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Resistivity and SP Surveying and Monitoring at the Sädva Embankment Dam, Sweden

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ABSTRACT: Initial monitoring trials of resistivity and self potentials (SP) in order to study the seepage through dams, was carried out in the Sädva embankment dam, Sweden. A portable surveying equipment was connected to electrodes that were installed in the dam in 1999. The SP study (including a downstream and offshore survey) showed quite smooth variations. Most anomalies could be related to known features of the dam construction. The result gives basic information of the geo-electric situation, essential for future evaluation. The resistivity study comprised measurements at two different times (October 1999 and June 2000). The data sets are of good quality thanks to good electrode contact and stable conditions. Most parts of the resulting sections show low seasonal variation whereas there are some areas with larger variation, notably on the dyke. An automatic monitoring system will be installed in 2001 within a research project. Daily data will then improve the possibilities for interpretation and seepage evaluation.

1 INTRODUCTION

Internal erosion is one of the major reasons for embankment dam failures. To improve dam safety in this aspect, there is a need to develop more sensitive and fully covering monitoring systems. Such monitoring systems should be possible to install in existing dams, and be able to detect small seepage changes, as well as anomalous leakage. Experience from research and field installations carried out in Sweden since 1993, shows that monitoring systems based on resistivity and streaming potential (SP), may be able to meet this need. Resistivity and SP measurement are monitoring techniques under development, which have the advantage of being essentially non-destructive. This is particularly important when working with embankment dams where drilling and other penetrating investigations are normally avoided. In the evaluation of repeated measurements, the focus is on discovering and locating zones of larger change and variation in time within the dam core, and less consideration is given to absolute values.

Installation of electrodes for resistivity and streaming potential (SP) measurements was done at the Sädva dam in 1999, as part of research aiming at the further development of the monitoring techniques used at Hällby dam since 1996. A monitoring system, which automatically acquires daily resistivity and SP data, will be installed during the early part of year 2001.

The results from an upstream (offshore) and downstream (land based) SP survey are presented. The survey was carried out to provide baseline information for evaluation of the SP monitoring data.

Furthermore, the paper describes the first results measured on the electrodes of the permanently installed monitoring system. Data from two different times of the year are compared, the first from October 1999 and the second from June 2000.

2 SITE DESCRIPTION

2.1 *The Sädva embankment 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 dyke along the old river channel, see Figure 1. The core is made of moraine and is slightly inclined as shown in Figure 2. The maximum height is 32m. The upper and lower retention levels are 477.00m and 460.70m respectively. The main dam is founded on bedrock, while the dyke is founded on moraine, except where it connects to the main dam.

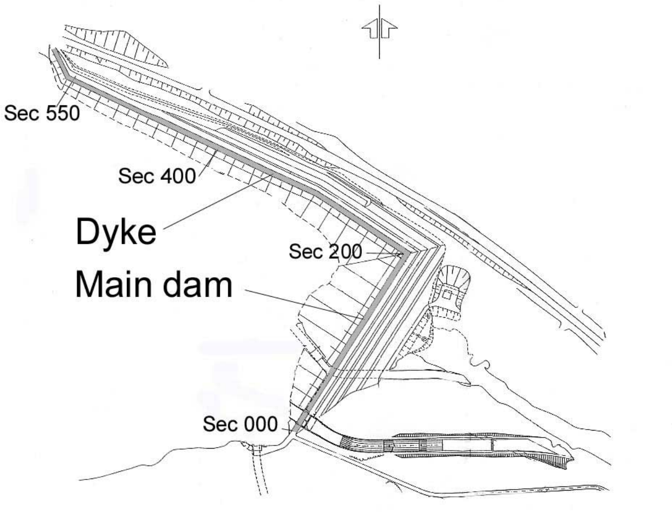


Figure 1. Plan over Sädva dam (1) Main dam with both resistivity and SP electrodes (2) Dyke with resistivity electrodes.

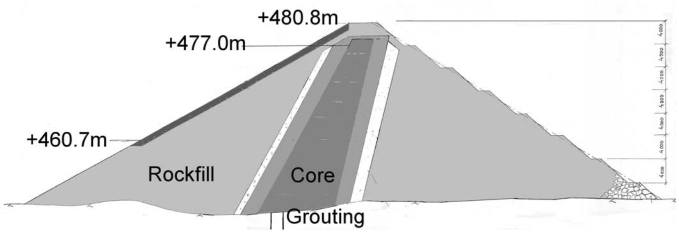


Figure 2. Cross section of the Sädva dam.

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 (Johansson et al. 2000).

2.2 *Installations*

A correct electrode type and a proper installation are fundamental for all electric measurements. Based on the experience from the Hällby dam (Johansson and Dahlin 1998) it was decided to use stainless steel electrodes for the resistivity measurements. However, it was decided also to install non-polarisable electrodes for the SP-measurements on the main dam. This would allow comparisons between the different electrode types.

The electrodes were installed on the original core crest, about 2.1m below the dam crest. An insulation layer was placed on the top of the core to prevent it from freezing, see Figure 3.

The resistivity electrodes consist of 0.25m x 0.25m stainless steel plates. The electrodes are connected to polyurethane (PUR) covered stainless steel wires, Figure 4, which are joined to cables splits (pig-tail splits) on a PUR covered multi core cable.

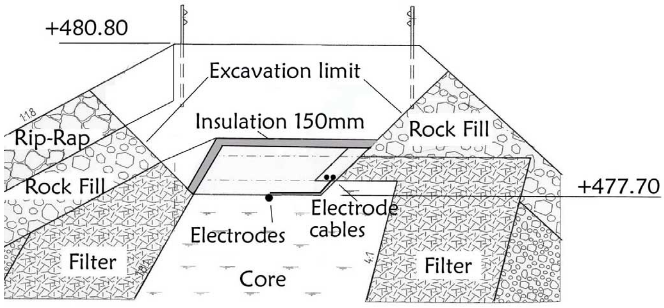


Figure 3. Installation of the electrodes and cables on the dam crest at Sädva.

Figure 4. Installation of resistivity electrodes.

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 5.

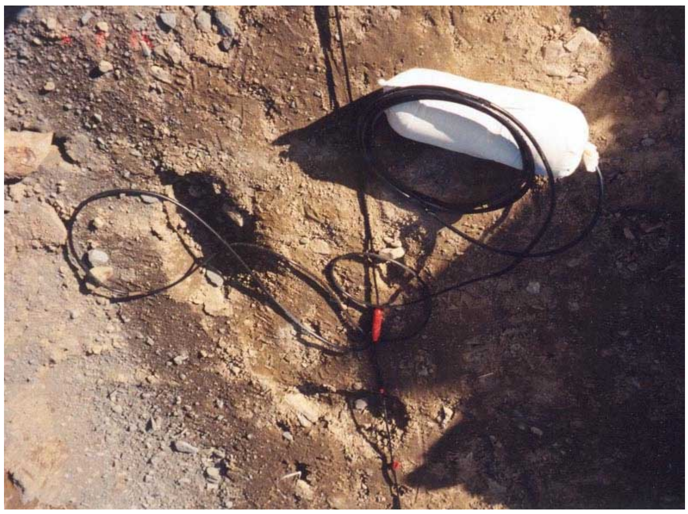


Figure 5. Installation of SP electrodes.

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.

A spacing of 6m between the electrodes was chosen for the entire dam. The total number of electrodes is 128. The special SP-electrodes were 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.

3 SELF POTENTIAL (SP) MEASUREMENTS

3.1 *Data acquisition*

The self potential survey was carried out primarily to provide a baseline for the interpretation of the future monitoring data. However, the data also serve to put the spatially limited SP monitoring data on the dam into a larger geo-electrical context. The reservoir elevation at the time of the land survey as well as the offshore survey was 476m. Both surveys can consequently be considered high pool surveys.

Land data was acquired along 13 profiles, using the potential mapping method with the permanently installed copper-copper sulphate electrode #9 on the main dam as reference. The end points of the profiles were positioned using differential GPS measurements, and the stations along the profile were located with a tape measure. Station separation was 5 metres. The roving electrodes were ordinary rugged copper-copper sulphate electrodes manufactured for the occasion. Voltages were measured using a Lawson Labs AD201 A/D-converter adapted for field use.

Offshore data was acquired through the gradient method, where a 5-metre, and a 10-metre dipole were towed after a boat on the reservoir. The electrodes used were commercial, sealed, silver-silver chloride reference electrodes. They were towed at a depth of 1 metre. The location of the boat was determined by differential GPS, and the distance between the boat and the dipole was measured with a special hydroacoustic transponder system. Dipole positions were consequently found by combining these data sets. Voltages were registered every second, corresponding to a distance between observation points of about 1m.

During the land survey, the telluric activity was monitored, by registering the variation of the potential difference across two fixed, approximately perpendicular dipoles. One dipole was located on the main dam (permanent copper-copper sulphate electrodes, dipole length 144 m.); one was located on the dyke (permanent stainless steel electrodes, dipole length 150 m.). Two high-impedance multimeters registered the voltages every two seconds.

Telluric monitoring during the offshore survey was similar, but it employed temporary installed perpendicular 50-metre dipoles, located just past the northwest end of the dyke, instead. Copper-copper sulphate electrodes were used for these. Voltages were registered every second.

3.2 *Data processing*

The telluric monitoring was performed to allow correction of the observed self potentials. The amplitude of the telluric activity was, however, so small that this step was considered unnecessary. During the land survey the telluric variation never exceeded 3 mV/100m, and during the offshore survey the variation was below 10 mV/100 m.

The offshore SP gradient values obviously depend directly on the direction of the dipole at the time of observation. Since the profiles were run in several directions, we therefore calculate the absolute value of the gradient before presentation. Attempts to use numerical integration of the gradient data to yield absolute SP values proved unsuccessful, probably because of limitations in the accuracy of the positioning of the survey boat. The two data sets for the 5- and 10-metre dipoles are very similar; hence only data from the 10-metre dipole survey will be presented here.

3.3 *Results and interpretation*

Figure 6 shows a contour map of the SP land data.

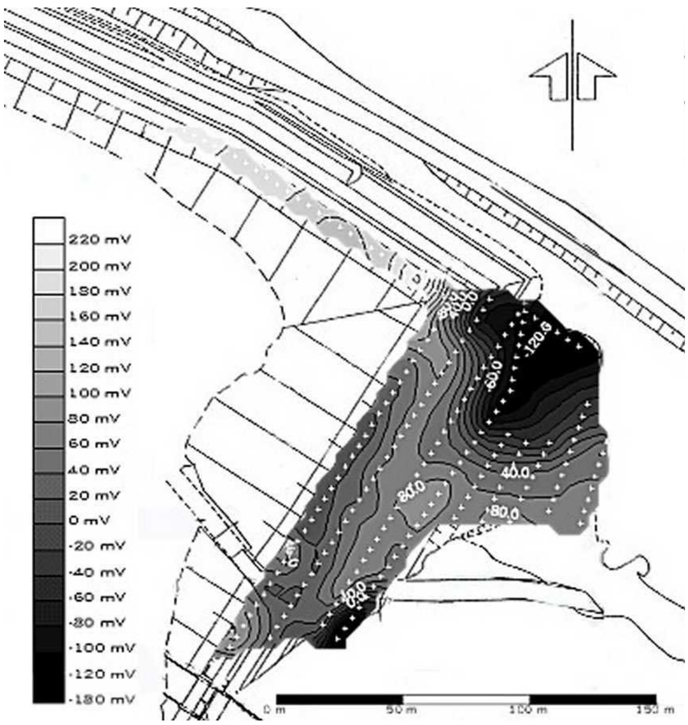


Figure 6. Contour map of SP potential land data.

The data from the permanently installed copper-copper sulphate electrodes are not included, although they agree well with data from the profile on top of the main dam, see Figure 7. The reason is that the permanent electrodes are buried, which means that only qualitative comparisons between the data sets are possible. The similarity verifies that both data sets apparently reflect the same subsurface structures or processes.

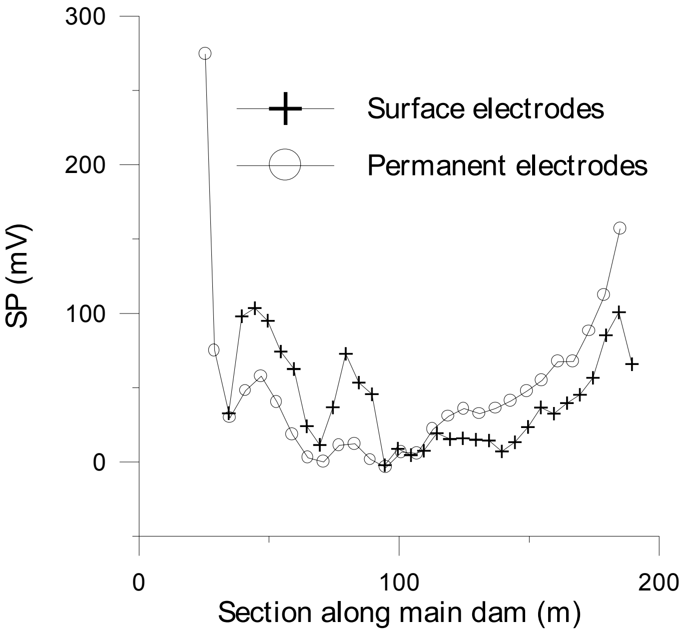


Figure 7. Comparison of SP data on the main dam. Open circles denote measurements on the permanently installed electrodes, crosses show results of surface measurements.

Simple kriging interpolation was used to create a regular grid of data before contouring. The map shows that the variation of the self potentials in the area is very smooth. All notable anomalies can likely be traced to construction elements in the dam. The concrete spillway near the southwest end of the surveyed area causes a distinct positive SP anomaly that extends sideways in both directions from it. Likewise, the sharp SP gradient near the knee of the dam is associated with a buried concrete structure. The large negative anomaly in the northeast corner of the area, however, is probably, at least partly, caused by the topography. The northernmost parts of the profiles that define this anomaly all go uphill, and high points in the topography are often associated with negative SP anomalies.

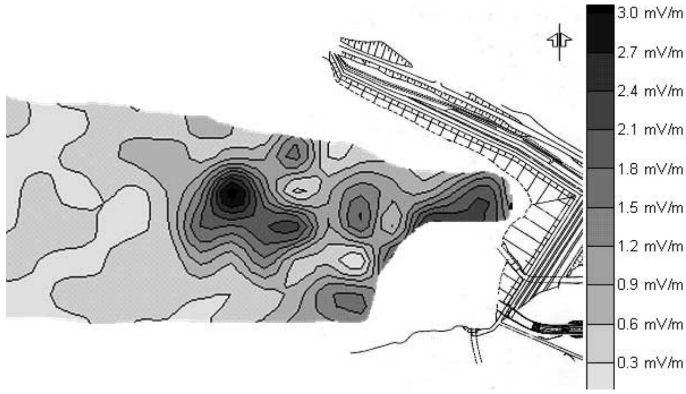


Figure 8. Contour map of SP gradient offshore data.

The results of the offshore SP survey using the 10-metre dipole is shown in the contour map of Figure 8. The area in the vicinity of the intake was not surveyed since it was not considered safe to navigate that area. There is a general increase in the magnitude of the SP gradient towards the dam itself, much as expected. A strong local maximum in the middle of the map turned out to be well correlated with a minimum in the water depth of the reservoir.

4 RESISTIVITY MEASUREMENTS

4.1 *Data acquisition*

Data acquisition was carried out using a modified version of the ABEM Lund Imaging System, a multi-electrode data acquisition system (Dahlin 1993; Dahlin 1996). It consists of an A/D-converter (Lawson Labs AD201), a current transmitter (Booster SAS2000), a relay switching unit (Electrode Selector ES464) and a computer with a modified version of the control software Eric.

The data acquisition process is completely controlled by the software, where the software scans through the measurement protocols selected by the user. The configurations tested so far were Wenner, Schlumberger and dipole-dipole, where reciprocal measurements were also carried out in order to assess the measurement errors. Since the electrodes are permanently installed in the dam core, the electrode cables just needed be connected to the switching unit before the measurements could proceed.

Data has so far been acquired in October 1999 and June 2000. Reservoir level elevations differ 4m between the two occasions (473m in October 1999 and 469m in June 2000). The measurements were carried out on the main dam as well as the dyke. The measurements were done using 200mA measurement current in October 2000, giving very stable data. In June 2000 the measurements on the main dam were carried out using a current of 100mA, it was not possible to transmit more, which might have been due to a partially frozen top part of the core. However, the current transmitter used broke down due to old age during the survey, and it is quite possible that it started sending erratic current before. After the breakdown, the measurements continued with an ABEM Terrameter SAS300 that was brought along as back up, which was slower and only allowed transmission of 20mA current. As time was running out Wenner and Schlumberger data on the dyke was measured without stacking the data, only one sample was taken for each data point to allow both normal and reciprocal data to be measured, and no dipole-dipole data.

The data quality was evaluated by calculating the measurement errors from the difference between normal and reciprocal measurements. Reciprocal measurements are carried out by using the potential electrodes for transmitting current and vice versa. In theory, this should give identical results, and differences are due to measurement errors. The data quality for the Wenner data is presented in Table 1. It can be noted that the data quality for the main dam is inferior in June 2000 compared to October 1999, which is more pronounced for the dipole-dipole array (not shown). There is also a slight difference in data quality for the side dam data, but it is still of very good quality considering that it was measured using a current of 20 mA only and no stacking of the data (Table 1).

Table 1. Data quality for Wenner data expressed as observation error in percent estimated from reciprocal measurements.

Data set	Main dam 1999/2000	Dyke 1999/2000
No of data	155/155	534/531
Maximum	3.1/12.5	0.6/1.7
Mean	0.5/2.8	0.0/0.3
Median	0.3/0.9	0.0/0.2
Std. Deviation	0.6/3.4	0.1/0.3

4.2 *Data processing*

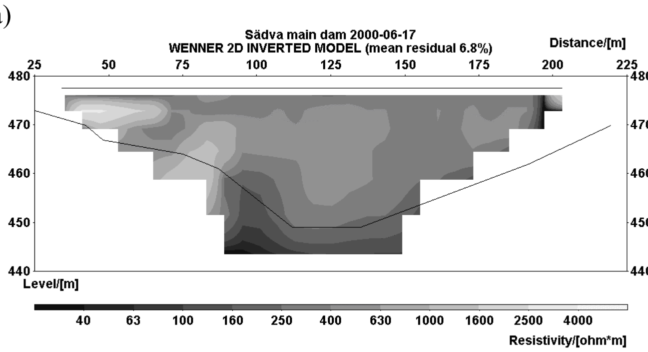
The true resistivity structure was interpreted using 2D smoothness-constrained inverse modelling (inversion), where the inversion program Res2dinv (ver 3.50w) was employed (Loke 1999a). In the inversion 2D structures are assumed, i.e. the ground properties are assumed constant perpendicular to the line 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 minimising the residuals between model response and measured data. Either the absolute differences (L1-norm) or the squares of the differences (L2-norm) are minimised. The smoothness constrain prevents unstable and extreme solutions.

The corresponding data sets of the different times of surveying were inverted jointly, with smoothness constrain applied not only on the spatial variation but also on the temporal variation between the data sets, so called time-lapse inversion. This approach has been shown to focus the difference between the models on the actual change and suppress artefacts due to the resistivity structure (Loke 1999b).

4.3 *Results and interpretation*

The inverted sections for the main dam gave relatively moderate variation within the depth ranges of the dam. The Wenner and dipole-dipole resistivity sections are shown in Figure 9a and Figure 10a, and the results are quite similar in character. Both array types gave model residuals around 6-7% in the inversion. Anomalous patterns are seen in each end of the section, but these are most likely due to disturbances from the reinforced concrete structure, and geometric errors in the electrode layout at the end of the line. These disturbances are not manifested in an identical way for the two array types, which can be explained by different sensitivity patterns for the different arrays.

a)



b)

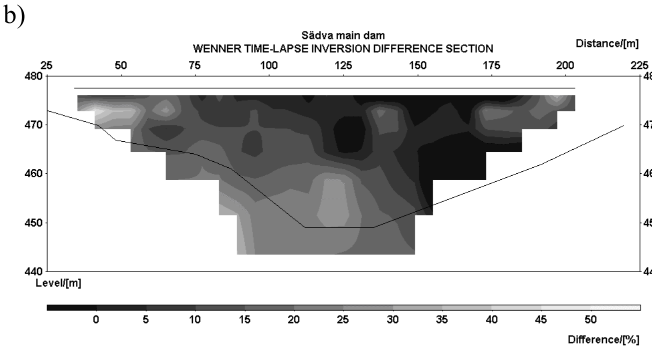


Figure 9. Sädva main dam Wenner model sections with foundation level indicated (solid line), a) resistivity, b) variation.

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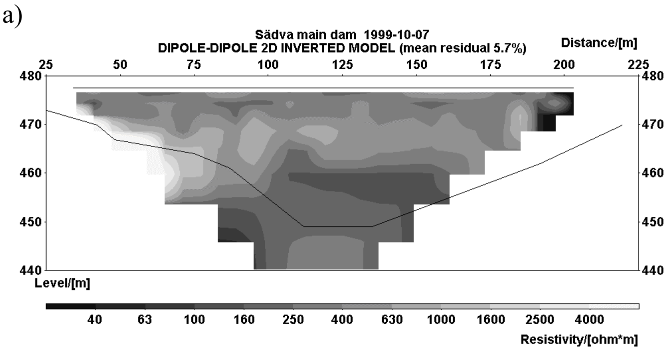
a)



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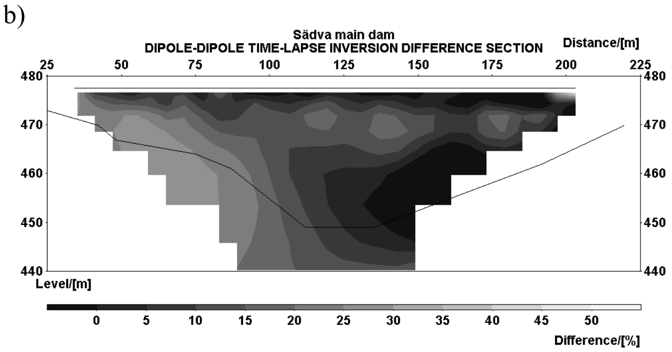
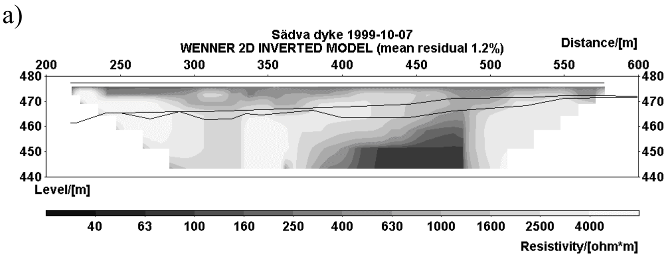


Figure 10. Sädva main dam dipole-dipole model sections with foundation level indicated (solid line), a) resistivity, b) variation.

a)



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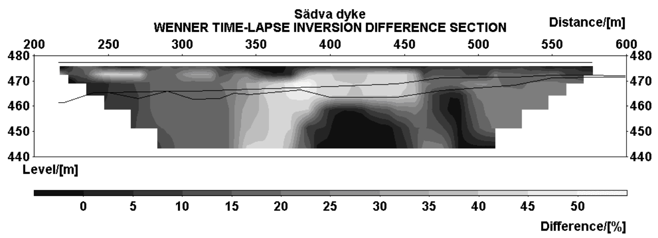

Figure 11. Sädva dyke Wenner model sections with foundation and bedrock level indicated (solid lines), a) resistivity, b) variation.

The consistent appearance of the resistivity distribution of the main dam indicates that it is rather homogeneous. 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 or effects from metal objects.

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.

The time variation for the main dam (Figure 9b and Figure 10b) is also most pronounced along the left edge from top to bottom of the model sections, where it reaches above 30%. There is also a band around 5 metres depth with variation in the range 10-20%, which may be related to the difference in reservoir level. Otherwise the variation is mostly less than 10%.

There is significant variation in properties along the embankment, which can be interpreted as larger variation in material properties than in the case of the main dam, see inverted Wenner section in Figure 11a. 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 Wenner and dipole-dipole results are quite similar. In this case inversion gave much lower model residuals for the Wenner array (1.2%) than for the dipole-dipole array (5.2%).

There is a large zone of high variation (>30%) between section 340m and 460m on the dyke. In section 375m to 460m the high variation reaches roughly down to the rock level, whereas there is a much deeper zone centred around 360m. There are also more limited and shallow high variation zones at approximately 240m to 280m, and 300m to 325m, centred around 5 metres depth. These shallow zones may also be associated with changes in reservoir water level between the two occasions. An elevated variation is also indicated for depths above 10m at the end of the line.

5 DISCUSSION AND CONCLUSIONS

The self potential surveys show that the variation is quite smooth in the area. The few significant anomalies found in the land data correlate well with known features of the dam construction. The major anomalies in the offshore data turn out to be well correlated with the depth of the reservoir. From a seepage investigation point of view, the SP data are fairly inconclusive. Additional surveys at different reservoir elevations, or preferably long-time monitoring will be necessary to identify any seepage related SP-anomalies.

The resistivity measurement tests clearly showed that very good electrode contact was achieved at 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 high electrode contact resistance. Data quality and bad electrode contact was a problem along the dam crest at Hällby dam (Johansson and Dahlin 1998). Despite having only measured on two occasions it appears as if these problems will not be repeated in Sädva. A possible reason might be the placing of the electrodes, which was done at 2.1m depth in Sädva whereas electrodes in Hällby were placed only 1m beneath the crest. Furthermore the electrodes in Sädva are located below a thermal insulation layer, which is not the case in Hällby.

The anomalous patterns at the ends of the main dam inverted sections are not due to poor data quality, as shown by the error analysis, 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 resistivity values below the foundation level of the dam, which is interpreted as a variation in rock type or rock quality. Variations in the shallow areas may be explained by a difference in reservoir elevations between the two monitoring occasions. Generally, effects from reservoir water level and possible 3D effects ought to be more carefully studied to make future interpretations easier.

The monitoring equipment that is installed at Sädva is 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 are to be carried out.

6 ACKNOWLEDGEMENTS

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