Detection of Internal Erosion in Embankment Dams – Possible Methods in Theory and Practice.

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SUMMARY

Flow dependent methods are more sensitive than material dependent parameters to detect internal erosion. The most appropriate parameters for monitoring of internal erosion are thus seepage, temperature, resistivity and SP. The methods that are used to measure these parameters give different resolution and accuracy and require different kind of installations. Temperature, resistivity and SP are methods that are possible to install in existing dams where drillings should be avoided, and where installations for seepage monitoring are practically impossible to construct. The methods are also appropriate for long term monitoring, which probably is needed to achieve the required accuracy A single investigation with any of these methods will normally not be able to detect internal erosion in its early stage.

1 INTRODUCTION

Monitoring of dams is made in order to obtain key information about the dam safety status. This is normally given by measuring seepage/leakage, pressure, and movements (of the crest, slope or internal). Seepage measurements give a good coverage of the entire dam, while pressure and movement measurements give detailed information in single points. Small local changes, such as internal erosion, may therefore be too small to be detected by the seepage measurements and may occur where no pressure measurements are carried out. This may be the main reason why most internal erosion incidents have been detected by visual inspections and not by any monitoring system. Another reason may be that visual inspections are sensitive and reliable.

Internal erosion is a major cause of failures in embankment dams. The seepage flow increases slowly; closely coupled to material transport that can take place over a long time. Such a problem should be possible to detect by a monitoring system that has both a high accuracy and a high resolution. Of particular importance are methods that 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.

Development of geophysical methods during the last decade has increased the use of such methods for dam investigations. However, those methods have generally been developed for other applications and have to be further improved before they can easily be adopted on dams. Furthermore, the demand for monitoring is not the same as for investigations. Long term monitoring must have a high reliability and give stable result, so that they can be compared with each other. If there are any seasonal variations they must be considered, which not is the case at single investigations.

Several Swedish projects were carried out in the late 80ties in Sweden in order to find appropriate methods to detect seepage changes and internal erosion. A general study of possible non-destructive methods identified temperature, resistivity and Streaming Potential (SP) as the most appropriate methods to study internal erosion and seepage (Johansson et al, 1995). Those methods have since 1993 been applied in several dams for long term monitoring. Extensive research within this field have also been carried out in several other countries especially Germany, US, Canada, and South Korea.

Experience from field measurements has further focused on the need of a better physical understanding of the basic process and how all the fundamental parameters interact. The monitoring aspects of the fundamental internal erosion processes in a dam have been found more complicated than for many other applications for those methods. A fundamental research project was made by the Dam Safety Interest Group during 1999-2000 in order to further evaluate the sensitivity of the parameters that was identified in the Swedish study mentioned above.

2 PARAMETERS FOR DETECTING INTERNAL EROSION

2.1 Conventional methods

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. The possibility to detect internal erosion with measurements of movements will thus be small.

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. Seepage weirs, equipped with devices for continuous monitoring, are appropriate to detect internal erosion if they are accurate enough.

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.

Visual inspection is the most common method of dam surveillance. Inspections of the upstream slope, the crest and the downstream slope are normally done on weekly basis in Sweden. Special checklists are developed in order to guide the inspector. Important observations on the downstream slope and dam toe may be:

- Wet areas
- Increased drainage flows
- Surface erosion
- Deformations, cracks, sink-holes

The general problem is to document the observations in a systematic way, despite the use of checklists. A large problem is that all observations are more or less relative, i.e. a comparison between actual status with the previous status observed. The main reasons are that inspectors may have different ability, and the weather conditions may influence the observations. Photos are sometimes helpful to verify slow changes. Inspectors with long experience will however be able to observe small changes, but will in general not be able to quantify the defect. Visual inspections will probably also in the future be the most common surveillance method, despite some weaknesses in the methodology.

2.2 Primary and secondary parameters

Parameters indicating internal erosion are based on the fact that 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 therefore initially studied. A study made by Johansson et al (1995) concluded that **material dependent** parameters (such as density and dielectricity) are less sensitive than **flow dependent** parameters (such as hydraulic conductivity, temperature/tracers). Sensitivity alone however is insufficient to evaluate the potential of a method. Accuracy and resolution must also be considered when evaluating appropriate methods.

At internal erosion monitoring only seepage, porosity, fine contents (in the soil), and may be pressure can be strictly considered as “primary parameters”, as far as they are measured inside the internal erosion area. If they are measured outside the area they will be secondary parameters. They may often also have some influence of changes from other parameters (e.g. seepage depends on viscosity that is temperature dependent or pressure that depends on density that also is temperature dependent). Three main secondary parameters were identified:

Temperature

For some dams temperature variation can be directly related to seepage. Evaluation methods exist for some geometrical sections, but general simulations can also be performed. These methods can be used to give input to the other parameters as well as study the sensitivity and limitations of the method itself. Thermal properties are also influenced by porosity changes, but at minor extent and can therefore normally be ignored.

Resistivity

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. However, resistivity also depends on pore water properties, such as the concentration of total dissolved solids (TDS) and temperature. The latter is normally neglected in resistivity measurements, but it cannot be ignored in the case of resistivity measurements in embankment dams. The resistivity variation in the dam is thus complex and depends on both properties in the dam and in the water that seeps through the dam.

Streaming Potential

The streaming potential generated SP-anomaly observed on an embankment dam depends on the following parameters: the cross-coupling coefficient, the hydraulic boundary conditions and the electric resistivity. The first two parameters define the primary driving convection current sources The strength and location of these sources together with the resistivity distribution define the self-potentials in the ground. The parameter unique to SP is the cross-coupling coefficient, which has been found to depend on pore geometry, temperature and chemical composition of the pore water and mineral grains. Of these the pore geometry is directly affected by internal erosion. The temperature distribution within the dam will change as a secondary effect due to the increased water flow. To summarize, internal erosion will cause an increase in the porosity through a removal of the fines of the core. This will have a primary effect on the cross-coupling coefficient, the resistivity, and the pressure gradient. The increased hydraulic conductivity (and may also an increased pressure gradient) leads to an increased water flow, which in its turn will cause temperature changes. Both the resistivity and the cross-coupling coefficient are temperature dependent. Consequently, an increased self-potential anomaly could be equally well explained by an increase in the cross-coupling coefficient, an increase in the resistivity, or an increase in the fluid flow.

The interaction between those parameters is complicated as seen in Figure 1. The flow depended influence is shown by the arrows from the "seepage" box and the material dependent influence is shown by the arrows from soil gradation and water content/porosity. Solid thick lines denote the strongest influence. However, the influence may sometimes amplify, and sometimes reduce the influence. Seasonal variation of the parameters will also complicate the real monitoring situation. All these parameters and there influence on each other must be considered at dam monitoring using either of these methods. These methods will be further discussed in the following.

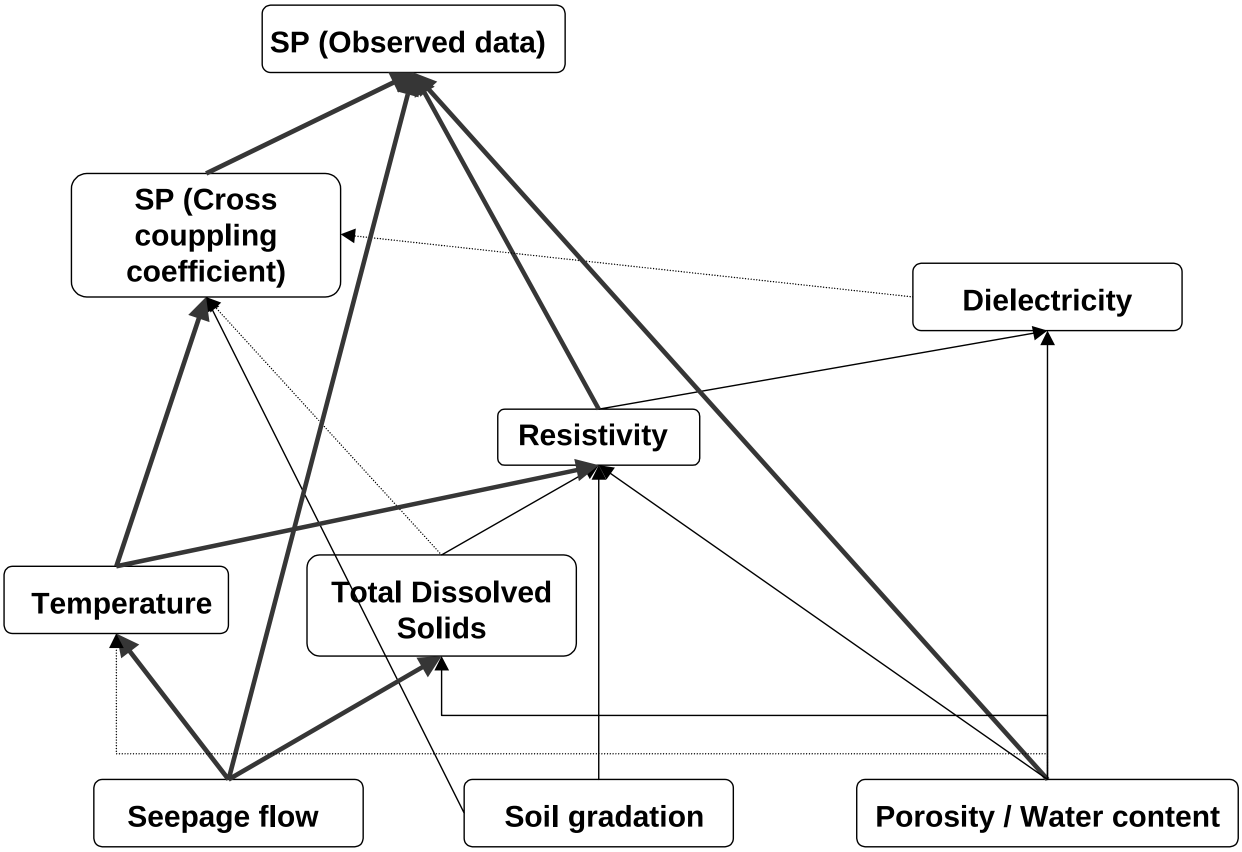

Figure 1 **Internal erosion's influence on the studied parameters. (Solid thick line= major influence, thin black line= uncertain influence, and dotted line= no significant influence)**

Examples of material dependant methods are acoustic and electromagnetic methods. Acoustic methods, which have been applied on dams, are the seismic methods, primarily refraction, reflection, cross hole, and shear wave (cf. Hales et al, 2003 and Gaffran et al 2004). These methods may detect loose zones, which may be caused by internal erosion. Among electromagnetic methods Ground Penetrating Radar is the most common. It measures the differences in electrical conductivity or dielectricity of the soil. These parameters depend on grain size, degree of saturation and porosity. Measurements are made by moving antennas along the dam. The method has been used on several dams, with mixed experiences. Neither acoustic nor electromagnetic methods seem to be appropriate or accurate enough to be used for long term monitoring for detection of internal erosion.

2.3 Monitoring in new dams versus old dams

The best possibility to detect internal erosion is to build in adequate monitoring system already when the dam is constructed. This has sometimes been done, but several dams need to be re-instrumented. All Swedish dam owners are now upgrading the instrumentation at several dams, in connection with other measures to further improve the dam safety.

Installation of monitoring devices in old dams requires normally some kind of drilling, which must be done carefully. For example, low pressure drilling methods must be used to avoid damage to the core by hydraulic fracturing. Drillings allow also continuous soil sampling and infiltration tests that 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.

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.

Non-destructive testing as resistivity and SP can be installed on the crest of the dam, preferably in connection with an increasing of the core crest level. Measurements are performed by electrodes that are placed along or perpendicular to the dam. Permanent installations allow continuous measurement, as described below. 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.

2.4 Investigation – monitoring

Some methods are more appropriate for investigation than for long term monitoring. Such methods are Ground Penetrating Radar, some of the seismic methods, and borehole methods. These methods are useful as a means of examining dams in order to obtain additional information. Repeated measurements are possible, even though a perfect repetition may be difficult to obtain. The streaming-potential method is also useful for single examinations of dam performance. However it should be combined with resistivity measurements.

The greatest problem at single dam investigations using geophysical methods is the number of unknowns. Material properties will change along the dam, as well as seasonal variations. An extremely good knowledge is therefore needed to make a good interpretation based on a single investigation. Small defects caused by internal erosion may be detected, but they will be uncertain and in some case wrong. Repeated measurements are preferred since the results can be compared. In order to detect internal erosion defects, some kind of regular monitoring or repeated measurements is needed.

3 TEMPERATURE MEASUREMENTS

3.1 Background

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, see Figure 2.

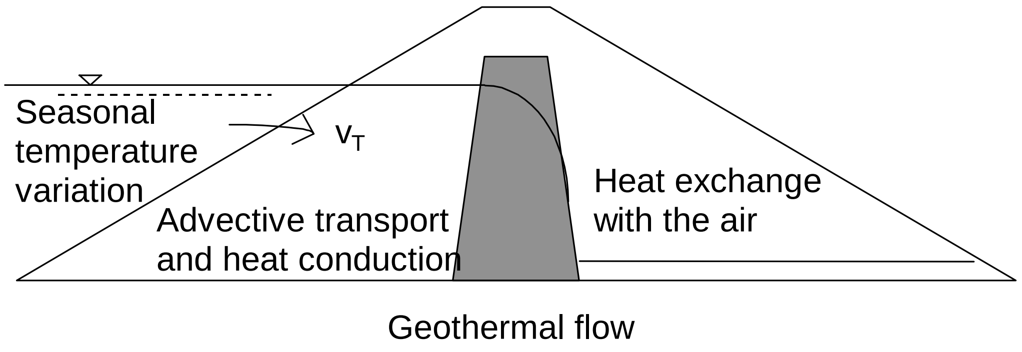

Figure 2 **Basic thermal processes in an embankment dam.**

The seepage flow is normally small in embankment dams (the hydraulic conductivity is often less than 10^{-6}m/s) and the seasonal temperature variation in the upper part of 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 10m and is therefore negligible beyond such depths. This process must however be considered in small dams with heights less than about 20m. In larger dams with heights above 100m the geothermal flow must be considered, as well as the thermal stratification in the reservoir.

Temperature acts as a tracer with the seasonal temperature variation as source. Low seepage flows will not affect the thermal condition in the dam. The temperature will remain constant. At increasing seepage flows the temperature in the dam will begin to vary seasonally. The amplitude of the variation is dependent on seepage flow, the seasonal variation at the inflow boundary, and the distance from the boundary to the measuring point.

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 of water 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 generally to be made. The general problem can however be studied using coupled transport models (based on FEM or FD, cf. Johansson 1991 or Aufleger 2004). Both heat conduction from the surface, and geothermal heat can be ignored at many applications, which simplifies the evaluation.

The thermal properties of different have been studied by many researcher such as Johansen (1975), Abrahamson (1984), Farouki (1986), and Sundberg (1988). The knowledge of the thermal properties of the material (thermal conductivity and thermal heat capacity) is thus sufficient for use on dams.

In order to increase the evaluation possibility, especially at investigation of smaller dams a heat source could be added in combination with temperature monitoring (i.e. the heat pulse method, Dornstädter 1997). The seepage can then be calculated based on the temperature rise when heating up and the thermal response when the heating is finished. This approach is protected by a patent. This method will be valuable at lower dams or dykes where the temperature variation on the surface of the dam will disturb the temperature variation in the seepage area, but seems less appropriate for long term monitoring of high dams.

3.2 Monitoring methods

3.2.1 Single points

Temperature is a basic parameter for many types of sensors, and is therefore measured in order to calibrate the readings from the sensor. The sensors are often connected to an Automated Data Acquisition System (ADAS). If temperature data also is stored it will provide an excellent possibility for another use – seepage evaluation from temperature measurements. This is shown in Figure 3, where a seasonal variation is found for each sensor.

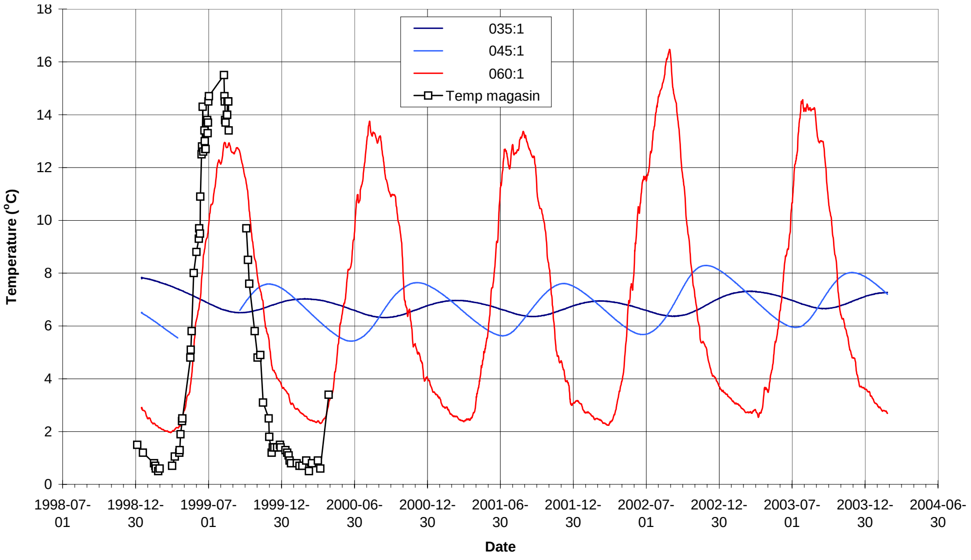

Figure 3 **Temperature measurements at Lövön made in the piezometers 35:1, 45:1 and 60:1, located in the bedrock at chainage 35, 45 and 60.**

The absolute accuracy for those systems varies from 0.5ºC to better than 0.01ºC. Relative accuracy is normally often higher, although some sensors have exhibited limited long-term stability and reliability. A great advantage for the purpose of the seepage flow evaluation is that data is sampled and stored at an interval of hours or days.

3.2.2 Vertical profiles in standpipes/wells

Vertical temperature profiles in standpipes at different dates may give useful information about the seepage flow through dams. Monthly measurements have been found to be appropriate. Manual measurements using a thermal probe are easy to carry out and are normally performed by the operational staff on the dam. Standpipes with a diameter up to 70 mm diameter can normally be used for temperature profiling without convection currents arising due to buoyancy effects within the standpipe. Disturbance of temperature profile may occur in larger diameter wells, if the thermal condition cause density differences.

Manual measurements should be taken from the water surface and to the bottom of the well in order to minimize any disturbance when the probe penetrates the water column. The probe should also be lowered slowly to minimize any disturbance. This is more important when the diameter of the probe is close to the inside diameter of the standpipe. Measurements are recommended to be taken at least at each meters depth. A high vertical resolution is useful for the first measurements, but can be reduced when the result is analyzed.

A possible procedure to measure and record temperature is to use thermistor strings connected to a read-out box. Such strings can be fixed in order to eliminate any risk for mixing within the water column. However, it is important to have enough vertical resolution, which is more important than very frequent sampling. One way to increase the vertical resolution is to move the strings after the measurements, and take a new set of readings between the first measuring points.

3.2.3 Distributed temperature sensors with fiber optics

The development of fibre-optic systems has been followed carefully, primarily for distributed temperature measurements (Dornstädter 1997, Johansson and Farhadiroushan, 1999) that seem to be an appropriate solution for new dams, where the fibre could be built in. Such installations have been made in some dams in Germany, Sweden, Turkey China and Canada. In existing dams, fibres can be installed in standpipes, along the downstream toe or in the drainage system. The accuracy may be down to 0.01ºC with advanced systems. However, less expensive systems with accuracy of 0.1ºC are also available.

Fibres can also be used in existing dams, either buried in the downstream toe or in existing standpipes. Different systems are available and the technique will be further developed and adopted for dam monitoring.

3.3 Evaluation methods

An qualitative evaluation of the seepage can be performed by studying the seasonal variation, where large temperature variation indicated higher seepage flow, unless the heat conduction from the surface can be ignored. From the three examples shown in Figure 4 (that is a detail of Figure 3) it is easy to find that the highest seepage is found at sensor 60:1, and the lowest in sensor 35:1. In this case a concentrated seepage can be assumed and the seepage can then be assumed using a simplified evaluation method (Johansson, 1997). A good agreement was found for the seepage flow per metre dam from $2.5 \cdot 10^{-6}$ $m^3/(s,m)$ to $30 \cdot 10^{-6}$ $m^3/(s,m)$.

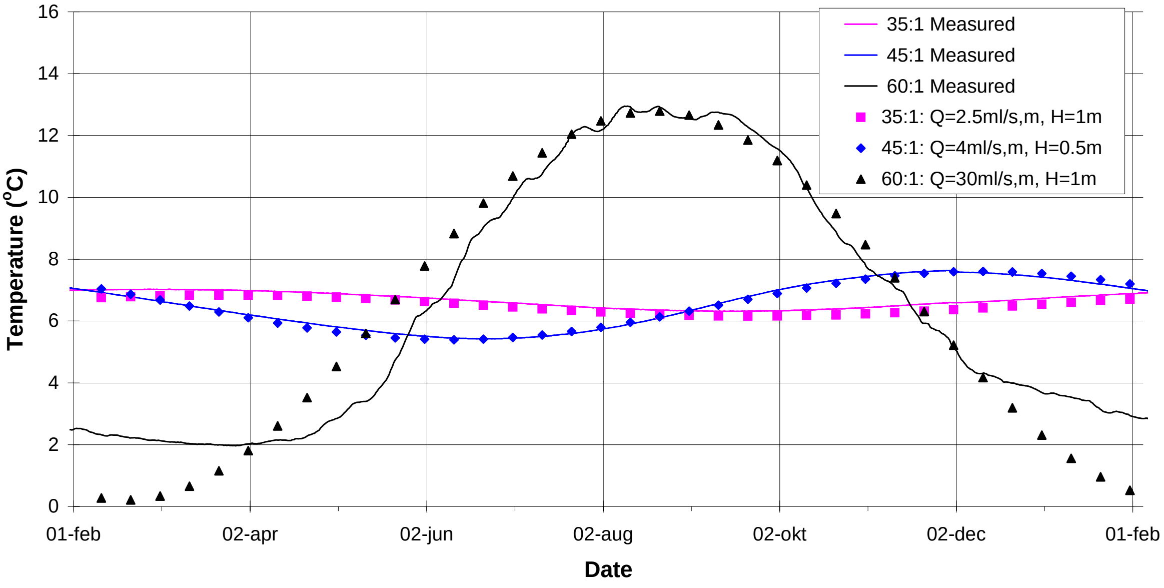

Figure 4 **Measured and calculated temperature for three seepage flow rates at Lövön dam. (The flow unit is milliter/s, and metre dam, i.e. $10^{-6}m^3/(s,m)$)**

3.4 Experience from Monitoring in old dams

Temperature measurements have been used in many dams and many examples can be found in the literature. Some interesting result was recently achieved from the Hylte dam, in the south of Sweden, which not has been shown before.

Optical fiber cables were installed by the dam owner Sydkraft AB at the dam toe of the Hylte dam and dyke at in late 2002. The purpose of this installation is to identify areas with higher seepage or increasing seepage. The site consists of a 200m dam with a maximum height of about 10m and a 1.8km dike with maximum height of 8m. The cable is placed at a depth of about 1m, all along the dam toe. The coordinates of the cable is measured for each 10m.

A first measurement including check of the installation was done in April 8-9, 2003, which has been followed by three short time measurements and one long term measurement. The latest measurements were made in August 2004, when also a short test was made by infiltrating water from the reservoir at the dam toe as shown in Figure 5. A first initial test was made during three hours, without any result. The second test was performed during 18 hours, when water was infiltrated at Cable Marking CM 1894 and CM1907.

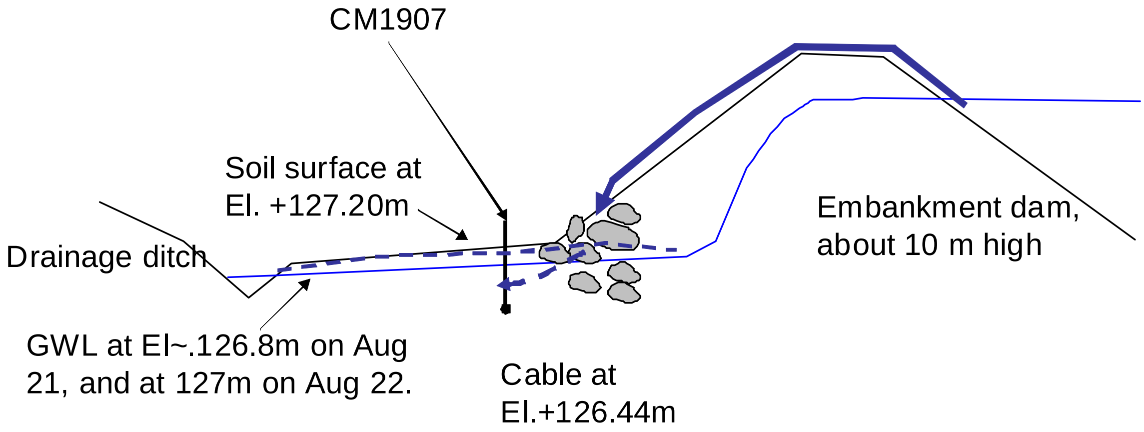

Figure 5 **Sketch of the infiltration test at Hylte Dam at Cable Marking 1907. A similar test was also made at CM 1894, where the water was infiltrated further downstream.**

A small but significant temperature change was observed at cable marking 1906 and 1907 after about 7 hours, which finally increased to 0.2ºC. This change is the largest along the entire cable where it is located in the dam. The temperature change is about four times the accuracy. By calculating the temperature trend, the leakage will be more obvious. A smaller temperature change can also be observed at CM1894 where also water was infiltrated. However, this temperature response is more uncertain and closer to the measuring accuracy, and can only be detected by comparing the result along the cable. The leakage flows at the two infiltration points were similar, and the reason why just one was clearly detected was probably that the water disappeared and was spread out in the rock fill over a larger area.

Further measurements and test will be made this year, in order to install a fixed system for the next year including monitoring and automated evaluation and alarm.

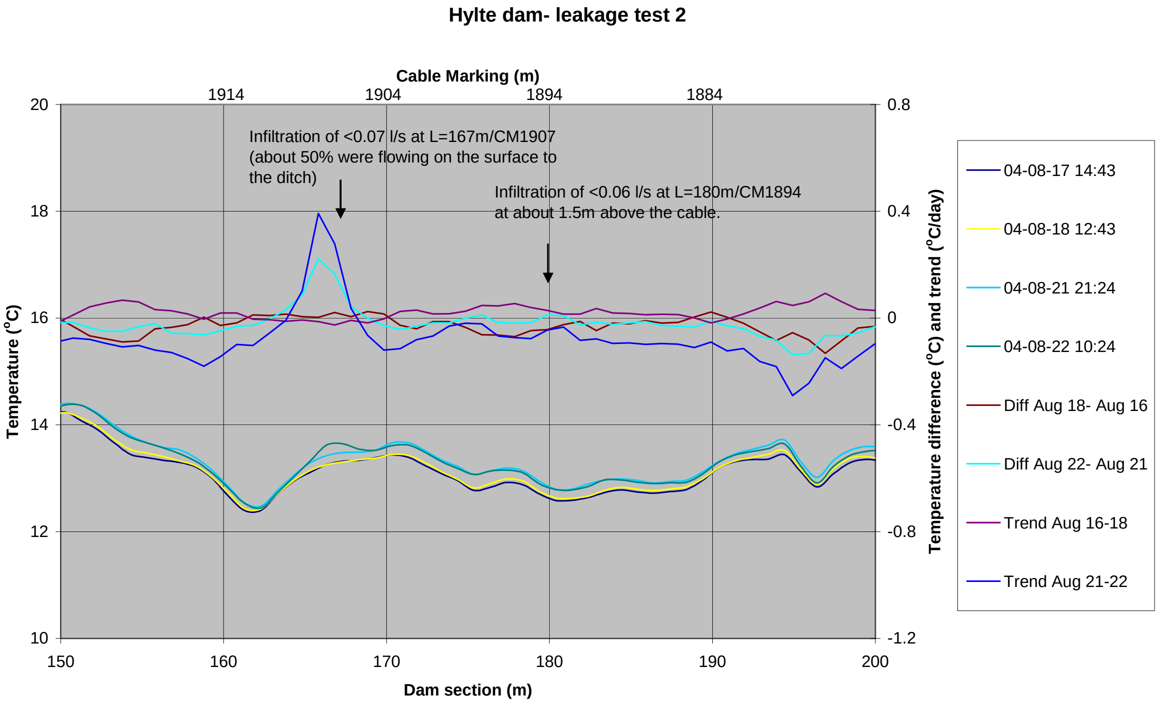

Figure 6 **Result from the temperature measurements at Hylte Dam at the leakage test 2.**

3.5 Experineces from temperature monitoring at Røsvatn test site

3.5.1 Installation and measurements

Temperature measurements were carried out along the dam toe using 23 temperature sensors, in order to estimate the temperature change within the dam, and to detect seepage outflow at the dam toe. Sensors with high accuracy (Greisinger PT100) were installed at the toe at 5cm depth, starting at section 1.1m and ending at section 34.3m with separation of about 1.5m. Some sensors were exposed to sunshine while other was placed in the shadow between large boulders, depending on the installation possibilities.

Temperatures measured at the dam toe are neither able to determine exactly where a leakage will be located in the core, nor able to define the extent of the leakage because: a single leak through the dam may give several outflows at the toe, a large concentrated leakage flow may be wider at the toe, while a smaller leakage will have a more constant width, and; the distance between the sensors (1.5m) will be the smallest resolution. The several fillings in this case will, however, give some indications of the elevation of the leakage as well of the flow. Evaluation can also be done based on: how quick the temperature response will be at a changed filling level, length of the transient temperature pulse, and; temperature difference between the reservoir water and the outflow water.

Some results are presented in Figure 7. At section 23.7m diurnal variations occur during the entire test period. This indicates that the heat conduction dominates, i.e. a low seepage. The effect of a significant seepage is shown at section 28.4m. The diurnal variation is seen both at Filling #1 and #2, until the temperature rise is interrupted, due to the outflow of seepage water. The temperature is then slowly approaching the temperature in the reservoir. The same is seen in section 20.7m at the Filling#3. Significant seepage outflow areas were found in four areas from the temperatures showed in Figure 7 and Figure 8.

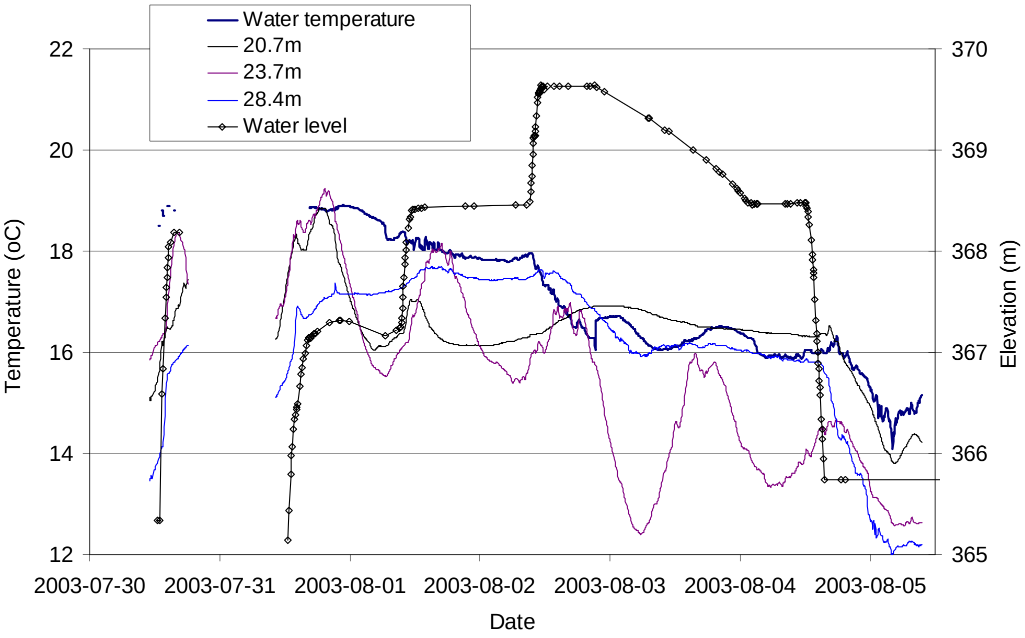

Figure 7 **Selected temperature measurements between section 20m and 30m (left axis), and reservoir water level (right axis).**

3.5.2 Result and evaluaton

The data were analysed further to estimate the transient temperature change due to the advective energy transport by the seepage flow. Some seepage flow estimations were also made at Filling #1-#3, indicating flows exceeding 0.6l/(s,m^2) at section 27, about 0.2l/(s,m^2) at section 20.7m, about 0.4l/(s,m^2) at section 5.7m, and about 0.3l/s,m^2 at section 10.2/11.6m. The total area of the defect cannot be determined from the temperature data, so the total flow cannot be estimated.

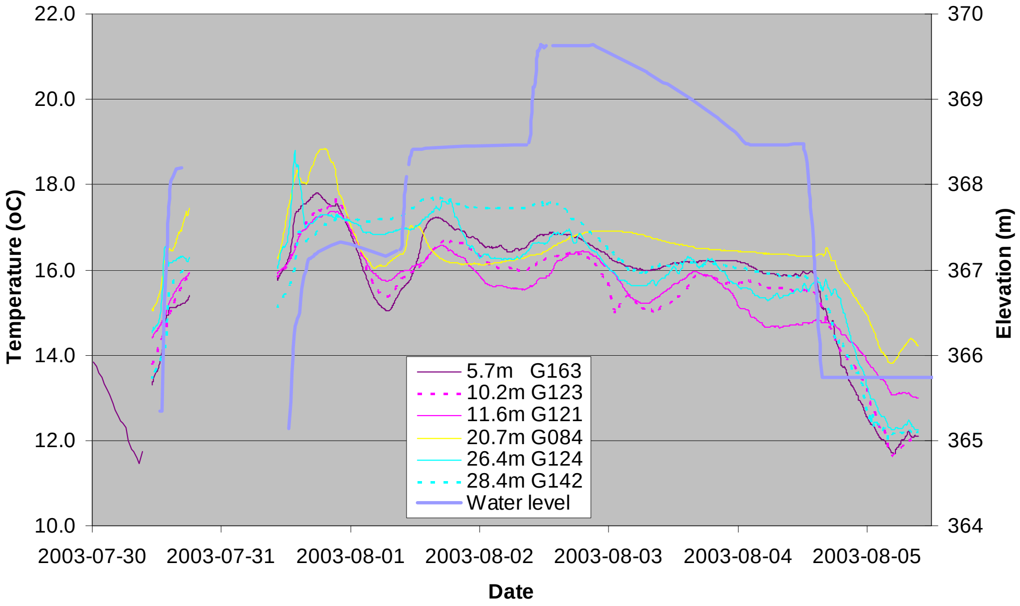

Figure 8 **Selected temperature measurements between section 20m and 30m (left axis), and reservoir water level (right axis).**

Four significant leakage paths were detected as summarised in Table 1. The locations at the dam toe may not correspond to the location in the core, but will probably be close. Information about the level and area are interpreted data based on the information from the different fillings. Only the inflow level can be used to estimate the level of the defect. The thermal response is clear at large flows, but at small flow the response may be delayed. It may then be seen after further fillings, which could be misleading when estimating the level of the defect.

Table 1 **Summarised result from temperature measurements.**

Dam section	Detected at	Estimated inflow level	Final width at the dam toe
5.7m	Filling #1 and #2	365.5m	1.5m
10.2 – 11.6m	Filling #3 or #2	368	2- 3m
20.7m	May be already at Filling#1, but definitively at filling #3	366	1.5m
26.4 – 28.4m	Filling #1 and #2	365.5m	2 - 3m

3.5.3 Comparison with real defects

These detected leakages areas agrees well with the real ones (Figure 9). Another leakage area was also detected close to the drainage pipes. The elevation in the figure is set to the inflow level ±0.5m. Temperature measurements at the dam toe can normally not exactly determine the level of a defect, just the location along the dam. In this case, however, information from the different fillings could be used to estimate also the level.

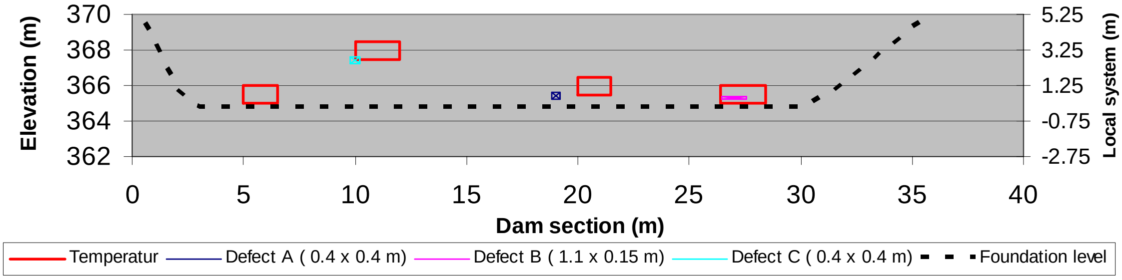

Figure 9 **Defect location and defect areas evaluated from temperature measurements. Note that the level is estimated only from the water level in the reservoir.**

From the knowledge given after information about the defects were revealed, the flow can be calculated in each defect using the known area (0.16 m^2) of the defects and flux estimation made from the temperature data analysis above. The flow at section 27 (defect B) will thus be about 0.6*0.16=0.1l/s, and about 0.2*0.16=0.3l/s at section 20.7m (defect A). Total flow measured in the weir is about 0.35l/s, at Filling #3. Those values agree well.

4 RESISTIVITY

4.1 Background

The resistivity of natural soils and rocks vary within very wide ranges and this difference in resistivity is the foundation of resistivity imaging surveying. The most common soil and rock forming minerals are insulators in the dry state, and thus the water content largely determines the resistivity. Hence the amount of water, i.e. the porosity and degree of saturation, the ion contents of the water and the connectivity of the pore spaces are important parameters. The presence of clay minerals normally affects the resistivity strongly, since these minerals bind water molecules and ions. Clay particles coating the surfaces of the larger mineral particles may have a dominating effect on the bulk resistivity of a predominantly coarse grained soil, creating so called surface conduction. In addition, ore mineralization can produce very low resistivity (high conductivity) through metal conduction.

4.2 Application aspects at embankment dam monitoring

The materials present at embankment dams can be expected to vary significantly in resistivity. The bedrock should generally be high resistive where fresh, 1000 Ωm or more, whereas in fractured, weathered or mineralised zones the resistivity can be dramatically lower. The core of the dam should be relatively low in resistivity due to the fine material content, possibly below 100 Ωm. The filters of the dam would be higher in resistivity than the core if unsaturated, and the saturated resistivity depends on the resistivity of the water. The total volume of filter material is relatively small, and the resistivity of the filter is somewhere in between the resistivity of the core and the fill. This reduces influence from the filter zones significantly, and it is generally not expected to have much influence on the resistivity measured in embankment dams. The downstream rock-fill support should have a resistivity of thousands of Ωm, whereas on the upstream side saturation with reservoir water will reduce the resistivity dramatically. How much it will be reduced depends on the porosity of the rock-fill and the resistivity of the water. The resistivity of the reservoir water is rather high in Scandinavian fresh water, typically a few hundreds of Ωm, resulting in formation resistivities often expected to be in the thousands.

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.

The seasonal variation of the absolute resistivity in the reservoir water is separated into two parts when the seepage water passes through the dam (Figure 10). 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.

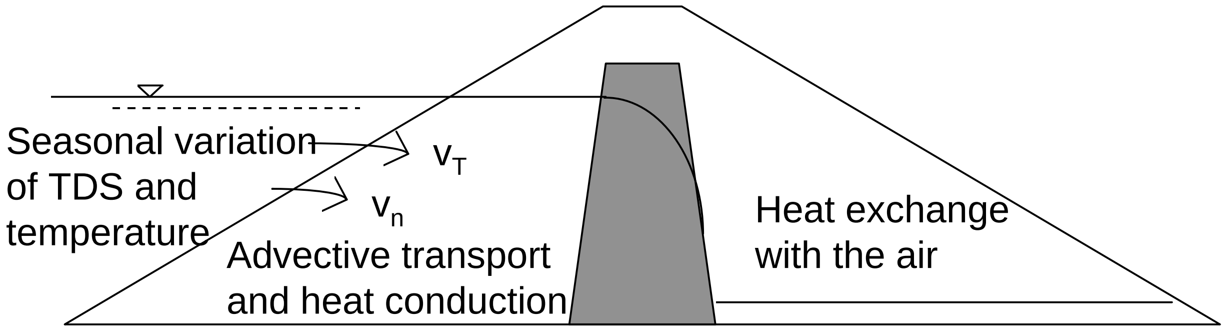

Figure 10 **Important transport processes that affect the resistivity variation in an embankment dam.**

At internal erosion fines are transported from the core that will reduce increase the porosity (decrease the resistivity) and reduce the fine content (increase the resistivity). In theory, internal erosion may thus increase or decrease or not change the resistivity. Laboratory test performed by Bergström (1998) indicate an increasing resistivity in typical Swedish moraines when the fine content decreases.

Variation in temperature can be a significant source of resistivity variation in embankment dams (Figure 11), due to variation in mobility of ions in the pore water. A water temperature of 0ºC in the winter and over 20ºC in the summer means a change in resistivity of around 100% due to temperature variation alone. If the ground freezes the resistivity generally goes up an order of magnitude or more (Palacky 1987). A temperature variation of 7ºC to 12ºC is equal to around 20% change in resistivity.

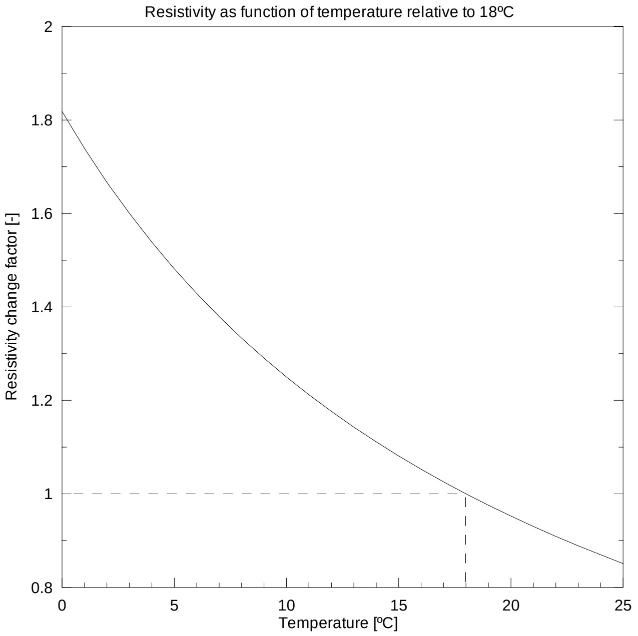

Figure 11: Resistivity as function of temperature relative to 18ºC.

The temperature variation in a dam (5-15ºC) can cause a larger resistivity change than the resistivity difference between fine sand, coarse sand and gravel that varies between 2000 and 4000Ωm (Figure 12). A measured resistivity of 3000 Ωm can be either gravel at 5ºC, coarse sand at 10ºC or fine sand at 15ºC. A significant difference between these material and moraine will however be possible to detect, unless an uncertainty of the actual temperature.

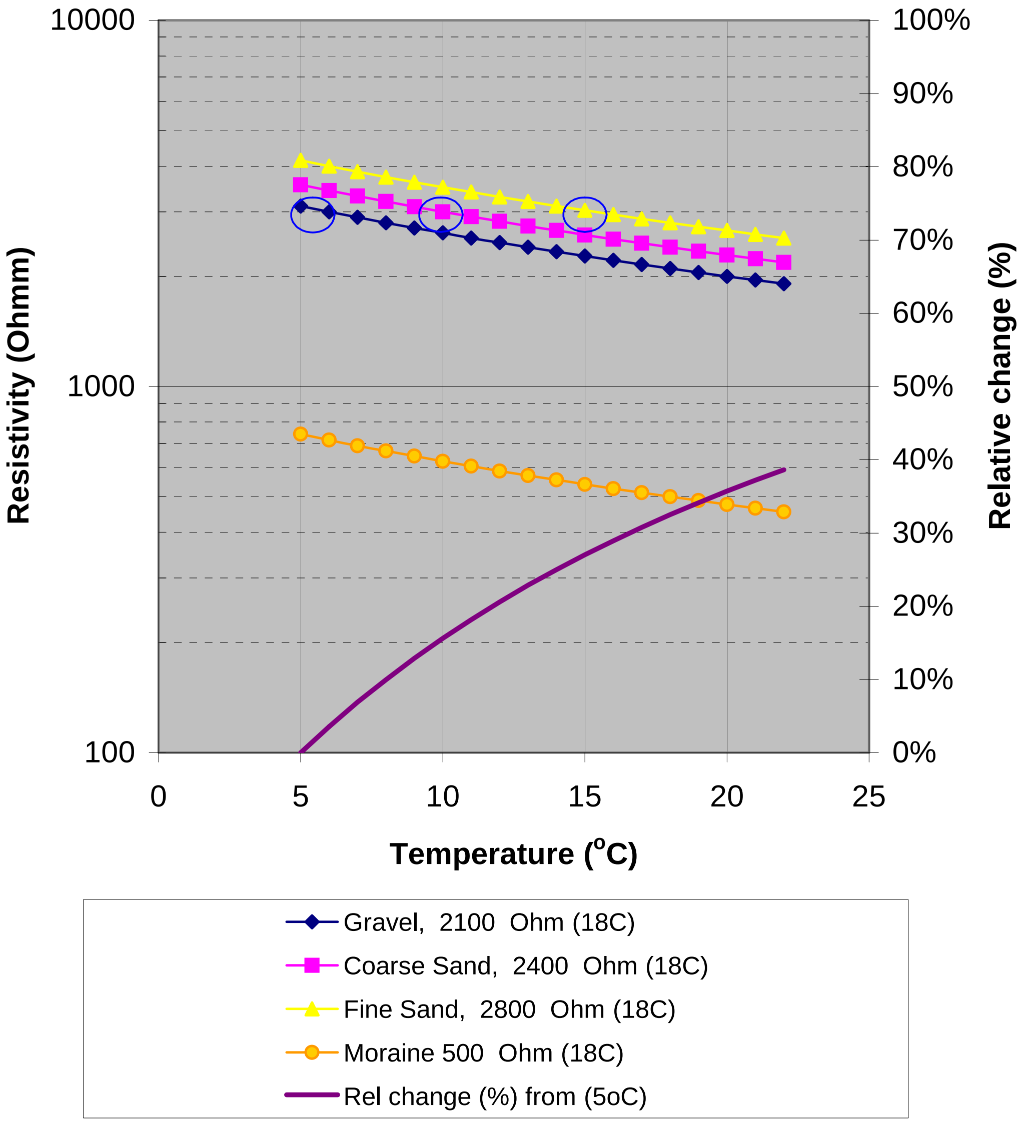

Figure 12 **Temperature influence on resistivity for some soils (theoretic calculations)**

4.3 Monitoring, data processing and evaluation methods

Resistivity measurements that are made must be inverted in order to see the resistivity along the dam and at different depths. This is a time consuming work and must be automated if the method would be implemented for daily measurements. Before inversion can be done several ways of improving the data quality must be performed. Different inversion techniques can be applied as described by Loke 2001, and Loke et al 2003.

For the Swedish research installation following steps are used (This is described in detail by Dahlin et al, 2004):

- Carry out a time base median filtering over a specified number of days (e.g. 7), or apply combined predictive filtering and de-spiking technique.
- Calculate a data file consisting of the all time median as the time base median of the whole period (for example a year), or calculate sliding damped reference data sets.

- Convert all the time base filtered raw data files to the format used by the inversion software (see below) to allow time-lapse inversion.
- Create a batch control file for the inversion software Res2dinv and run the inversion in batch mode.
- Extract the desired information from the inverted output files and save it in a format suitable for continued processing and presentation.
- Scan through the inverted models and calculate statistical parameters for the whole period, such as annual median and mean resistivity sections, a section showing the variation coefficient, and sections showing the maximum and minimum interpreted resistivities of the period. A threshold for the mean model residual can be applied to filter away inverted model sections of too poor quality, which applies mainly to data recorded during the winter when the electrode contact resistances are highest and initially when the system was tuned in. The statistical evaluation can be repeated with different settings without necessarily re-doing the inversion.

These steps will be further improved within the ongoing research project at the Lund University.

4.4 Experiences from Monitoring in old dams

Hällby was the first Swedish embankment to get a permanently installed monitoring system intended for resistivity measurements. Daily measurements started to take place already in late 1996, and several report have been published (Johansson et al. 2000 and 2003, and Sjödahl et al. 2004).

The embankment at Hällby is divided into a left and a right part by a centrally placed power plant and spillways. The left dam is 120m and the right dam is 200m long. Both dams have a maximum height of around 30m in the central part of the river section and level out at the abutments. The dams have a vertical central core of moraine surrounded by filter and rockfill. Annual water level variations are less than 0.8m which gives ideal conditions for the measurements.

The installation comprises full instrumentation for resistivity measurements. The system is based on the ABEM Lund Imaging System, with modifications for automatic monitoring needs including lightning protection. A PC controls the data acquisition, with a modem for remote control and data transfer. Five cables with permanently installed electrodes are situated on the reservoir bottom along the upstream slope of the dam (left and right), buried along the dam crest (left and right) and along the downstream toe (right only). In total 102 electrodes are installed on the dam, of which 43 on the crest and 21 on the downstream toe. Stainless steel plates were used as electrodes on land. The remaining 38 electrodes were installed in the reservoir on the dam upstream face, using stainless steel ring electrodes. The distance between each electrode is seven meters.

The temperature and resistivity of the water in the reservoir have been measured since the start of the monitoring program (Figure 13). The pattern of the temperature variation is sinusoidal over the year but with a clear cut over the lower part of the curve at 0°C. The resistivity curve show similar characteristics as it is depending heavily on temperature, but the higher winter resistivity is clearly affected by differences in ion content as well, probably due to seasonally varying inflow of groundwater to the river.

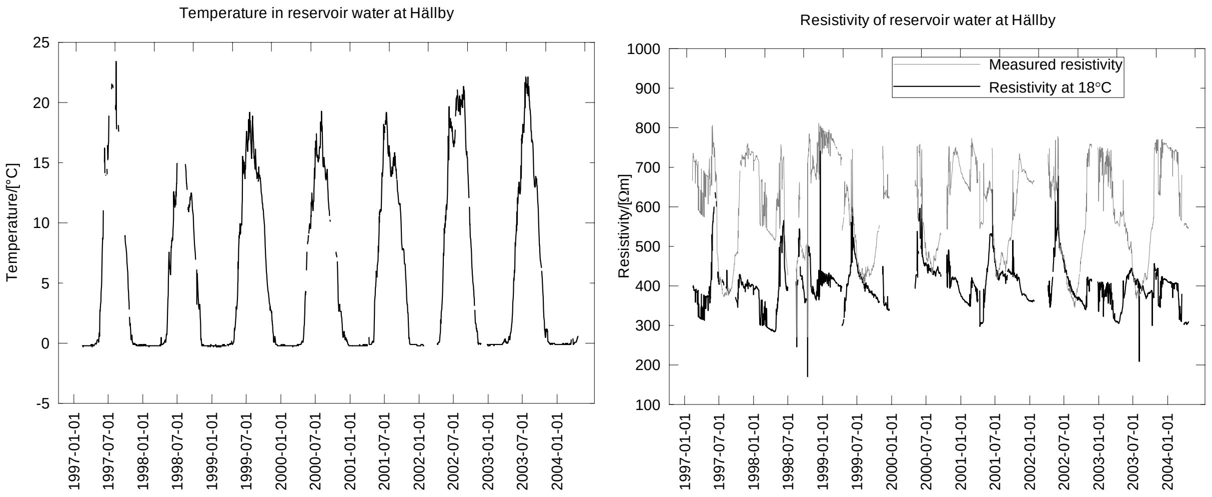

Figure 13: **Temperature in the reservoir water (left). Measured resistivity and normalized resistivity at 18°C (right).**

One example of inverted data along the dam is shown in Figure 14 (left). The lower resistivity at the lower part is partly due to 3D-effects, but a slight lower resistivity is found in the bottom at chainage -40 to -50m. A higher variation is also seen in this area (right figure) which shows the distribution of the relative variation $(\rho_{max} - \rho_{min}) / \rho_{median}$. The electrodes are installed 1m below the crest (+293.5m).

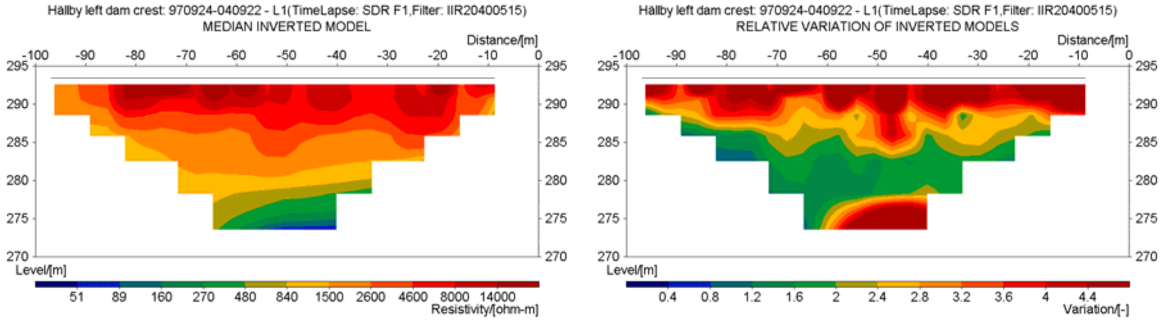

Figure 14: **Median resistivity distribution (left) and its relative variation (right) at Hällby left dam crest over the period 970924-040420. Data was filtered with an infinite impulse response filter before L1-inversion. A sliding damped reference value is used for the time-lapse inversion method.**

One example of the response in the dam is showed in Figure 15, where regular seasonal variations are shown for all depths. This indicates constant seepage. Another example at chainage -47.25 indicate however an increasing resistivity and increasing seasonal variations (Figure 16), especially at 19.9m depth. A weak increase may also occur above that depth. The increasing resistivity variations can be explained by an increasing flow, while the increasing trend indicates a material change. These two effects may be a sign of ongoing internal erosion. The observation has so for not been confirmed by any other observation. No muddy water have been observed and no seepage increase have been measured in the weirs.

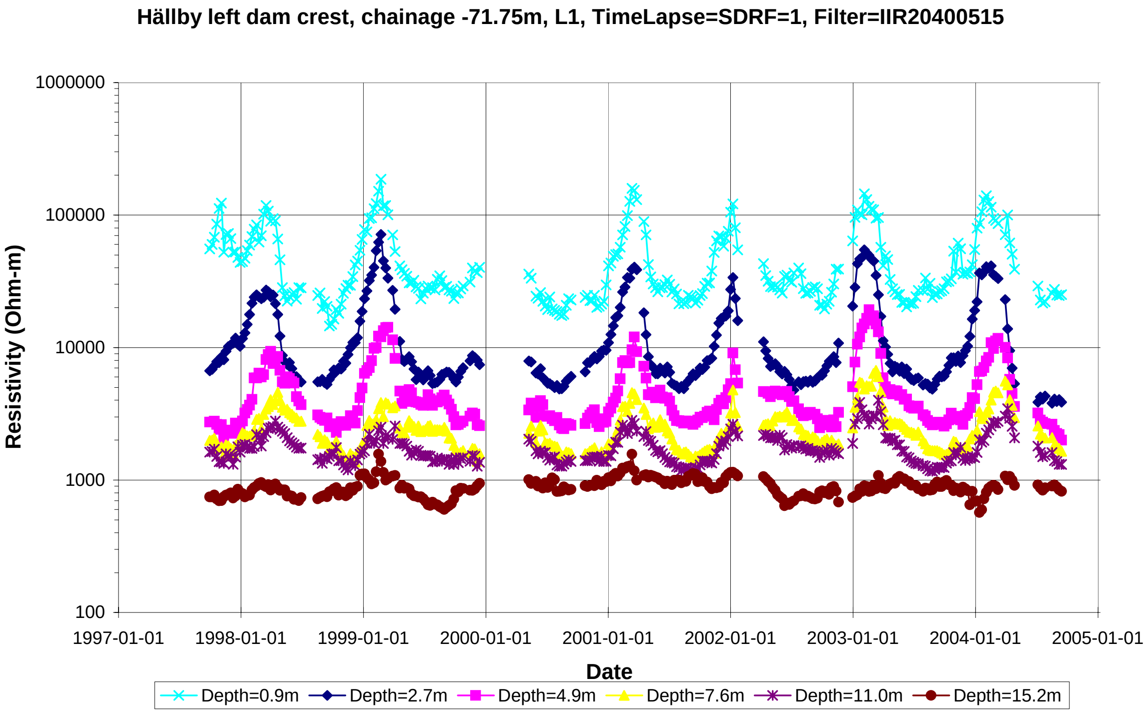

Figure 15 Resistivity variation at chainage – 71.25 at some depths.

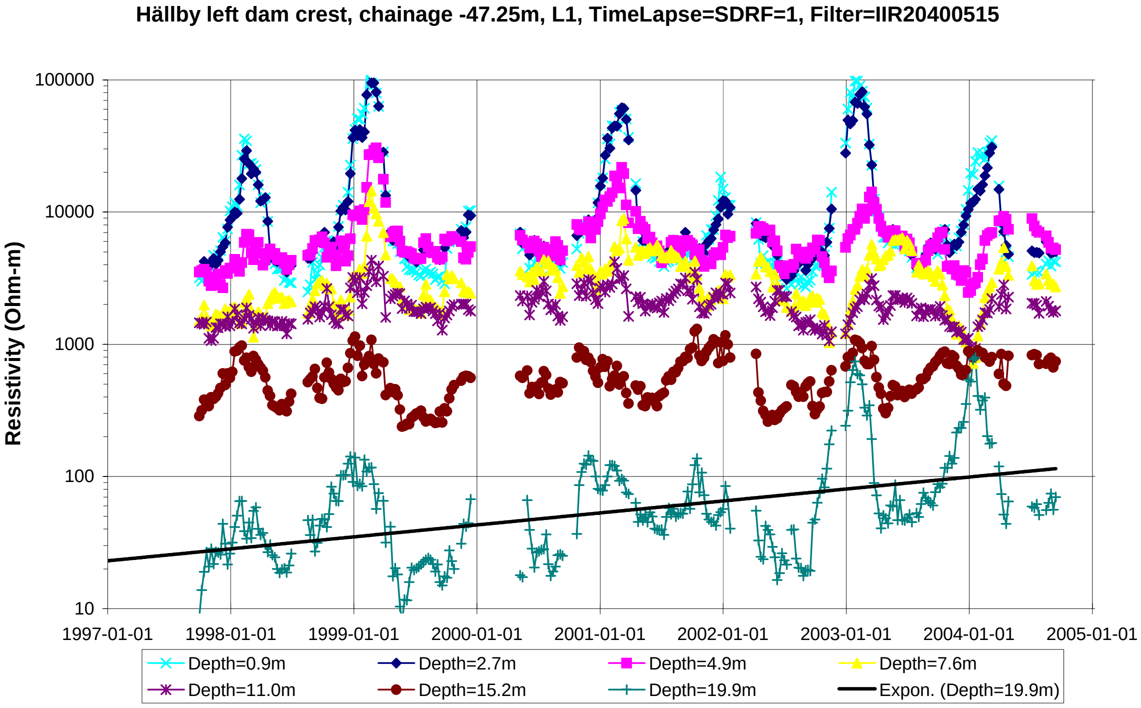

Figure 16 Resistivity variation at chainage – 47.25 at some depths.

5 SELF POTENTIAL

5.1 Background

Self-potential measurements (SP) have long been considered interesting for dam seepage investigations (Corwin et al, 1988 and 1989, Merkler et al 1989). The main reason is the methods theoretical capability to detect fluid flow through the streaming potential mechanism, which generates electric potential variation in response to fluid flow through porous media. Streaming potentials are generated when a fluid flows parallel to an interface between fluid and mineral. The fluid flow causes a mechanical displacement of the electric charges that are loosely bound to the mineral surface (the so called electric double layer). The movement of electric charge causes an accumulation of charges downstream and depletion upstream. In most cases in nature the charges bound to the mineral surface are positive so that the downstream or outflow areas acquire a positive charge. Consequently upstream or influx areas become negatively charged. This charge separation creates electric potential differences that can be observed using common SP survey techniques.

Measuring SP is apparently, or maybe deceptively, easy all that is needed is a pair of non-polarising electrodes and a high impedance voltmeter. Making sure that the observations made are relevant is more complicated. Factors that must be considered minimised or corrected for include: electrode polarisation effects, telluric disturbances (natural time varying potentials that are not related to the anomalies sought in an SP survey, often with amplitudes exceeding these), electrode drift, external electrical noise (power lines, electric equipments etc.). A valuable field manual for SP-monitoring have been produced by Corwin within a DSIG project (Corwin 2002).

5.2 Monitoring and Evaluation and methods

Data from the monitoring installations are contaminated with several distinct types of noise: electrode polarisation effects, spikes (both external and instrument generated) and random noise (e.g. tellurics). It is therefore necessary to apply some filtering to the data before attempting to draw any conclusions from them. The following filtering sequence was developed within a research projects (Dahlin et al 2004) and applied to all data:

- Identify and remove occasions of obvious instrument malfunction (as indicated, e.g., by the measured values locking at the end of the A/D converter range)
- Apply a spike removal filter
- Apply a 7-day running median filter

The implementation of the first and last filter types is quite straightforward, but the spike removal filter may warrant some more detailed description. The spike removal filter is implemented as a threshold filter based on a 25-day running median value. If a data point deviates more than a given amount from this median value then it is replaced by a 7-day median centred on the data point.

Figure 17, show time series plots of the measured SP at Hällby (left crest, stainless steel). The plots illustrate the effect of the different filtering steps. The bottom pane shows raw data, the middle pane shows data after spike removal and the top pane shows data after spike removal and 7-day median filtering. In all cases the resulting data quality is acceptable. The spike at the start of the filtered time series is a filter edge effect.

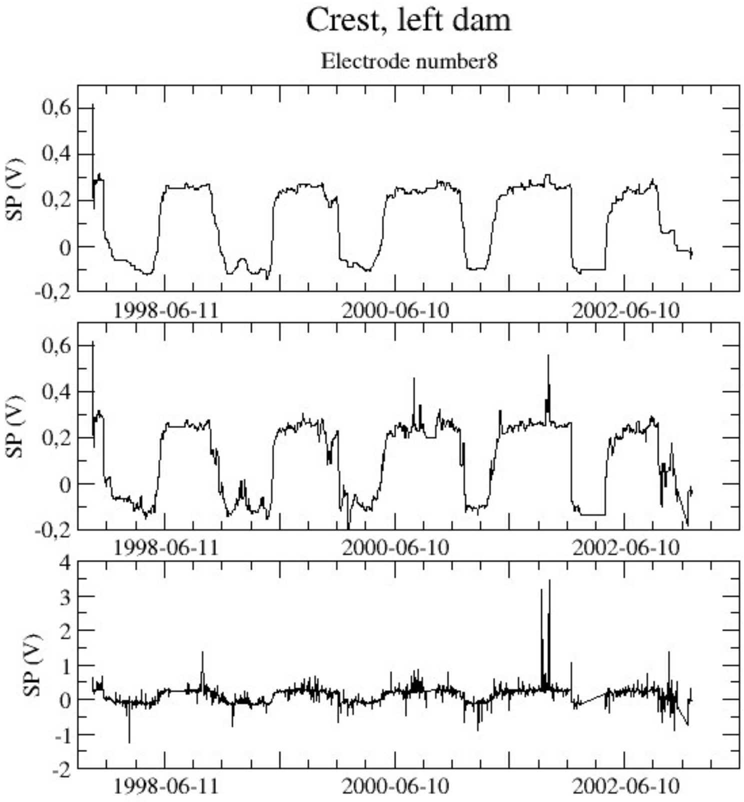

Figure 17: **Example of SP time series filtering of data from Hällby. SP measured at electrode #8 at the crest of the left dam. Spike removal and 7-day median (top), spike removal (middle), raw data (bottom).**

The final step is the calculation of residual SP, where the mean SP value for each electrode is subtracted from each data observed at the electrode. This procedure minimises station-to-station differences caused by electrode polarisation differences, and is most important for the data measured with metal electrodes.

Numerical models can be used to estimate the seepage as. This approach seems promising and well improve the possibilities to understand and evaluate the result. Different models have been used, (Sheffer, 2002, Johansson et al 2001 and Dahlin et al 2004).

5.3 Experiences from monitoring in old dams

Self-potential data from Hällby are stable and apparently have good repeatability, although they were measured with stainless steel electrodes. The time variation is generally fairly smooth and in several of the profiles there is a clear seasonal variation of the self-potential anomaly.

The measured anomalies are the sum of a true self-potential component and an electrode polarisation component, both of which appear to be stable and repeatable (Figure 18). The amplitude of the electrode polarisation potentials can be roughly estimated by comparing the amplitude of the short and long wavelength parts of the anomalies. Such an analysis indicates that the amplitude of the polarisation effect is comparable to that of the actual SP-anomaly in the land-based data. Data from the underwater profiles exhibit smaller polarisation disturbances. The reason is probably that the underwater milieu provides an electrically more stable and homogeneous environment for the electrodes. Differences in the properties of the electrodes cannot be ruled out. The data from Hällby show also a good correlation between SP and the apparent resistivity.

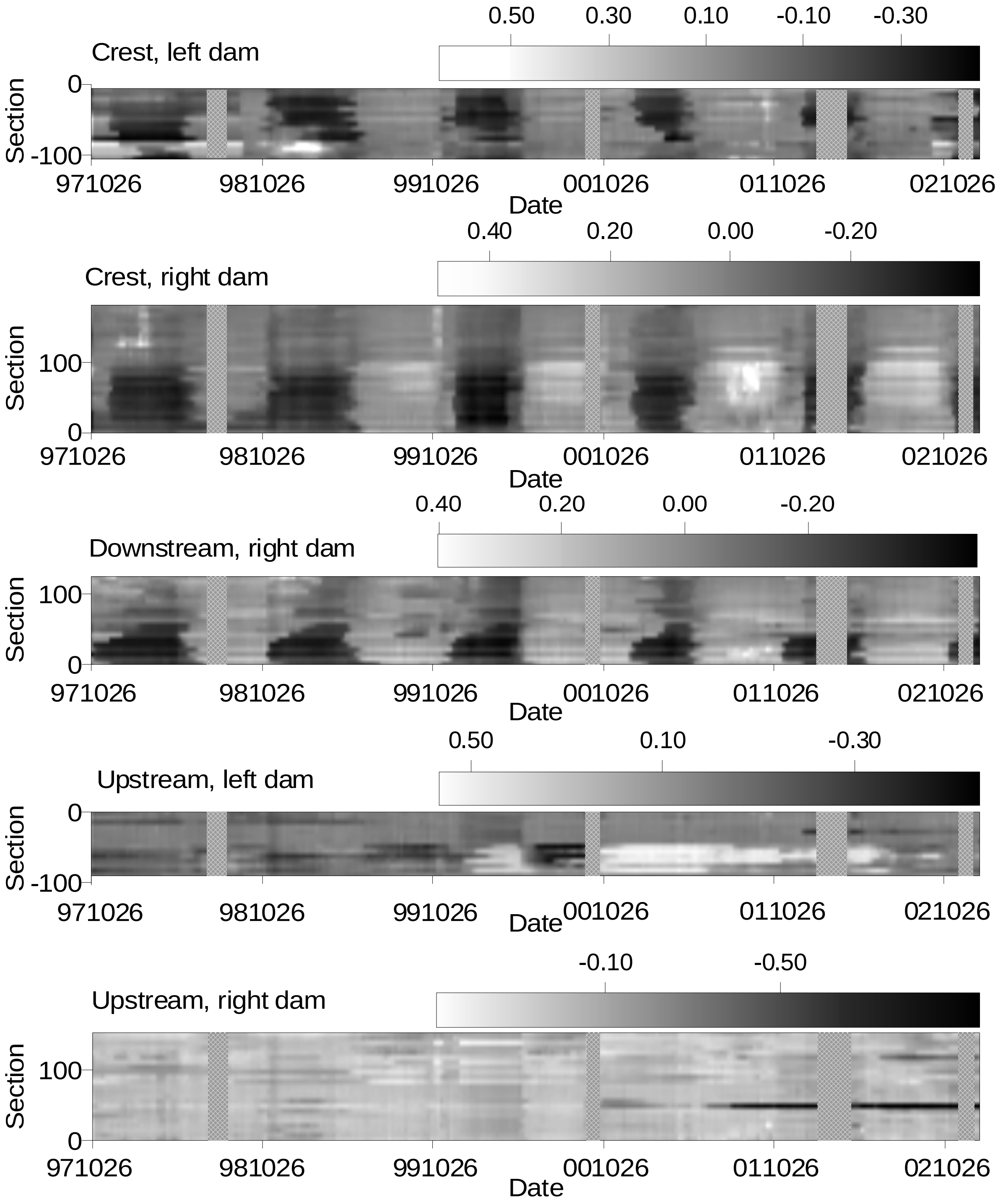

Figure 18: **Time variation of residual SP at Hällby (the mean SP value for each electrode have been subtracted). Hatched areas indicate periods of missing data.**

6 CONCLUSIONS

Flow dependent methods are more sensitive than material dependent parameters to detect internal erosion. The most appropriate parameters for monitoring of internal erosion are thus seepage, temperature, resistivity and SP. The methods that are used to measure these parameters give different resolution and accuracy and require different kind of installations.

Temperature measurement is in most cases the most sensitive method to detect seepage flow. The best application of the method is long term monitoring, where slow and small seepage flow changes can be detected. The sensibility is in the order of some $10^{-5}m^3/(s,m)$ for normal dams, but depends on where the temperature is measured. If the measurements are taken at a depth of 5-10m from the soil surface a higher sensitivity may be possible, since the influence of the seasonal air temperature variation can be ignored. Measurements taken close the soil surface will be clearly affected of the seasonal variation, which will reduce the sensitivity. The sensitivity decreases with the dam height.

Resistivity has a significant influence of the temperature, but also on the soil gradation and porosity. The latter two parameters counteract and the influence may therefore vary for different soils. The combined effect for moraine core is probably an increasing resistivity with porosity, and will probably be smaller than the thermal influence. They will however be possible to separate because the temperature will give a seasonal variation, while porosity changes at internal erosion will give a slow linear change. The seasonal variation component in resistivity data requires a high monitoring accuracy to be detected. This can be achieved at permanent installations.

SP is mainly given by changes in porosity and seepage flow, i.e. the two fundamental parameters, and the pressure gradient. The indirect change due to temperature must be considered, especially at higher seepage flow rates, where the temperature has an appreciable influence on the cross-coupling coefficient. In several cases the temperature variation makes the surface anomaly magnitudes for the different flow rates overlap. Moreover, evaluation of SP requires the resistivity over the entire dam that also is temperature dependent especially on the crest of the dam. Seasonal variation of SP due to seepage flow should be considered at flow rates about 10^{-5} m/s. A stronger influence can be found at large damages. This variation indicates that seepage modelling based on SP- must therefore include the seasonal effect, especially at seepage flow rates larger than 10^{-5}m/s. This effect will however be reduced for deeper locations.

Temperature, resistivity and SP are methods that are possible to install in existing dams. Drillings should there be avoided and installations for e.g. seepage monitoring is practically impossible to construct after the dam is fulfilled. The methods are also appropriate for long term monitoring, which probably is needed to achieve accuracy enough to detect internal erosion. Single investigations with any method will normally not be able to detect internal erosion in its early stage.

Internal erosion monitoring in existing dams can be performed using a combination of resistivity and SP with installations on the dam crest, or may be also in the reservoir/upstream slope. It is however important that the installations are performed well so that a high monitoring accuracy is achieved.

The dam toe is probably the most sensitive part of the dam for detection of seepage flow changes, and it is also easy to observe. Optical fibres, installed along a dam toe, will provide possibilities to both locate anomalous seepage areas and estimate the seepage flow after short time investigations (normally some days). Such measurements will be a valuable complement to visual inspection, but will probably not replace visual inspections.

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