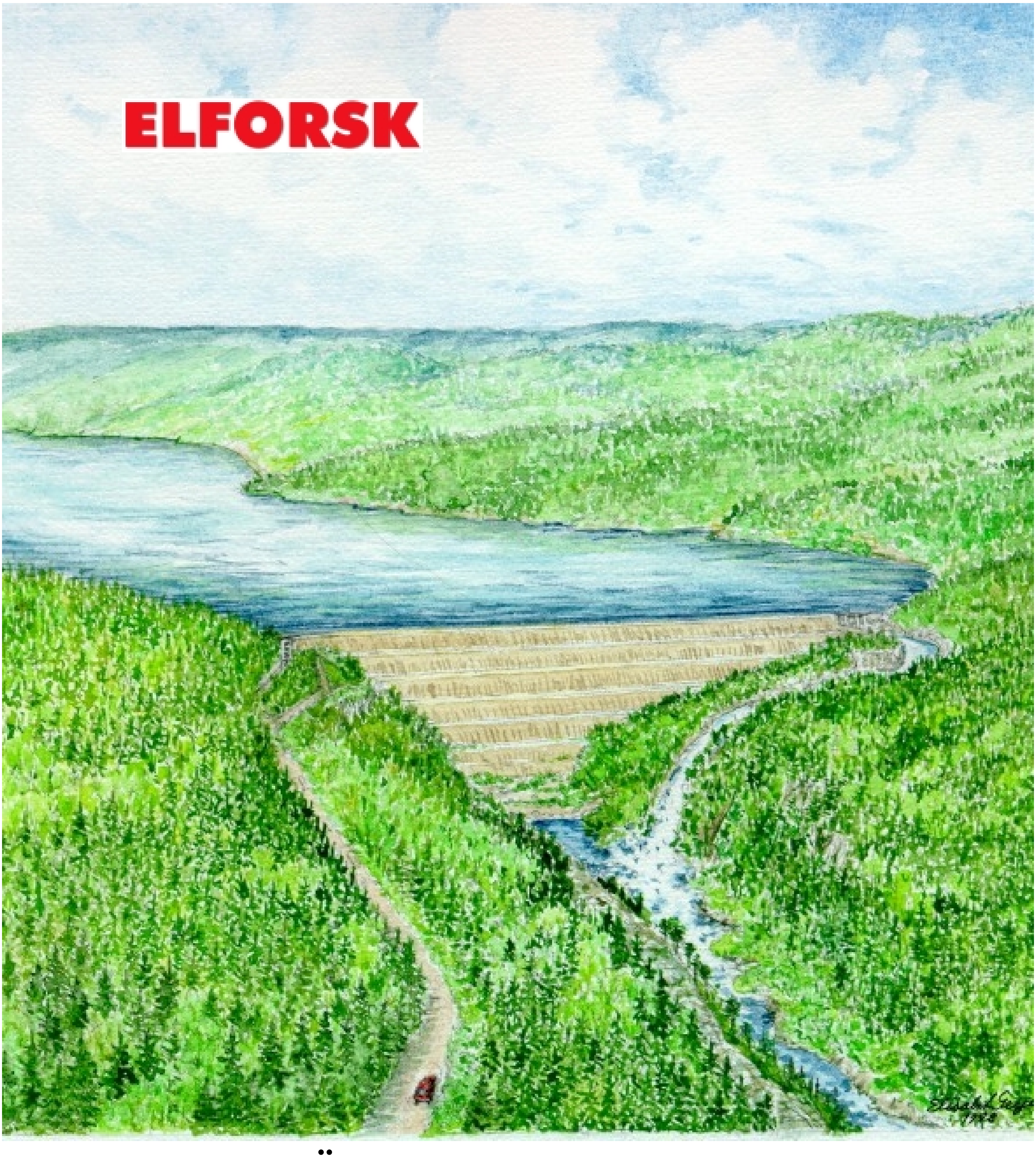

DAMMSÄKERHET

NEW AND IMPROVED MONITORING SYSTEMS FOR EMBANKMENT DAMS

Rapport 00:14

New and improved monitoring systems for embankment dams

Experience from initial resistivity, SP, strain and temperature measurements at Sädva dam

Elforsk rapport 00:14

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Maj 2000

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Elforsk rapport 00:14

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Sammanfattning

Sädvadammen är en stenfyllningsdamm, belägen högst upp i Skellefteälven, strax söder om polcirkeln. Dammen, som togs i drift 1985, dämmer upp ett magasin med en volym av 600 miljoner m^3. Magasinet används för årstidsreglering mellan nivåerna +477 och +460,7. Dammen utgörs av en 200 m lång huvuddamm samt en sidodamm med längden 350 m. Dammens högsta höjd är 32 m.

Mot bakgrund av de nya dimensionerande flöden som erhållits vid tillämpning av Flödeskommitténs riktlinjer byggdes sommaren 1999 ett ytterligare utskov. Dessutom höjdes tätkärnans nivå för att vid behov kunna dämpa flödet vid extrema nederbördsförhållanden. Liknande arbeten kommer att ske vid flera dammar under de närmaste åren. Det är därför angeläget att undersöka vilka mätinstallationer som är lämpliga att installera vid dammhöjningar.

I samband med höjningen av tätkärnan installerades utrustning för mätning av resistivitet, strömningspotential (SP), temperatur och rörelser. Utrustningen är avsedd att användas för långtidsmätningar inom olika forskningsprojekt. I denna rapport redovisas resultat från inledande testmätningar av resistivitet och SP. Dessutom redovisas erfarenheter från installationen av elektroder för mätning av resistivitet och strömningspotential, samt från installation av fiberoptisk kabel för mätning av temperatur och rörelser.

Installationerna omfattar sammanlagt 128 elektroder. För resistivitetsmätning finns 96 elektroder av rostfritt stål med 6 meters mellanrum. Dessa finns utmed både huvuddammen och sidodammen. På huvuddammen finns också 32 elektroder för SP-mätning, placerade med 6 m mellanrum. Dessa är förskjutna 3 m relativt resistivitetselektroderna. Elektroderna placerades på den gamla tätkärnans krön, vilken sedan påbyggdes med 0,7 m.

Resistivitets- och SP-mätningar har utförts vid ett tillfälle. Mätningarna visade utmärkt datakvalitet med låga brusnivåer. Detta kan förklaras av den goda mätmiljö som kan erhållas när elektroderna kan förläggas direkt i tätkärnans överdel. Såväl resistivitets- som SP-mätningarna visar små variationer, vilket innebär att dammens egenskaper är homogena. En anomali finns i berget under sidodammen, ca 10 m under grundläggningsnivån, förmodligen orsakad av avvikande geologiska egenskaper.

De speciella SP-elektroderna ger ett utmärkt resultat, varför denna typ av elektroder rekommenderas vid framtida installationer.

Den installation av fiberoptiska kablar som gjorts möjliggör framtida mätningar av temperatur och rörelser. Två kablar har därför installerats i dammens krön. Några mätningar har ännu ej gjorts i fält. Utrustningen har däremot testats i laboratorium. Fältmätningar planeras under hösten 2000. Syftet med dessa mätningar är att registrera relativa rörelser i dammens krön, samt temperaturen i krönet. Några sättningar är ej att

förvänta, utan de rörelser som avses studeras är sådana som orsakas av tjäle och olika vattenstånd i magasinet.

Summary

The installation in Sädva dam provides a monitoring system that can detect the most important and fundamental parameters for dam monitoring, i. e. seepage (using resistivity and streaming potential) and movements (by distributed fibre optic sensors).

All installation work was made when the core crest was raised in summer 1999. Similar construction work will be made in several Swedish dams as a consequence of the new Guidelines of Design floods. It is therefore of great value to examine different ways of installation of new monitoring equipment, which easily can be made when the core is open. Experiences from this installation may therefore be valuable for future installations.

A total of 128 electrodes were installed. A spacing of 6m between the 96 resistivity electrodes (steel plates) was chosen for the entire dam. 32 non-polarisable SP-electrodes were also installed in the main dam, with a spacing of 6m but shifted 3m relative to the steel plate electrodes. Thus, there are electrodes at 3m intervals on the main dam.

The resistivity measurement tests clearly showed that very good electrode contacts was achieved at in the installation, and the measured data exhibits low noise levels. It is obvious that installation of the electrodes inside the upper part of the dam core can be an efficient way to avoid data quality problems due to pore electrode contact. The anomalous patterns at the ends of the main dam inverted sections are not due to poor data quality, but are rather due to geometrical effects at the bend of the dam or strong contrasts in material properties within the dam. This can be caused by e.g. metal objects and concrete structures inside the dam.

The resistivity structure within the main dam is rather homogeneous, whereas there is a larger variation within the dyke, which can be interpreted as a larger variation in material properties in the latter case. There is also a significant variation in inverted resistivities below the foundation level of the dam, which is interpreted as a variation in rock type or rock quality.

The SP data recorded at Sädva appear very stable, probably because of the near ideal environment for the electrodes. Initial electrode tests, however, indicate that strong polarisation effects may be associated with the use of stainless steel electrodes, so the results should be interpreted with caution.

The development of fibre optic systems for temperature, strain and pressure, is promising. The installation made at Sädva will be used to test temperature and strain measurements at realistic field conditions.

Content

1 Introduction

Monitoring of the collected drainage water from embankment dams is the normal way of seepage monitoring in dams. This gives the total seepage flow over the entire dam or within a limited section. The potential to detect local internal erosion is thus limited. Seepage monitoring systems with higher accuracy and resolution are therefore needed. 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.

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. Internal erosion affects several parameters. Some of those can be measured by the installations made at Sädva dam (resistivity and Streaming Potential, SP). This report is primarily a description of the installations and some initial test measurements. Long term monitoring is planned to start in summer 2000.

Measurement of movements is also common way of dam monitoring. This is normally made at single points on the dam crest or inside the dam. The rapid development of fibre-optic systems within the last decade provides a possibility to measure movements along a fibre, as well as temperature. Such a fibre was installed at Sädva in 1999. Parameters such as temperature and strain can then be measured sufficiently accurately to be appropriate for monitoring of seepage and movements in dams.

The installation was made when the core crest was raised in summer 1999. Similar construction work will be made in several Swedish dams as a consequence of the new Guidelines of Design floods. It is therefore of great value to examine different ways of installation of new monitoring equipment, which easily can be made when the core is open. Experiences from this installation may therefore be valuable for future installations.

The installation in Sädva provides a monitoring system that can detect the most important and fundamental parameters for dam monitoring. However, all installations are not optimal for monitoring purpose. Improved system performance can thus be expected for installations in new dams.

2 Parameters and Monitoring Principles

2.1 Orientation

Research and development of geophysical methods to detect seepage changes and internal erosion started in Sweden in the late 80ties with temperature measurements (Johansson, 1991). Based on the development of resistivity monitoring made by Dahlin (1993), a new concept for seepage monitoring in embankment dams was presented. This new concept was based on seasonal temperature and resistivity variations. Initial tests were made in two dams, Lövön and Moforsen, between 1993 and 1995 (Johansson and Dahlin 1996 and 1998). Based on these first results a permanent installation for resistivity monitoring was made at Hällby embankment dam in 1996. Since the monitoring system allowed to also measure streaming potential (SP), it was decided to collect SP-data. Based on the experience from Hällby dam this new installation was made at Sädva dam 1999. The first long term SP-measurements in Sweden started however at the Sourva dam in 1993 (Triumf and Thunehed, 1996).

Temperature measurements have also been successfully used during the last decade in several dams in Sweden, Canada and the US. Different monitoring systems have been tested and the development of fibre-optic system has been followed carefully, primarily for distributed temperature measurements, see (Johansson and Farhadiroushan, 1999).

2.2 Resistivity

2.2.1 General

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 Ward 1990 and Parasnis 1986). 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.

2.2.2 Monitoring in embankment dams

This application of resistivity monitoring is based on the experience from temperature measurements in embankment dams. Seasonal temperature variations in the dams have been detected due to the seasonal temperature variation in the reservoir and the seepage water flow. Since the resistivity in the dam depends partly on the temperature it will also exhibit seasonal variations. The resistivity depends furthermore on the TDS in the water and this too varies seasonally. The combination of these parameters, temperature and TDS, is expressed by the resistivity of the reservoir water, which will create a seasonal variation in the resistivity in the dam due to the seepage through the dam.

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 (Lövön and Moforsen) started in 1993, after model calculations had indicated that seasonal resistivity variation 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. The project was reported by Johansson and Dahlin, 1996. Based on these experiences a monitoring system was installed in 1996 at the embankment dam at Hällby power plant, (Johansson and Dahlin, 1998).

2.2.3 Basic concepts 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, q, passes through the dam, see Figure 1.

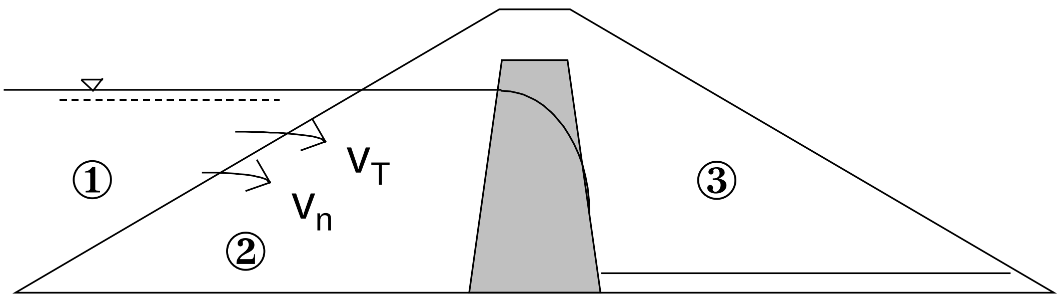


Figure 1 **Basic transport processes in an embankment dam.**
① - Seasonal variation of TDS and temperature
② - Advective transport with seepage and heat conduction
③ - Heat exchange with the air
v_T - Thermal velocity
v_n - Pore velocity

The solutes penetrate into the dam with the pore velocity v_n (= q/θ, where θ is the porosity) while the temperature travels with the thermal velocity v_T (=qC_w/C, where C_w is the volumetric heat capacity in the water and C in the soil). The resistivity variation in the dam is therefore a combined result of these two transport processes.

2.2.4 Seepage evaluation methods

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 as described above.

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. 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, that gives the transport velocity ($=x/t_d$). 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:

$$q_{TDS} = \frac{\theta x}{t_d} \qquad \text{Eq. (1)}$$

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, based on the thermal velocity. The evaluated seepage flow q_T depends on the volumetric heat capacity in the soil (C_0) and is:

$$q_T = \frac{C_0 x}{C_w t_d} \qquad \text{Eq. (2)}$$

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. However, 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.

The seepage flow limit depends on the dam height, and the value of about 10^{-6}m^3/s and m^2 is valid for typical Swedish dams with a height of about 30 metres. Zones where seepage changes occur, or zones with anomalous leakage, can therefore be located in such dams with a detection level of about 10^{-6}m^3/s and m^2.

2.3 Streaming potential

2.3.1 Background

Streaming potentials constitute one of several sources of self-potentials, i.e. spontaneous electrical potential variations in the ground. Other examples of self-potential sources are mineralisations and thermal activity. For investigation of seepage through embankment dams, streaming potentials are especially interesting since they have a direct primary coupling to the flow of ground water. Other self-potential sources are rarely important in dams, and if present they would generally be considered as a source of noise. Metal installations in the dam, like bare cables or fences, could act as such noise sources as they produce self-potentials of the mineralisation type. A thorough description of the use of the self-potential method is given by Corwin (1990).

2.3.2 Creation of streaming potentials

In general, all mineral surfaces in contact with an electrolyte will develop an electric charge. To preserve electro-neutrality, this surface charge must be balanced by an equal amount of opposite charges distributed in the electrolyte. The charges in the electrolyte constitute the electrical double layer, which will contain an excess of charges compared to the bulk of the electrolyte. When there is a flow of electrolyte past the mineral surface part of the double layer is sheared off, and some of the excess charges move downstream with the fluid flow. This charge separation is the basic physical mechanism behind streaming potentials. For most geological materials, the surface charge is negative and consequently areas of ground water influx become negatively charged, whereas areas of outflow acquire a positive charge.

Although not strictly true it may be illuminating to view the creation of streaming potential anomalies as a step-wise process:

1) A groundwater flow pattern is established. Hydraulic boundary conditions and the distribution of hydraulic conductivity in the subsurface determine this.
2) The water flow shears off part of the electrical double layer creating a convection current density, which causes a separation of charge.
3) The charge separation sets up an electric field, which will drive an electric current through the ground. The distribution of the current depends on the position of the areas of charge accumulation and the resistivity distribution. The measured self-potential anomalies are actually the potential drop caused by the current flow through the ground between the observation points.

In reality these steps occur gradually and simultaneously until steady-state conditions are reached.

2.3.3 Self-potential measurements as a seepage monitoring tool

From the previous section one can draw the conclusion that the convection current will increase as the flow of water increases. It can in fact be shown that the convection current (J_{conv}) density is directly proportional to the hydraulic gradient ∇P (see e.g., Sill 1983):

$$J_{conv} = L\nabla P.$$

The constant, L, is known as the cross-coupling coefficient, and depends on the properties of the minerals and the ground water, as well as on the pore geometry.

From the above one could be tempted to draw the conclusion that increased amplitudes of self-potential anomalies on dams could be directly linked to increased seepage flow. Unfortunately, the situation is slightly more complex than that. An important cause of increased seepage flow is internal erosion in the dam, causing an increase of the porosity and the hydraulic conductivity. The resulting removal of fines will also directly affect the electric resistivity and the cross-coupling coefficient. Things are further complicated by the fact that the resulting self-potential anomaly is directly dependent on the resistivity of the ground. Consequently, an increased self-potential anomaly could be equally well explained by an increase in L, an increase in the resistivity, or an increase in the fluid flow.

To effectively use self-potential data for monitoring purposes, they should ideally be complemented by data on resistivity and hydraulic conditions. A self-potential anomaly taken on its own is fairly inconclusive. On the other hand, an increased self-potential anomaly not correlated with a resistivity change or a change in hydraulic head could well indicate an area with seepage problems. One should bear in mind, though, that there is also a regular annual variation of the self-potential anomalies. Such variation is generally not associated with anomalous seepage. Significant self-potential anomalies are those that in some way deviate from the annual variation.

3 Electrical monitoring installations

3.1 The Sädva dam

The Sädva dam is located in the upper part of the Skellefteälven River just south of the Arctic Circle. The reservoir has a storage volume of 600 million m^3. The dam and power plant was put into operation in 1985.

The dam is a rock fill embankment dam with a total length of 620m, divided in 210m long main dam across the old river channel, and a 410m long dike along the old river channel, see Figure 2. The core is made of moraine and is slightly inclined. The maximum height is 32m. The main dam is founded on bedrock, while the dyke is founded on moraine, expect where it connects to the main dam.

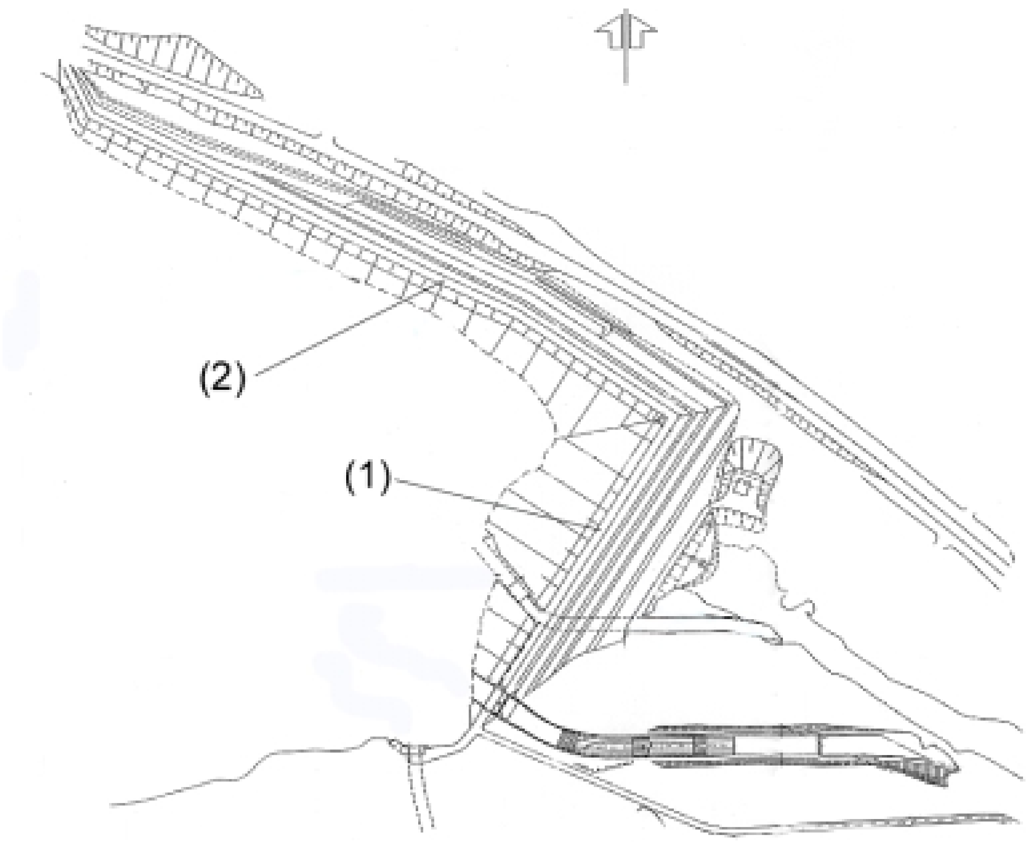


Figure 2 **Plan over Sädva dam (1) Main dam with both resistivity and SP electrodes (2) Dyke with resistivity electrodes**

According to the new Guidelines for Floods it was decided to increase the height of the core by 0.7m and to construct an additional spillway. This was made in 1999. Since the crest was excavated down to the core during this work, a unique possibility arose to install different monitoring equipment. It was therefore decided to use the dam as a research dam for dam monitoring.

3.2 Electrodes for resistivity and SP

A correct electrode type and a proper installation are fundamental for all electric measurements. Based on the experience from Hällby dam it was decided to use the same type of electrodes for the resistivity measurements. However, it was decided also to install special electrodes for the SP-measurements on the main dam. This would allow comparisons between the different electrode types.

The resistivity electrodes consist of 0.25m x 0.25m stainless steel plates (see Figure 3). The electrodes are connected to a polyurethande (PUR) covered stainless steel wire by bending and hammering one corner of the steel plate over the stripped wire end. These wires are joined to cables splits (pig-tail splits) on a PUR covered multi core cable. The multi core cables have 32 or 64 pig-tail splits each. The SP electrodes are so called non-polarisable copper-copper sulphate electrodes, Farwest Corrosion Control Company model SP-150 (Figure 4). These electrodes were delivered pre-packaged in a cloth bag filled with a bentonite mix designed to give a good coupling to the surrounding natural soil. The SP electrodes are joined to a multi core cable in the same way as the steel plate electrodes.

Figure 3 Installation of resistivity monitoring electrodes and cables.

A spacing of 6m between the electrodes was chosen for the entire dam. The total number of electrodes is 128. Special SP-electrodes were also installed in the main dam, with a spacing of 6m but shifted 3m relative to the steel plate electrodes. Thus, there are electrodes at 3m intervals on the main dam.

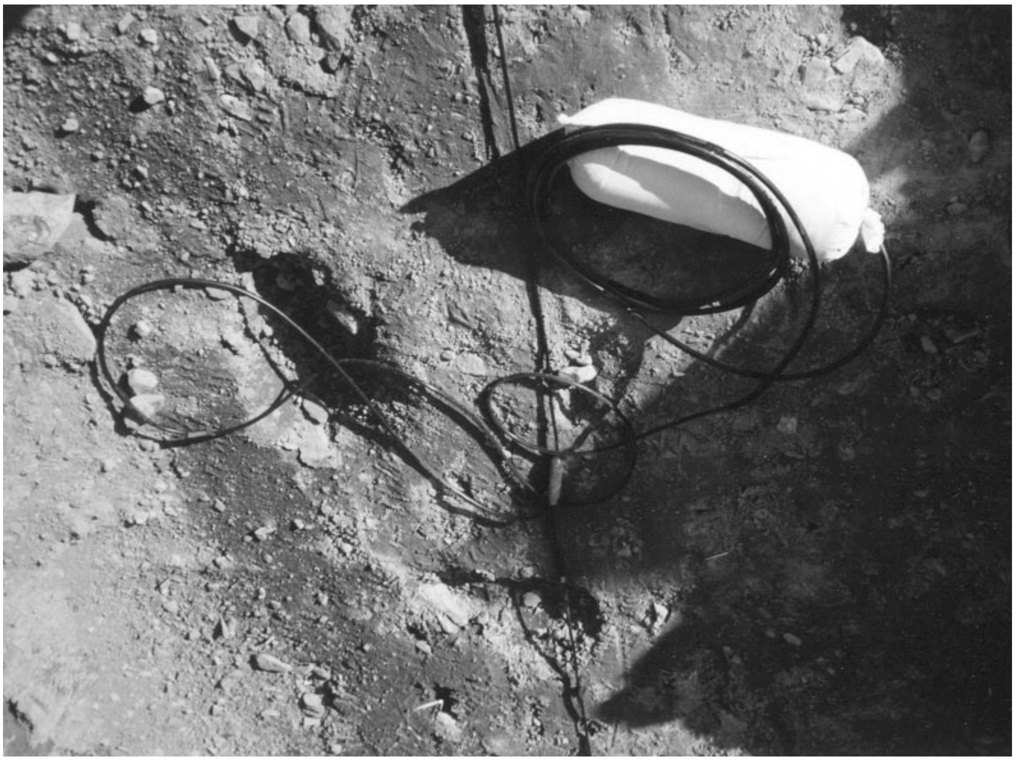


Figure 4 SP-electrode to be buried on the crest of the dam core.

3.3 Data acquisition

A multi-electrode data acquisition system developed at Lund University was used to obtain the resistivity and SP data (Dahlin 1993; Dahlin 1996). The data acquisition system is a modification of the ABEM Lund Imaging System, consisting of an A/D-converter (Lawson Labs AD201), a current transmitter (ABEM Booster SAS2000), a relay switching unit (ABEM Electrode Selector ES464) and a computer with the control software ERIC_AD.

The data acquisition process is completely controlled by the software, where the software scans through the measurement protocols selected by the user. The configurations so far have been Wenner and dipole-dipole, where reciprocal measurements are also carried out in order to assess the measurement errors.

3.4 Data processing and presentation

The true resistivity structure was interpreted using 2D smoothness-constrained inversion, where the Res2dinv inversion program was employed (Loke and Barker 1996; Loke 1999). In the inversion 2D 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 3D sources. A finite difference or finite element 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.

4 Result from resistivity measurements

4.1 Result

Test measurements were carried on Sädva dam in October 1999. Measurements were carried out using both the Wenner and dipole-dipole arrays. The tests showed that very good electrode contact had been achieved, and the measured data exhibit excellent quality. Measurement errors assessed by means of reciprocal measurements gave mean errors of around 0.5% and maximum errors around 3%. The following equation was used for estimating the measurement errors:

$$e_{obs} = 100 \cdot \frac{\left| R_{normal} - R_{reciprocal} \right|}{(R_{normal} + R_{reciprocal})/2}$$

Table 1 **Measurement errors in percent for the Sädva dam calculated from reciprocal measurements (reciprocal dipole-dipole measurements were not carried out on the dyke due to time limitations during the field tests).**

Data set	Wenner main dam	Dipole-dipole main dam	Wenner dyke
Average	0.51	0.53	0.03
Standard Deviation	0.56	0.53	0.06
Maximum	3.06	3.70	0.63

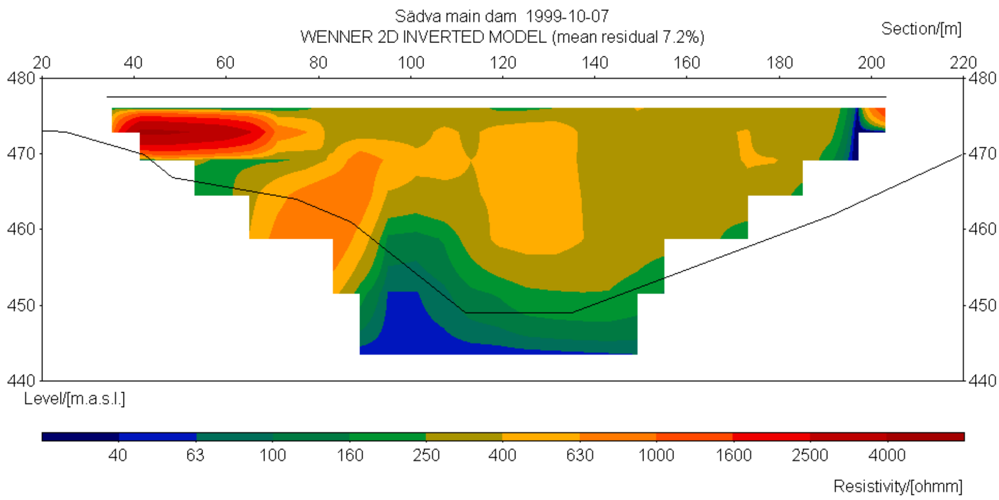
4.2 Main dam

The inverted sections for the main dam gave relatively moderate variation within the depth ranges of the dam. The Wenner and dipole-dipole sections are shown in Figure 5, and the results are similar in character. Both array types gave model residuals around 7% using least-squares inversion (inversion with L2-norm). Anomalous patterns are seen in each end of the section, but these are most likely due to disturbances from the structure, and geometric errors in the electrode layout at the end of the line. These suspected disturbances are not manifested in an identical way for the two array types.

The consistent appearance of the resistivity distribution of the main dam indicates that it consists of rather homogeneous material. The lower resistivities that are evident at the bottom of the section, at levels below the foundation level of the dam, may be caused by the properties of the underlying rock.

The higher resistivity in the leftmost part of the dam (up to around section 70 metres) is most likely caused by internal structures such as for example concrete or metal objects. The difference between the two array types in the ends of the sections is possibly explained by the differences in sensitivity function, where the dipole-dipole array is more sensitive to vertical structures and the Wenner array is more sensitive to horizontal structures (e.g. Ward 1990). However, the dipole-dipole array is also more sensitive to 3D variation in the investigated structure, i.e. deviations from the assumption of 2D structures (Dahlin and Loke 1997), which may be the main reason for the differences.

a)



b)

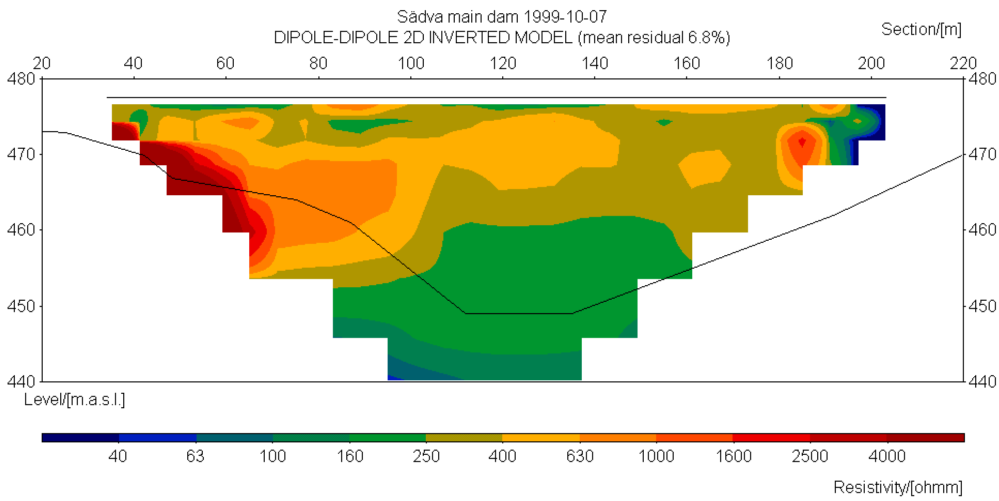
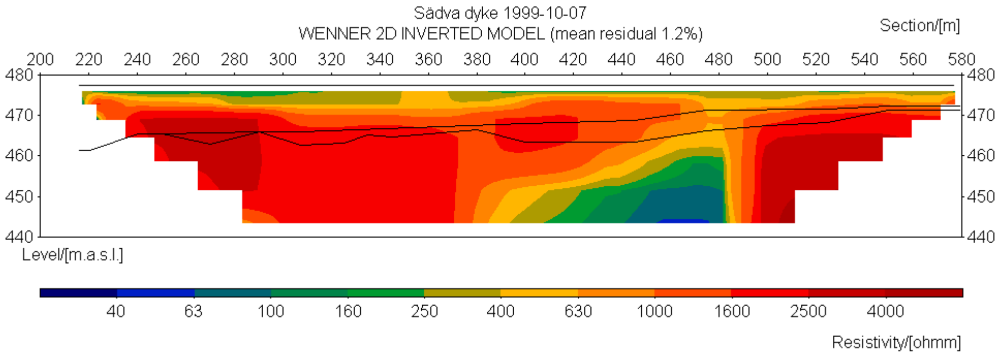


Figure 5 **Inverted resistivity sections for Sädva main dam, a) Wenner array, b) dipole-dipole array. The foundation level (equal to the bedrock level) is marked.**

4.3 Dyke

The inverted sections for the dyke also show relatively moderate variation within the depth ranges of the dam, see inverted sections in Figure 6. The Wenner and dipole-dipole results are quite similar. In this case L2-norm inversion gave much lower model residuals for the Wenner array (1.2%) than for the dipole-dipole array (5.2%). One feature that differs between the sections is a zone of higher resistivity near the surface in the dipole-dipole section, which is not present in the Wenner section.

a)



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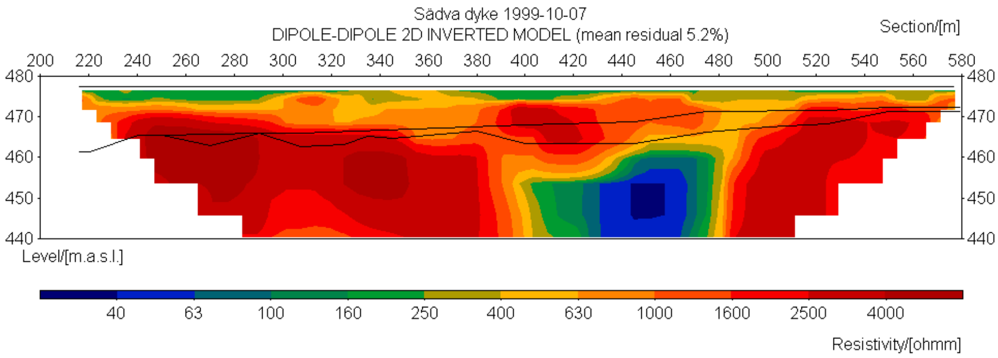

Figure 6 **Inverted resistivity sections for Sädva dyke, a) Wenner array, b) dipole-dipole array. The foundation level (about 5-7 m above the bedrock) and the bedrock level are marked.**

There is significant variation in properties along the embankment, which can tentatively be interpreted as larger variation in material properties than in the case of the main dam. The resistivity values are also higher than in the main dam. A distinct low resistive zone is exposed at the bottom of the section at 400-480 metres, below the foundation level of the dam. The zone is interpreted as a variation in rock type or rock quality of the underlying rock. The differences between the arrays types may be explained by e.g. different sensitivities to near surface variation and 3D effects as discussed above.

5 Result SP-measurements

At Sädva both non-polarisable and stainless steel electrodes were installed. This configuration makes it possible to estimate the influence of polarisation of the metal electrodes. Only a few sets of measurements have been taken so far. Figure 7 shows results of measurements with both types of electrodes from a profile along the crest of the main dam. The data exhibit very low noise levels and appear to be stable over time, as indicated by the lower plot, which shows the estimated standard deviation of the data. These results were, however, acquired over a fairly short interval of time and can only be used as an indication of the short-term stability of the data.

The non-polarisable electrodes, as expected, give an anomaly that varies smoothly along the profile. This is probably the best possible estimate of the true self-potential variation along the dam. The anomaly measured with the steel electrodes, on the other hand, has the same general shape, but there is also a strong short-wavelength component present. The absence of the short-wavelength component in the data acquired with non-polarising electrodes indicates that the effect is caused by electrode polarisation phenomena. That this really is the case was verified by the “short-circuit” experiments also shown in Figure 7. The assumption behind these was that if there was a polarisation charge build-up, it would probably be slow enough to be observable if only the electrodes could be depolarised first. Actual depolarisation of the electrodes is not feasible, but it is possible to connect all electrodes together to equalise the polarisation charge. If the electrodes are initially polarised then the SP-anomaly measured right after the equalisation should be different from that before. It should furthermore slowly change back towards the one measured before the short-circuit. This is exactly what was observed (see Figure 7). Before the short-circuit the anomaly had the shape shown by the blue line. Directly after, it had acquired the shape indicated by the green line, and after another 39 minutes (the red line) it had drifted back towards the original state. It is very interesting to note that the anomaly after short-circuit closely resembles that obtained with non-polarising electrodes. Further experiments of this kind will be performed in the future to determine whether this method could be developed into a tool to remove polarisation effects. At the moment it is uncertain to what extent the potential distribution in the ground is also disturbed by the procedure.

It can be concluded that the SP-anomaly measured is a sum of the self-potential of the ground and the polarisation potentials that the electrodes have acquired. It remains to be investigated to which extent these data are still useful for seepage monitoring. The fact that the electrodes are permanently placed in the ground might make it possible to remove the polarisation part of the anomaly. Even better, it might be possible to analyse and interpret the polarisation part of the anomaly. It is clear that as long as the electrodes are identical, variations in polarisation potential must be attributed to changes in local environmental conditions such as temperature and water content.

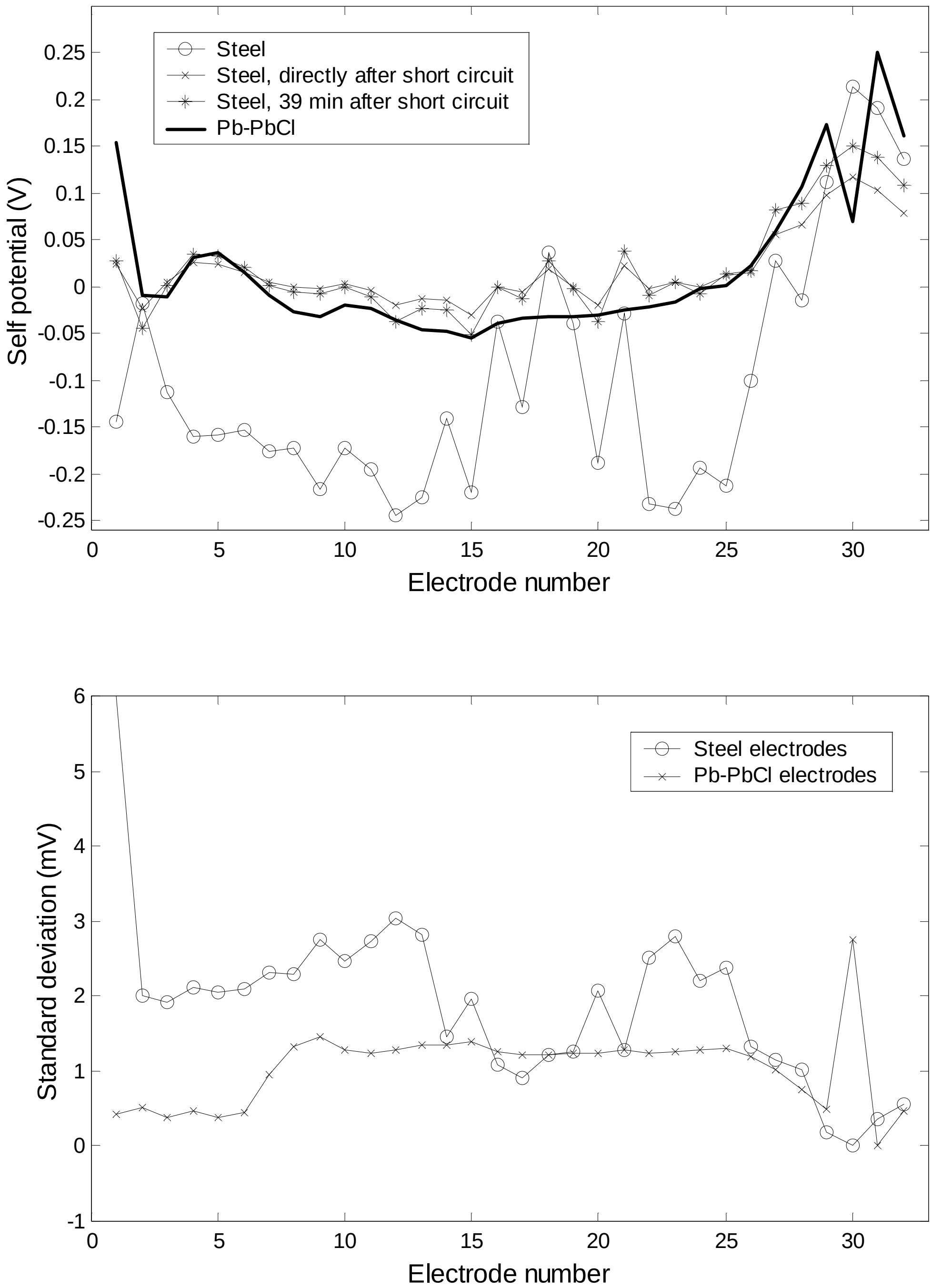

Figure 7 Measured SP on the main dam (upper plot) and standard deviation of the data (lower plot)

Figure 8 shows SP-data from the dyke of the dam. Only steel electrodes are available on this part of the dam, and hence no direct estimate of polarisation effects is possible. It is reasonable to assume, though, that geological conditions are not radically different, and that similar problems should occur at both locations. The presence of a pronounced short wavelength component corroborates this hypothesis, but it should be verified by short-circuit experiments similar to those on the main dam.

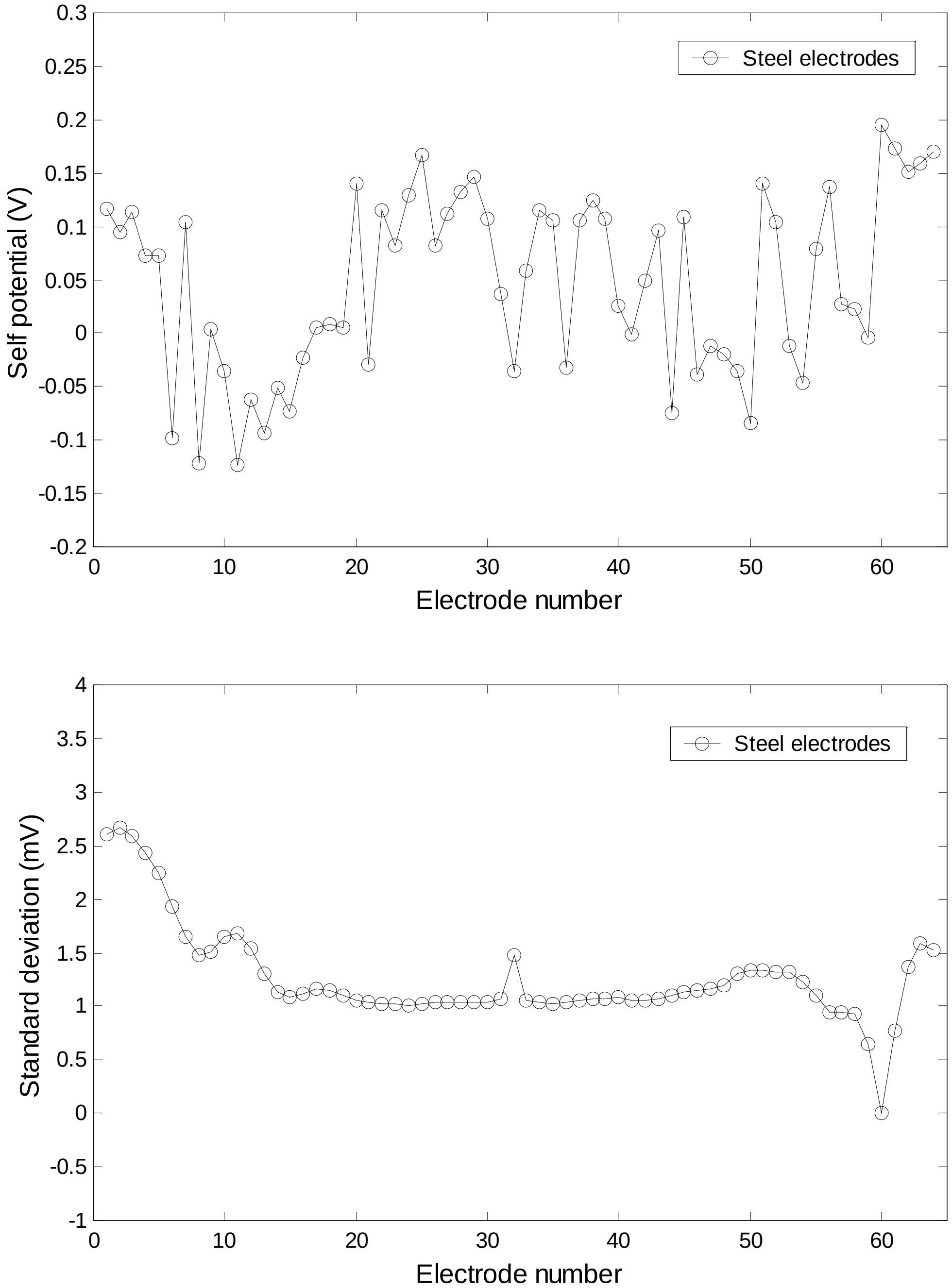

Figure 8 Measured SP on the dyke dam (upper plot) and standard deviation of the data (lower plot).

6 Monitoring of temperature and strain using optical fibres

6.1 Measurement processes

When light is launched down an optical fibre, a small fraction is scattered back towards the source. This light is formed of three principle components, which are separated in wavelength: Rayleigh light, Brillouin light and Raman light. Rayleigh light is not significantly changed by strain and temperature and may be used for referencing and loss measurements. The Raman light power depends upon the temperature at the point at which the light was generated, and so may be used for temperature measurement. The power of Brillouin light also depends upon temperature whereas the frequency shift of the Brillouin light depends upon both temperature and strain. Thus, provided both the amplitude and frequency shift of the Brillouin light can be measured, temperature and strain can be simultaneously determined, see Figure 9. Also, as pressure can be converted into strain in the fibre, the Brillouin technique may be used to simultaneously measure temperature and pressure.

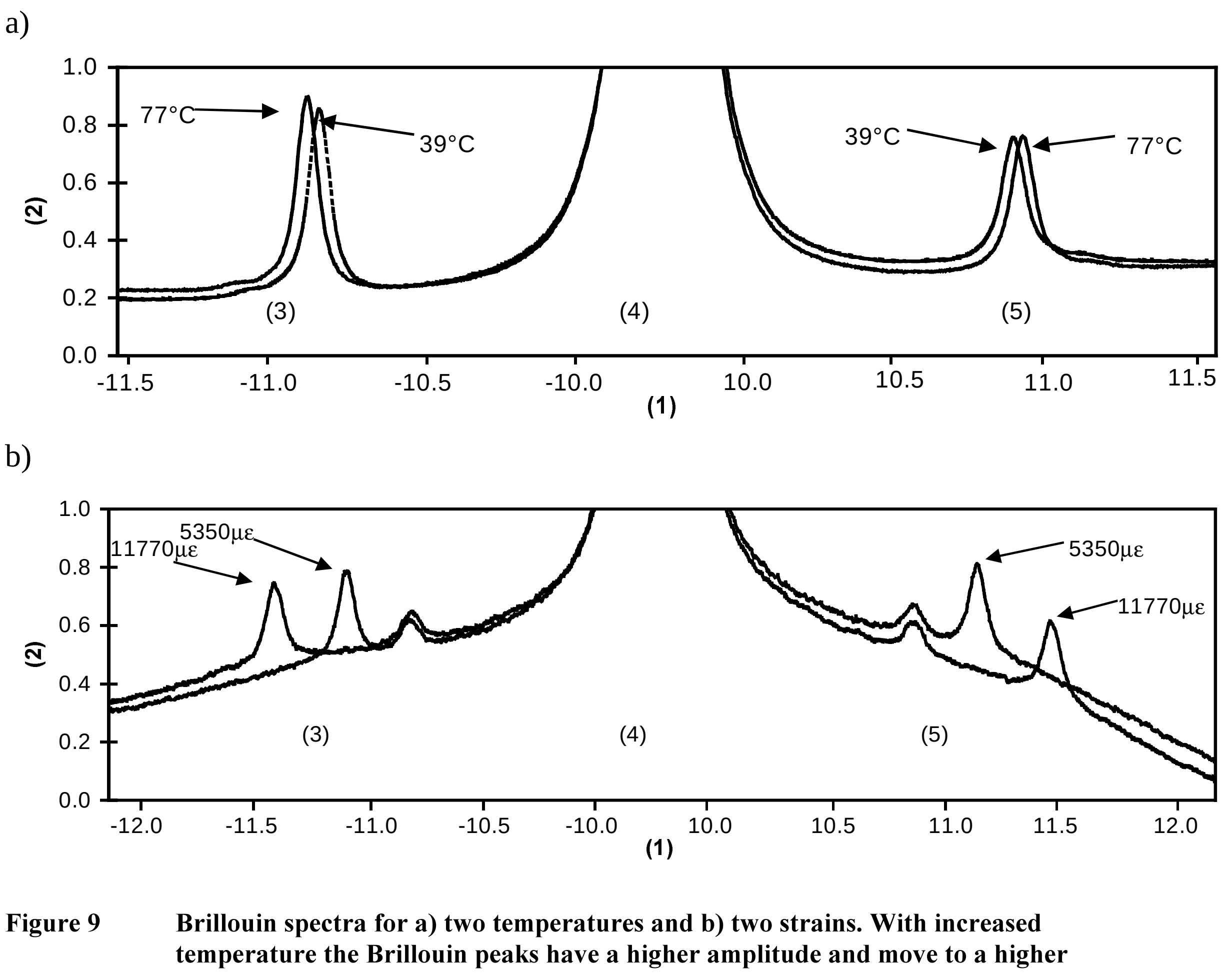

Figure 9 **Brillouin spectra for a) two temperatures and b) two strains. With increased temperature the Brillouin peaks have a higher amplitude and move to a higher frequency. With increased strain, the peaks move to a higher frequency and there is a negligible change in amplitude.**

(1) frequency shift from centre (GHz),
(2) power (arbitrary units),
(3) Stokes peaks
(4) Rayleigh peaks
(5) anti-Stokes peaks

6.2 Temperature sensing

The most established distributed optical fibre sensing technique uses Raman scattering to determine temperature. Here, a pulse of light is sent into the fibre and the power of the weak backscattered light at the Raman wavelengths is recorded against time. Analysis of the Raman light powers gives the temperatures at all points along the fibre. The important parameters defining the performance of such a system are the spatial resolution, the temperature resolution, the measurement time and the sensing length. For example systems with a spatial resolution of 1m, temperature resolution of ±0.25°C, measurement time of 60 seconds and a range of a few kilometres are now commercially available.

6.3 Strain and temperature

Raman light can be used to measure temperature, however the Raman signal is insensitive to the axial strain in the fibre. To measure strain, Brillouin scattering is used. This has the advantage of having a higher signal level than that of Raman scattering, but requires more care in the system design as it is necessary to measure the frequency, as well as power, of the Brillouin signal. The Brillouin frequency depends upon the strain and the temperature of the fibre. For isothermal conditions, it is possible to determine the strain of the fibre by measuring the frequency alone, however, in most cases, it is necessary to have some other means of determining the temperature of the fibre. This can also be achieved using Brillouin scattering since the power of the Brillouin light depends linearly upon the temperature of the fibre (and negligibly upon the strain of the fibre). By measuring the Brillouin power, then, it is possible to determine the temperature and use this to correct for temperature cross-sensitivity in determining the strain from the Brillouin frequency.

6.4 Pressure and temperature

Changing the pressure around a fibre induces a strain in the fibre. In this way, the technique described above can equally be used to determine pressure and temperature. The only difference between the two systems would be in the way the fibre is installed. For strain and temperature measurement, the fibre should be attached to, or placed within, the structure whereas for pressure measurement, the fibre should be loose and immersed in the fluid whose pressure is to be determined.

6.5 Installation at Sädva

Two fibre-optic cables for temperature and strain measurements were installed at the dam crest. The temperature measurements will, in this case, be used for studies of thermal behaviour at extreme weather conditions, especially freezing/thawing problems. Strain measurements will be used to detect relative movements in the dam. The measurements are planned to start in year 2000.

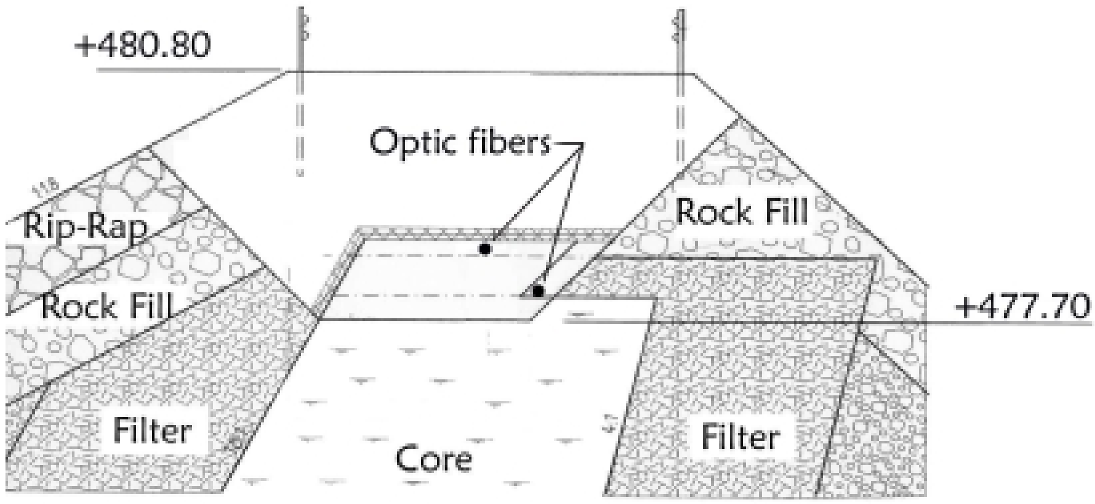

Figure 10 Location of the fiber optic cables at the crest of the dam.

Figure 11 Installations at Sädva.

6.6 Laboratory experiments

A prototype system is being developed that comprises a box containing the optics, power supplies and some electronics connected to a PC that controls the system and analyses and stores the data. The unit is currently operational as a laboratory system and some initial tests have been conducted to establish which are the optimum components to use for the prototype system.

Initial experiments (see Figure 10) showed the feasibility for measuring strain and temperature in an optical fibre, see (Parker et al 1999). More recent measurements demonstrated a temperature resolution of 2.5°C and a strain resolution of 50με for a sensing length of 500m, a measurement time of 5minutes and a spatial resolution of 10m. These experiments have allowed us to ascertain which are the weak points in the system and what components need to be replaced to improve the system performance. It is predicted that for a sensing length of 500m, a measurement time of 5minutes and a spatial resolution of 10m, it should be possible to obtain resolutions of 0.1°C and 2με. If the sensing length were increased to 2km, the resolutions are predicted to become 0.2°C and 4με.

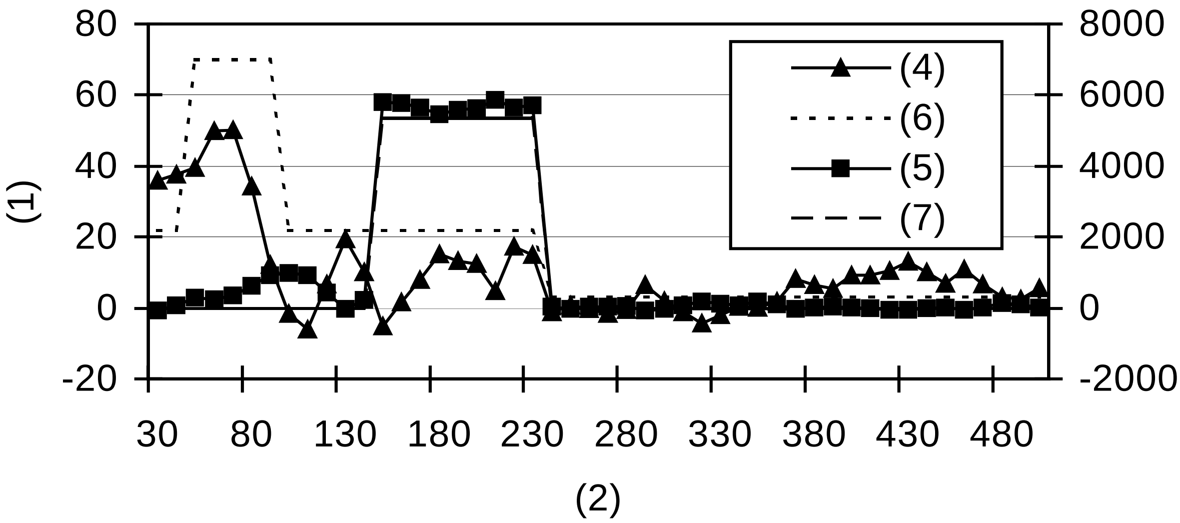

Figure 12 **Preliminary distributed simultaneous, independent measurements of temperature and strain (from Parker et 1997)**

(1) temperature (°C)
(2) distance (m)
(3) strain (με)
(4) measured temperature (°C)
(5) measured strain (με)
(6) actual temperature (°C)
(7) actual strain (με)

7 Conclusions

The resistivity measurement tests clearly showed that very good electrode contact was achieved at the installation, and the measured data exhibits low noise levels. These results show that the installation of the electrodes inside the upper part of the dam core can be an efficient way to avoid the data quality problems experienced along the dam crest at Hällby (Johansson and Dahlin 1998).

The anomalous patterns at the ends of the main dam inverted resistivity sections are not due to poor data quality, but are rather due to geometrical effects at the bend of the dam or strong contrasts in material properties within the dam. This can be caused by e.g. metal objects and concrete structures inside the dam. Apart from these effects the results are consistent between the tested electrode arrays, bearing in mind the differences in sensitivity between the arrays.

The resistivity structure within the main dam is rather homogeneous, whereas there is a larger variation within the dyke, which can be interpreted as a larger variation in material properties in the latter case. There is also a significant variation in inverted resistivities below the foundation level of the dam, which is interpreted as a variation in rock type or rock quality.

The SP data recorded at Sädva appear very stable, probably because of the near ideal environment for the electrodes. Initial electrode tests, however, indicate that strong polarisation effects may be associated with the use of stainless steel electrodes, so the results should be interpreted with caution.

The development of fibre optic systems for temperature, strain and pressure, is promising. The installation made at Sädva will be used to test temperature and strain measurements at realistic field conditions.

The monitoring sensors that are installed at Sädva are easy to install and seems to be appropriate for dam monitoring. Similar installations should therefore be considered also for other dams where similar construction works.

8 Acknowledgements

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