily measurements were performed both in the reservoir and in the dam. It would then be possible to determine the extreme values with high accuracy. (Such a system was installed in June 1996 in the Hällby embankment dam in Sweden).

RESULTS FROM THE LÖVÖN EMBANKMENT DAM

Background

The embankment dam at Lövön in the river Faxälven is 1600 m long and has a maximum height of 25 m, see Fig. 4. The variation of the water level in the reservoir is less than 2.5 m. The dam and the power plant were completed in 1973.

The dam is founded on moraine, except where it connects to the water intake of the power station where it is founded on rock. The core is made of till and slopes towards the upstream side, except close to the intake where it is vertical. The surrounding earthfill consists mainly of gravel and coarser material.

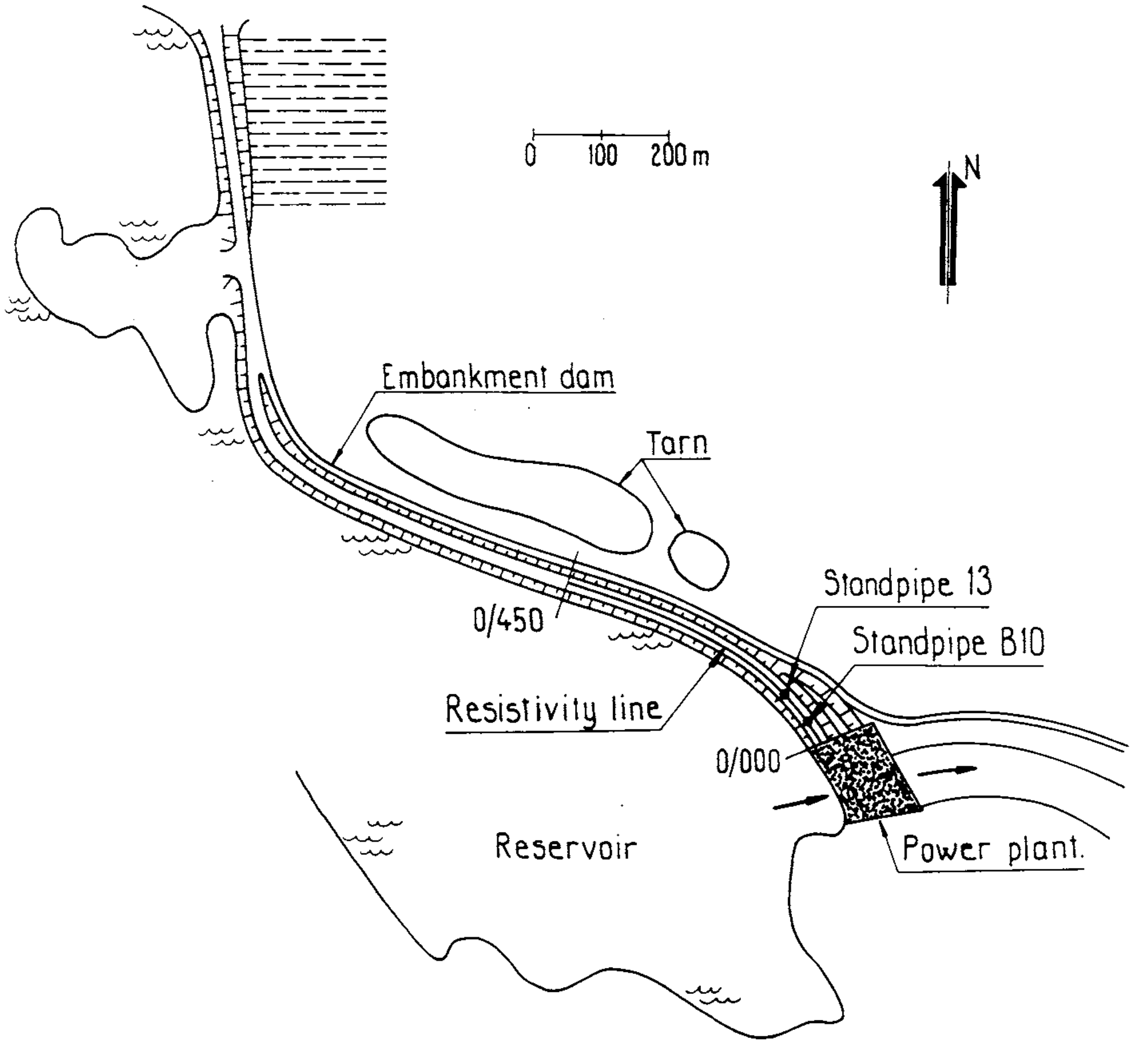

Fig. 4. Overview map of the Lövön power plant with location of resistivity line and some standpipes indicated. Distances are given in metres, where section 0/450 is situated 450 metres from the power plant.

Temperature and resistivity variation in the reservoir

The temperature in the reservoir is normally near 0°C during the winter and up to around 18°C in the summer. The absolute resistivity of the water varies seasonally between around 300 and 750 Ωm, as shown in Fig. 5. Both variables can be approximated with ordinary sine-functions. The lowest absolute resistivity occurs during summer when the temperature is highest. The content of TDS, represented by the resistivity at 25°C, has its maximum during the winter. The relative change in the absolute resistivity is about ±50%, compared with about ±20% 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.

The maximum value of the absolute resistivity in the reservoir is 2.5 times higher then the minimum. This large variation affects the resistivity in the dam. In this case, where the temperature variation dominates, the resistivity variation within the dam will be smaller than that in the reservoir because the heat losses decrease the temperature variation along the flow path.

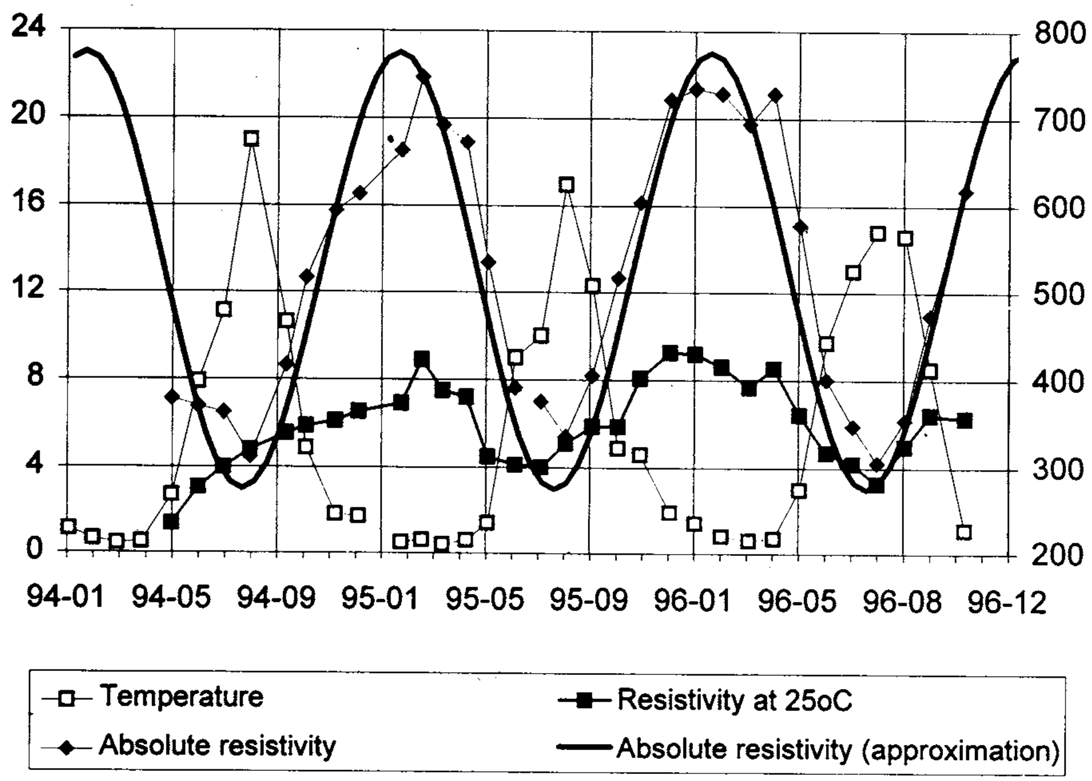

Fig. 5. Temperature and resistivity variation in the reservoir at the Lövön power plant.

Temperature measurements in the dam

Regular temperature measurements started in January 1993 in the reservoir and in 18 standpipes. In general, the temperature variation within the dam is large, with the maximum variation being about 10°C. The mean seepage flow through the dam is evaluated at about 7 ml/sm², and the maximum seepage flow is about 20 ml/sm² (Johansson, 1997).

Only one of the standpipes, No. 13, is located within the main area where the resistivity measurements were carried out. Standpipe B10 is situated in the beginning of the measuring profile at section 0/043. Seepage rate calculations from temperature measurements in these two standpipes can therefore be compared with the seepage rates evaluated from the resistivity measurements. The other standpipes are located close to the water inlet, between section 0/000 and 0/038 and therefore no comparison can be made.

Standpipe 13 is drilled partly through the downstream filter and penetrates also into the underlying till layer. Temperature profiles at different times (see Fig. 6), show large temperature variations between 268 and 273 m below the foundation level. The amplitude method gives a seepage flow for standpipe 13 of about 18 ml/sm² around 270 m and the lagtime method gives a seepage flow of larger than about 9 ml/sm².

The temperature measurements in standpipe B10 indicate a significant zone with increased seepage around 267 m, and another one probably below 260 m, see Fig. 7. The upper zone is just above the bedrock level, and the lower

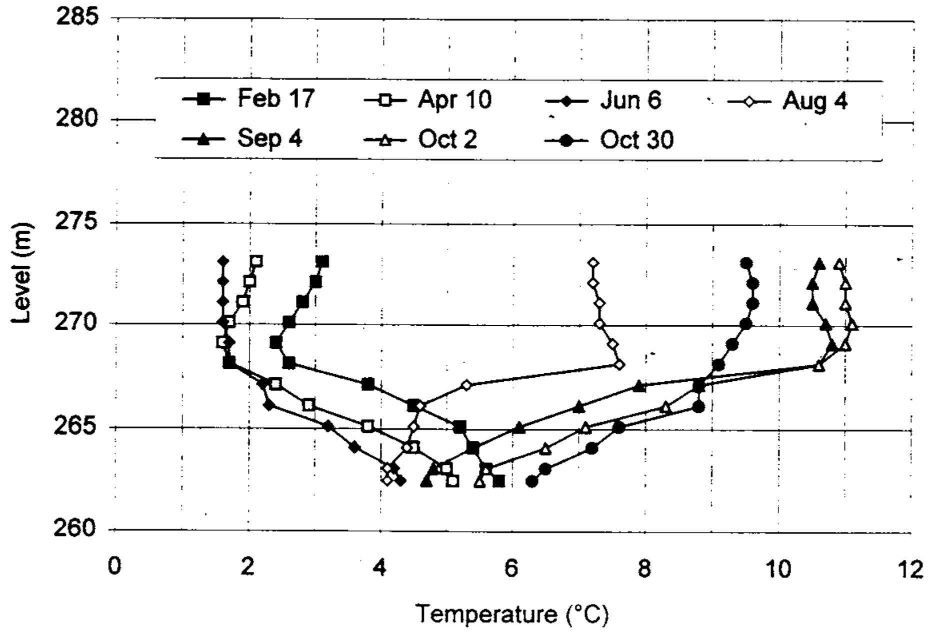

Fig. 6. Temperature profiles in standpipe 13 during 1995.

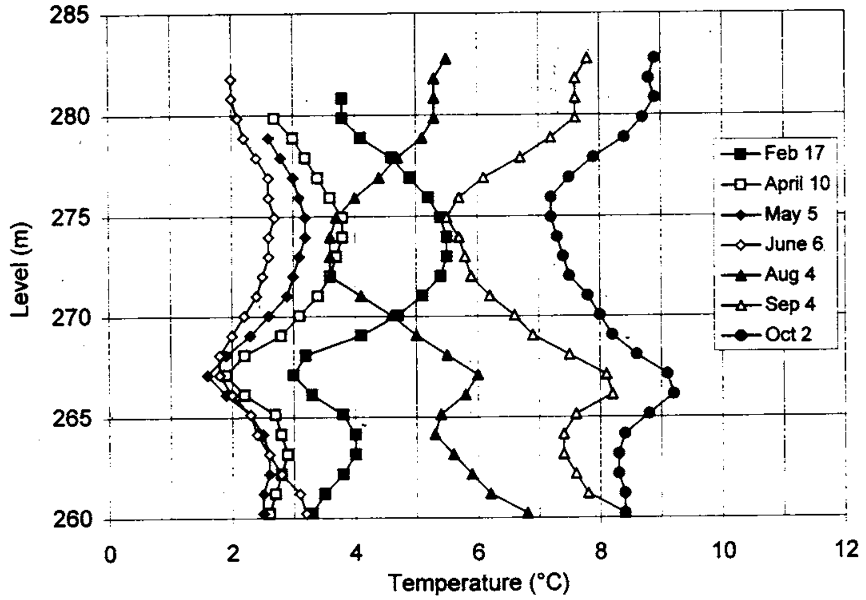

Fig. 7. Temperature profiles in standpipe B10 at some dates during 1995.

zone is within the bedrock. The temperature variations and lagtimes are equal in both zones. The evaluated seepage flow around level 267 is larger than 3 ml/sm using the lagtime method and 11 ml/sm, using the amplitude method. Evaluation with the amplitude method gives a seepage flow in the rock of about 10 ml/sm, and evaluation with the lagtime method gives a seepage flow larger than 6 ml/sm. Thus, the total seepage flow in the section around B10 is between 10 and 20 ml/sm.

Resistivity data collection

Data were collected at Lövön on eight occasions over a period of 18 months. The measuring profile was around 450 metres long. Electrodes of stainless steel were installed permanently on the dam crest. A portable data acquisition system was connected to the electrodes each time. Initially, 0.5 metre long steel stakes were used. These were later replaced by plate electrodes buried at a depth of 0.5 metres. Finer soil material was used for backfill around the plates to improve the electrode contact.

If permanently installed electrodes are used, the electrode positions are identical each time, a point that has crucial importance for the accuracy of the results. Furthermore, it is essential from a practical point of view because snow and freezing of the ground make it difficult to get the electrodes in place during the winter.

Resistivity measurements in the dam

The resistivity along the embankment dam varies significantly (see the mean resistivity pseudosection, Fig. 8a, and the mean inverted section, Fig. 8b). Inversion of the resistivity sections resulted in low model residuals, i.e. small differences between measured data and interpreted model response. The model residuals were in the range 3.5-6.3% (3.5-4.2% after the change to plate electrodes), which is good considering the relatively high resistivity contrast recorded. The relatively low model residuals also show that the 2-D assumptions made are reasonable, although 3-D effects must be expected to have some influence on the result.

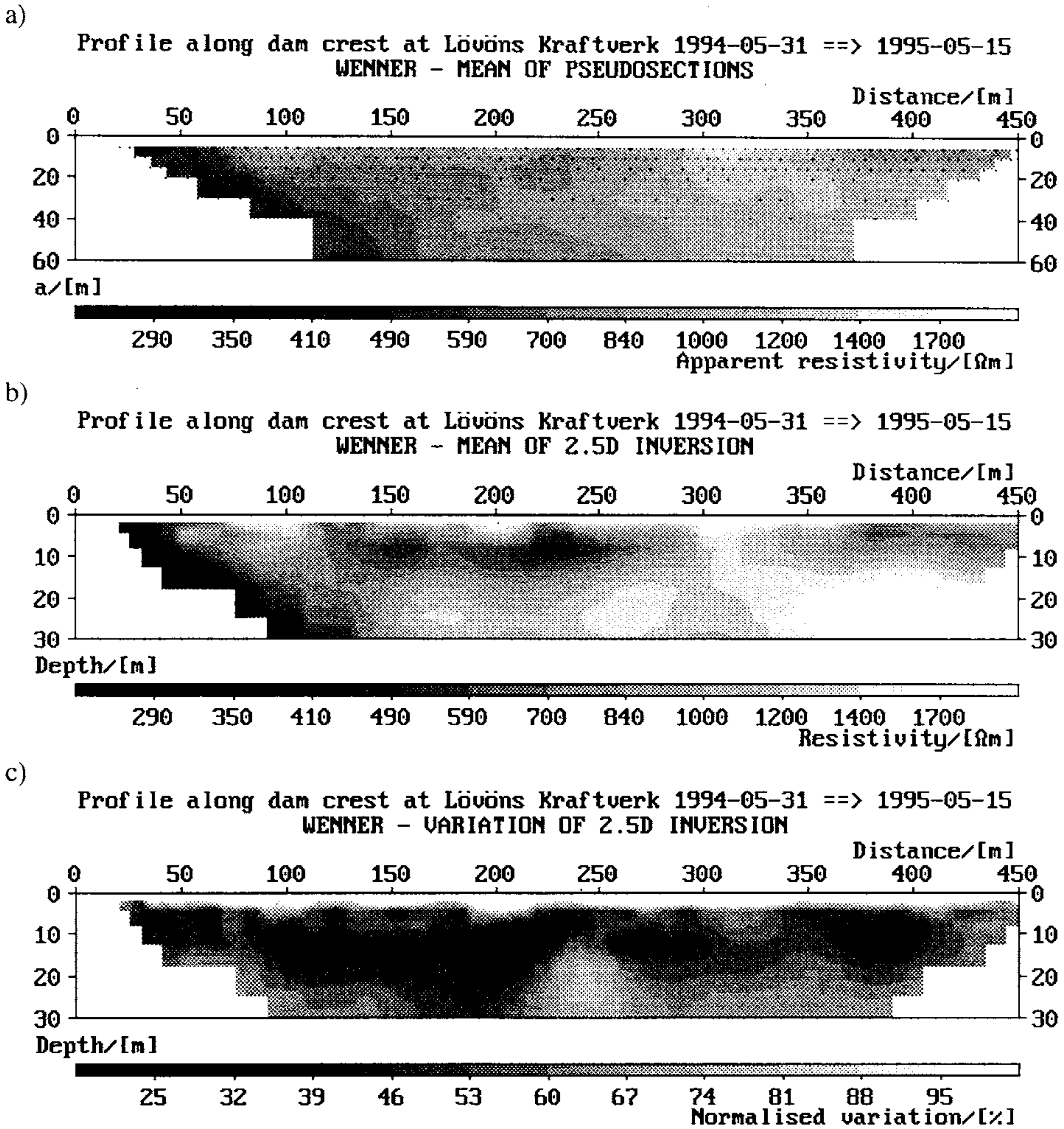

Fig. 8. Results from resistivity measurements at Lövön:
a) mean pseudosection
b) mean of inverted sections
c) normalised variation of inverted sections.

The resistivity was found to vary seasonally, with a maximum in spring and a minimum in autumn. A more precise evaluation of the time for the extreme points cannot be made due to the one to three month intervals between the measurements. The variation in interpreted resistivities inside the dam is most marked near the surface, as much as five times higher than the absolute water resistivity variation in the reservoir (Fig. 8c). This strong variation must largely be caused by variation in soil moisture content and temperature, including freezing of the ground, in the zone nearest the surface. However, the variation is also significant at larger depths, and there is a marked difference in resistivities along the investigated line.

The low resistivities in the lower left part of the resistivity section are probably caused by various metal objects such as well casing, which are plentiful close to the intake. Furthermore, there is an uninsulated cable buried inside the dam for electrical grounding purpose, which may have influence here. The normalised variation, see Equation (6), is between 20 to 80% as shown in Fig. 8c.

The resistivity variation within the dam (see Figs. 9 and 10) shows seasonal variations similar to the temperature. Unfortunately the measuring intervals are large which complicates the evaluation. The seasonal variation is

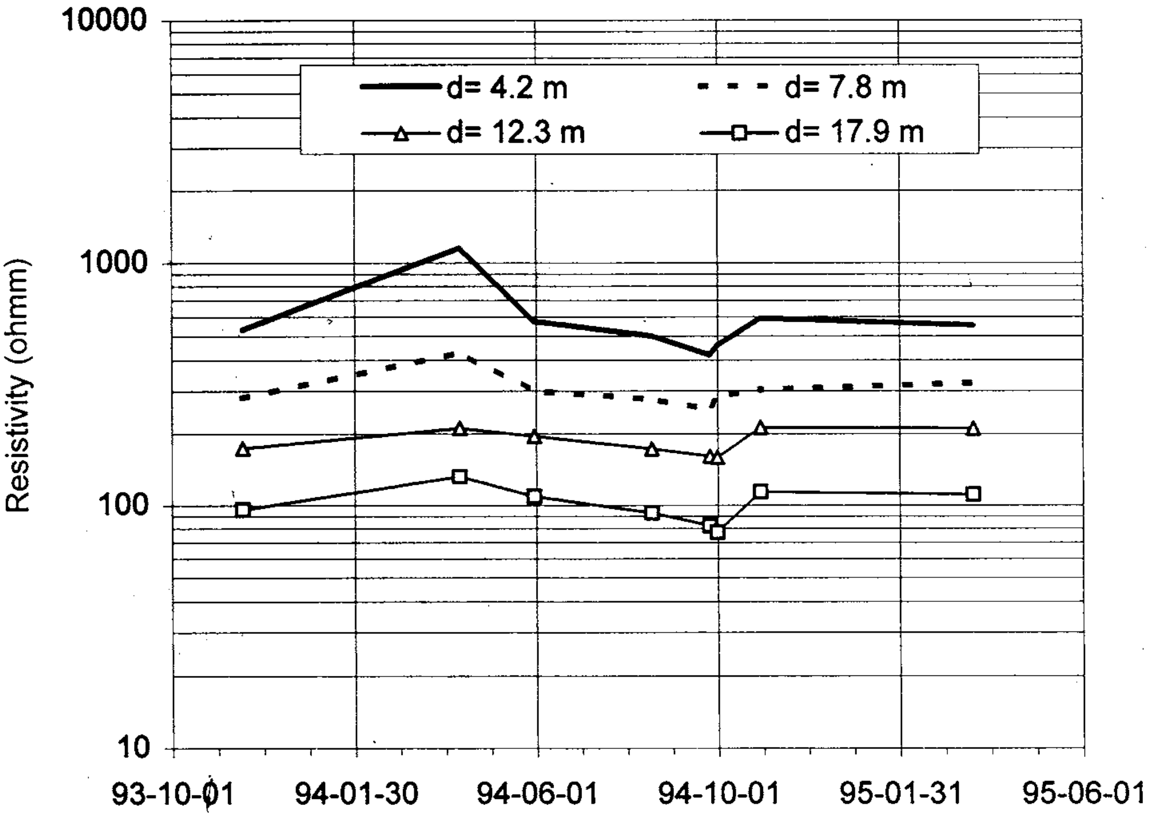

Fig. 9. Resistivity variation in section 0/045 metres.

in general similar in all evaluated cells at midpoints located at different depths d from the crest. The minima occur in the beginning of October, which gives a lagtime of two months (see Fig. 5). The lagtimes for the maxima are more difficult to evaluate, but two months also seems reasonable here.

Seepage evaluation

The seepage flow can be evaluated from the normalised resistivity variation for all cells along the dam, using the methods described above. If the TDS concentration is constant, the amplitude method from temperature measurements can be used. However, the amplitude method can also be used as an approximation when the absolute resistivity mainly depends on the temperature. Some examples of this are described below. The seepage flows can be compared with those obtained using temperature measurements.

The low resistivity-measuring frequency allows only an estimation of the lagtime and the data give the same lagtimes for different depths, about two months as described above. These values are equal to the interval between the measurements and therefore the real lagtime may be shorter than the evaluated value.

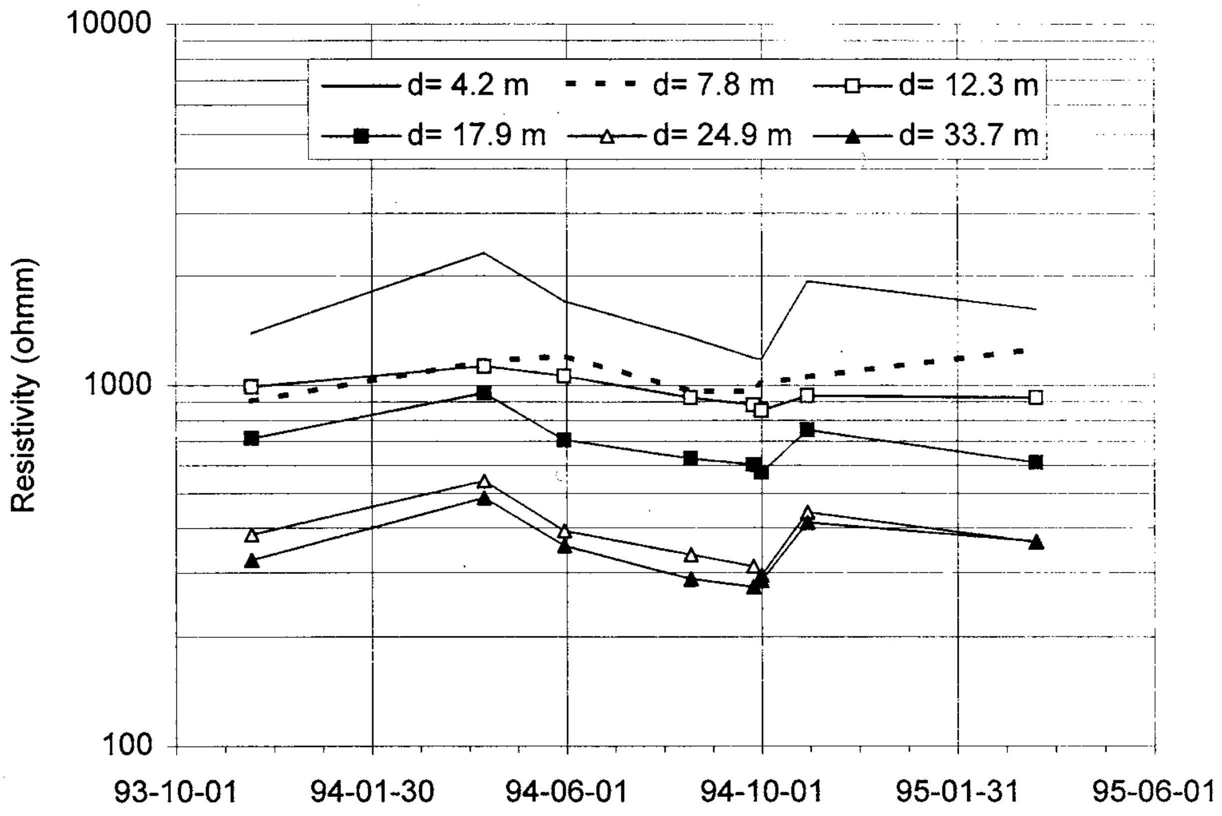

Fig. 10. Resistivity variation in section 0/100 metres.

Seepage flow at section 0/043 metres around standpipe B10

It is generally difficult to determine the depth in resistivity measurements. In this particular case, depth determination is further complicated due to the slope of the core. In the calculation below it is assumed that the depth to the midpoint of the evaluation cells is equal to the depth below the dam crest. The slope of the core will not be taken into account. The distance from the inflow section to the evaluation cell is approximately equal to the depth to the midpoint of the cell, 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 can then be estimated using Equation 4. With $C/C_w = 0.5$ the seepage flow, q, will be between 1.7 and 3.5 ml/sm^2, which for the three cells between 14.8 and 38.6 m depth gives a total seepage flow, Q, of 40 to 83 ml/sm.

A comparison between the variation with depth of the normalised resistivity and the dimensionless temperature shows the higher vertical resolution achieved by the temperature measurements (see Fig. 11). The maximum values are similar but not at the same elevations. This however, is not so sensitive for the seepage evaluation since T′ or R′ have a larger influence on Q than the distance x (see Fig. 2).

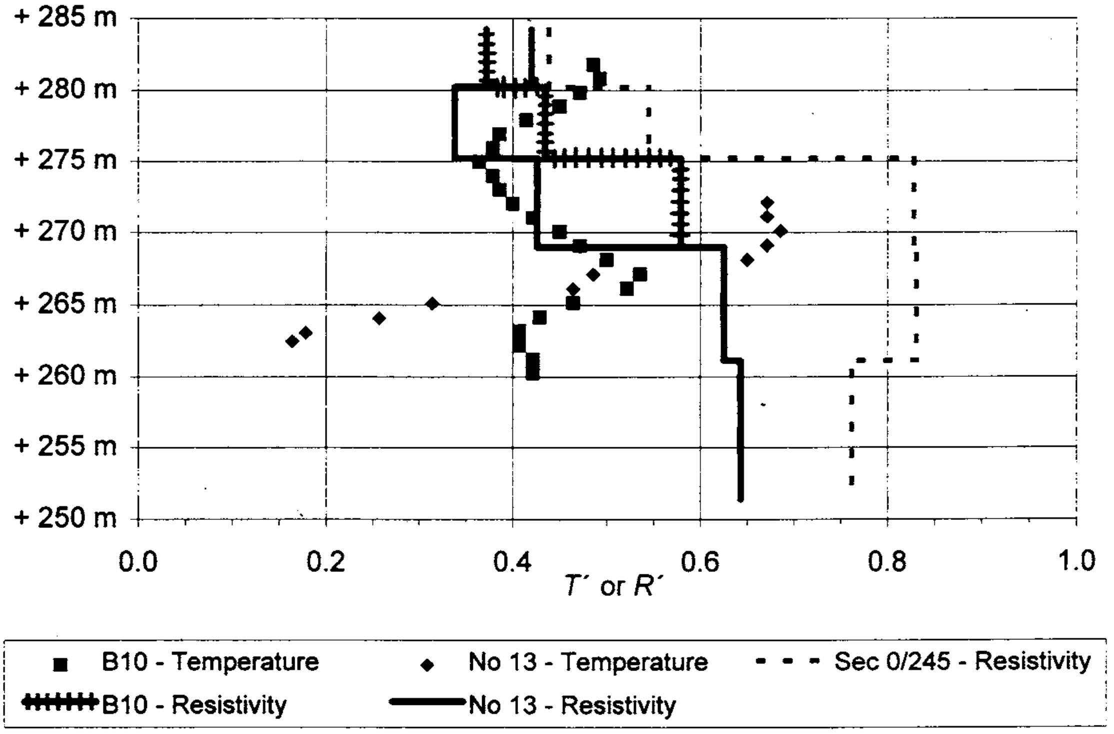

Fig. 11. T′ and R′ at different levels for standpipe B10 and 13.

The temperature measurements indicate the highest seepage around 268 m while the resistivity measurements show an increasing flow with depth. The figure gives R′ = 0.58, which with Fig. 2 gives an approximate seepage flow of about 13 ml/sm assuming x = 18 m. The temperature measurements also give a seepage flow of about 13 ml/sm with T′ = 0.56 and x = 20 m using the amplitude method, and larger than 9 ml/sm using the lagtime method.

It can be concluded that these results are in broad agreement with each other although some of the evaluation methods are based on large assumptions. However, 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.

Seepage flow at section 0/100 metres around standpipe 13

The lagtime for standpipe 13 is about two months for the maximum value and about three months for the minimum value (see Figs. 5 and 10). The distance from the boundary of the dam to the measuring section is approximated as the depth to the midpoint of the two bottom cells, which is 30 m. With the same values and assumptions as above, the seepage flow is between 14 and 20 ml/sm. Evaluation of the amplitude, using the approximate solution in Fig. 2, gives an approximate seepage flow of 22 ml/sm with R′=0.63. These values are larger than 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. A seepage flow of about 10-20 ml/sm seems a reasonable estimation.

Seepage around section 0/245 metres

The largest resistivity variation occurred between section 0/230 and 0/250 at about 25 m depth. In this area no temperature measurements are available, and therefore only resistivity measurements can be used for seepage evaluation. The lagtime in section 0/245 is between 1 and 2 months which gives a seepage flow of 20 to 40 ml/sm, assuming the height of cell as H and x = 25 m. The normalised resistivity is 0.83 which, from Fig. 2, gives a seepage flow of 40 ml/sm. Thus, the total seepage flow will be about 0.8 l/s between section 0/230 and 0/250.

DISCUSSION AND 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 concentration of total dissolved solids in the reservoir. Other factors, which affect the upper part of the dam, may also influence the measurements such as 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 this case.

A complication for resistivity measurements may be the presence of various conductive objects in the dam, in this case metal borehole casings, ground cable, etc. The influence from such objects is normally difficult to assess, but since the aim here is to analyse temporal variations in resistivities, it should be less serious than otherwise.

Data of good quality were obtained, which is crucial for analyses of temporal variation. However, the 2-D data acquisition and interpretation technique used is a simplification of the 3-D reality. The reservoir water could be expected to have a smoothing effect on the resistivity variation along the dam. Alternatively, the dam core may have a channelling effect on the current due to its higher fine-particle content compared to other parts of the dam. This would tend to emphasise the variation. Finally, a variation in the properties of the embankment dam on the downstream side may affect the results.

The seepage flow can be evaluated from the resistivity data using methods similar to those employed for seepage evaluation from temperature data. At seepage flows larger than around 10^{-6} $m^3/sm^2$the resistivity variation inside the dam is mainly caused by the seasonal variations of the resistivity in the reservoir.

Seepage flows evaluated from resistivity and temperature measurements show good agreement. Further development of evaluation methods is possible, and is recommended once a system for continuous surveillance and monitoring has been installed.

Resistivity measurement is a promising technique but there is a need for further investigations of measurement strategies, including the choice of electrode arrays, as well as data processing and interpretation techniques. Techniques for inversion and interpretation might be developed for operating directly on the differences between data from different occasions, instead of calculating differences from inverted sections. Furthermore, there is, in general, a significant ambiguity in the interpretation of resistivity data, due for example to the equivalence principle, and it was not within the scope of this project to assess this issue in detail. However, it is important to assess the resolution power of the technique under different conditions. In many cases, 3-D measuring and data processing strategies may be needed.

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 as the result is incomplete without the time variation and may even be misleading. The resistivity variation depends mainly on the seepage through the dam, which therefore can be quantified over the entire dam. Zones with anomalous leakage can then be localised, with a detection level of about 10^{-6} m^3/sm^2. The monitoring is non-destructive apart from the electrode installation and provides measurements of time-dependent processes such as internal erosion. A few boreholes with temperature measurements in selected points can provide good reference data for interpretation. Thus, combined resistivity and temperature measurements could be used for seepage monitoring.

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