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INVESTIGATION OF GEOPHYSICAL METHODS FOR ASSESSING SEEPAGE AND INTERNAL EROSION IN EMBANKMENT DAMS:

A GUIDE TO RESISTIVITY INVESTIGATION AND MONITORING OF EMBANKMENT DAMS

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INVESTIGATION OF GEOPHYSICAL METHODS FOR ASSESSING SEEPAGE AND INTERNAL EROSION IN EMBANKMENT DAMS

Tasks 1&2 – SP & Resistivity

- Self-Potential Field Data Acquisition Manual [T992700-0205B /1]
- Laboratory Testing of the Streaming Potential Phenomenon in Soils [T992700-0205B /2]
- SP3D Software Package [Please contact us for more details]
- SP Interpretation Manual [T992700-0205B /3]
- Resistivity Investigation and Monitoring Manual [T992700-0205B /4]

Task 3 – Dam Crest Seismic Investigations

- Engineering Seismic Surveys at a Test Embankment Near Seven Sisters, Manitoba [T992700-0205D]

Task 4 – Through-Dam Seismic Investigations

- A Study of Through-Dam Seismic Testing at WAC Bennett Dam [T992700-0205E]

Task 5 – Temperature Evaluation

- DamTemp Software Package [Please contact us for more details]

Task 6 – Parameter Study

- A Parameter Study for Internal Erosion Monitoring [T992700-0205A]

Task 7 – Monitoring Study

- Long-Term Resistivity and Self-Potential Monitoring of Embankment Dams – Experiences from Hällby and Sädva Dams, Sweden [T992700-0205C]

This volume marks one of a series of reports on the subject of geophysical methods and their use in assessing seepage and internal erosion in embankment dams. These reports are available from CEA Technologies Inc. (CEATI) both separately and as a package.

ABSTRACT

The resistivity method is an established geophysical method with a broad range of engineering and environmental applications. It has been tried numerous times on embankment dams, mainly for seepage investigations, dam status control and investigations of known defects. In previous use of the method on embankment dams some success has been reported, but only occasionally. The method is still not completely adapted to customary industrial use, although there is rapid progress.

The purpose of this guide is to help the user to optimize use of the resistivity method for dam status control and dam seepage investigations. To this effect, the guide covers resistivity survey design, equipment, data acquisition and other practical issues. The guide includes a few recent examples of the method being used both for investigation and for long-term monitoring, and also briefly covers theoretical discussions on the method. It is assumed that the reader of this guide is acquainted with basic theory of geophysics and knowledge about design and function of embankment dams.

Keywords:
Resistivity method, Embankment dams, Geophysical investigations

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Dedication: This report is dedicated to the late Gary Salmon who passed away in October 2007. Gary was a well respected professional, with over 30 years of experience in the field of Dam Safety. After 32 years at BC Hydro, he retired as Director of Dam Safety, but continued his work as an international consultant. Gary was among the co-founders of the Dam Safety Interest Group (DSIG) in the early 1990's and led the DSIG as its Technology Coordinator for over 10 years. Since the very beginning, he served as a tremendous resource to both CEATI and DSIG participants.

EXECUTIVE SUMMARY

The resistivity method is an established geophysical method with a broad range of engineering and environmental applications. It has been tried numerous times on embankment dams, mainly for seepage investigations, dam status control and investigations of known defects. In previous use of the method on embankment dams some success has been reported, but only occasionally. The method is still not completely adapted to customary industrial use, although there is rapid progress.

The purpose of this guide is to help the user to optimize use of the resistivity method for dam status control and dam seepage investigations. For this purpose the guide covers resistivity survey design, equipment, data acquisition and other practical issues. The guide includes a few recent examples, where the method has been used both for investigation and for long-term monitoring. To get the full picture, the guide also briefly covers theoretical discussions on the method. It is assumed that the reader of this guide is acquainted with basic theory of geophysics and knowledge about design and function of embankment dams.

The method can be used in two ways. Firstly, resistivity investigations as a one time survey may detect spatially anomalous zones along the dam, and can be used to investigate suspected structural weaknesses. Secondly, long-term resistivity monitoring make use of the seepage-induced seasonal variation inside the embankment to detect anomalies not only in space, but more importantly in time, by studying deviations from the time-variation pattern. The second approach is more powerful as repetition of measurements provides additional evaluation possibilities for seepage analysis.

The use of the resistivity method on embankment dams can be challenging and the anomalies are often small. Complicating factors for interpretation, such as for instance complex dam geometry, plentiful noise sources, rather small signals and reservoir level fluctuations are discussed. Advantageous factors for the method are also mentioned. These include it being non-destructive, the possibility to cover large volumes, the possibility to install on existing dams and the sensitivity of the method to changes in material properties and seepage flow among others.

The monitoring approach is based on the principle that the resistivity in an embankment dam varies seasonally, mainly due to variations in temperature and ion content of the seepage water. Both these parameters vary seasonally, and their variation in the dam depends on the seepage flow. This implies that areas in the dam with larger seepage may stand out as areas with larger seasonal resistivity variation, and increasing seepage may be noticed as increasing variations. Moreover, material change due to washout of fines may be detectable through resistivity measurements, implying that trends of changing resistivity over time may relate to internal erosion.

This guide also discusses practical aspects of performing resistivity measurements on dams. Most common is still to perform 2D-measurements using an array of electrodes placed along a line. The complex geometry of the dam leaves two options, i.e. measurements where the survey line is placed along the dam, usually along the dam crest, or measurements where the survey line crosses the dam axis. The latter is often difficult to conduct in practise but whenever possible, it is a good complement providing detailed information in a specific part of the dam. Using a survey line along the dam is the most straightforward option and provides information on a larger part of the dam,

although less detailed. The final choice of survey design should always depend on site-specific conditions.

Standard resistivity surveying equipment is used for dam investigations. For repeated measurements it is advisable to leave the electrodes in the ground between measurements. It is essential to make sure that good electrode contact is provided, especially in the case of permanent installations where the contact can often not be improved after installation works are completed. Processing of resistivity data includes data quality assessment, inverse numerical modelling and presentation and analysis of the results. Data quality is preferably checked in the field, typically by examining the pseudosection. Standard inversion packages may be used for data processing of 2D-measurements. Interpretation should be made with as much reference data as possible.

A few case studies from Scandinavia are briefly presented, and some other examples in literature are referred to. Based on experiences from the case studies it is confirmed that long-term monitoring is more powerful than one time surveys, which however still may be useful in many cases. Repeated measurements confirm that resistivity variations inside the dams are obvious. A zone with an increasing resistivity trend has been detected at one of the dams. This may be explained by ongoing internal erosion, which is supported by other observations, but has not been confirmed by direct investigations in the zone. Under good circumstances quantitative seepage evaluation from resistivity monitoring data can be performed.

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1.0 INTRODUCTION

Methods for monitoring seepage and internal erosion are essential for evaluating the safety of embankment dams. Internal erosion occurs progressively inside an embankment dam and is sometimes difficult to detect with conventional methods. It is of great value to detect internal erosion at an early stage, which is something that very few of the current methods can accomplish. Consequently, there is a need for new and improved detection methods.

The resistivity method is an established geophysical method with a broad range of engineering and environmental applications. It has also been tried numerous times for seepage investigations and dam status control. However, the breakthrough to become the industry standard has not occurred, which is likely a sign of the difficulty in using the method for this purpose. In previous use of the method on embankment dams only occasional success has been reported. The method is still not completely adapted for standard industrial practice, although rapid progress has been made.

The use of the resistivity method on embankment dams can be challenging. The anomalies are often small in relation to other engineering applications, such as materials exploration, landfills and site investigation in civil engineering projects, where the method is well established. Furthermore, embankment dams often provide relatively high noise levels and difficult site conditions. The geometry of embankment dams has also been found to be a complicating factor in the evaluation process.

Although there are numerous complicating factors, the resistivity method has some important advantages. It is a non-destructive method, which is particularly important on existing dams where intrusive investigations are avoided. It is an active geophysical method, as opposed to SP, magnetics, gravity and others. This means that the source signal can be varied and therefore it can be more easily adapted to suit specific site conditions. In addition, the method may be characterised as both primary and secondary when it comes to seepage detection investigations, as it is both directly sensitive to water flows and it may also indirectly detect seepage by detecting potential seepage paths regardless if water flow is occurring or not. The method responds to variations in temperature and ion content of the seepage water, which have a direct relation to seepage flow. Moreover, the method responds to changes in material properties (e.g. washout of fines affect dam core resistivities), which may be indicative of internal erosion.

When applied for dam safety examination, the resistivity method can be used in two principal ways. Firstly, a single set of resistivity investigations may detect spatially anomalous zones within the dam, and can be used to investigate suspected structural weaknesses. Secondly, long-term resistivity monitoring makes use of the seepage-induced seasonal variations inside the embankment to detect anomalies not only in space, but also more importantly, anomalies in time, by studying the pattern of resistivity variations over time.

The purpose of this guide is to help the user to optimize the use of the resistivity method for dam status control and dam seepage investigations. For this purpose the guide covers resistivity survey design, equipment, data acquisition and other practical issues. The guide includes a few recent examples, where the method has been used both for investigation and for long-term monitoring.

However, to get the full picture, the guide also briefly presents some theoretical discussions on the method. It is assumed that the reader of this guide is acquainted with basic theory of geophysics and also is familiar with the design and function of embankment dams.

The guide does not list the required equipment or measurement configurations. Standard mobile resistivity surveying equipment comes in a variety of equipment packages. However, considering the limited number of cases of permanent installations on embankment dams, standardised equipment and methodologies for embankment dam monitoring have not yet been established. Experience from the two monitoring systems at Hällby and Sädva dam may be seen as examples for further work in this area.

The main content of the guide is found in Sections 2-6. Section 2 presents a general level guide to the resistivity method. The information presented there can be found in any textbook on geophysics, but is added here to guide the reader who has no or limited experience in using the resistivity method. The method is widely used in many other engineering and environmental applications, but using the method on embankment dams involves some special adaptations to specific conditions. Some of these conditions are discussed in section 3. Section 4 covers data acquisition techniques and section 5 deals with data processing and inverse modelling. These last two sections (4 and 5) are quite specific and are intended to support the reader in performing field measurements on dams. The structure of the presentation in sections 4 and 5 has been influenced by the CEATI Self-Potential Field Data Acquisition Manual (Corwin 2005). Much of the field strategy is similar and independent of the geophysical method used. In section 6 three case studies are presented.

In summary, sections 2-3 may be regarded as background material, which is preferably studied before going into the field. Sections 4-5 together with appendix A are designed as a direct support for carrying out the field survey and may also be used in the field. One intention of this guide has been to provide the relevant information in a condensed format. For the interested reader, who wants to find out more in this subject, there are plenty of sources in the literature. A few such sources are presented in the reference list. Moreover, appendices B and C give some mathematical background and section 6 serves to increase the understanding of the method for dam investigations by illustrating differences between the selected case studies and drawing conclusion from these.

2.0 THE RESISTIVITY METHOD

The resistivity method is a non-intrusive method used for investigating subsurface conditions. Conrad Schlumberger conducted the first electrical resistivity field surveys at the beginning of the 20th century (Ward 1980). Ever since, the method has been developing and new applications continue to be identified. During the last few decades these developments have been particularly rapid, enhanced by the introduction of innovative and efficient instruments and the rapid development of readily available computational power. In this section, some background to the resistivity method and the basic principles behind it will be briefly described. Other publications give greater cover and a more detailed description on the fundamentals of the method (e.g. Telford et al. 1990; Parasnis 1997; Reynolds 1997; Sharma 1997).

2.1 Resistivity of Geological Materials

The resistivity of natural soils and rocks vary over a very wide range (Figure 2-1), and these differences in resistivity are the foundation of resistivity surveying. It is, however, essential to be aware of the large overlaps in resistivity between the different types of earth materials. As a result measured resistivities should never be interpreted directly as a certain material category without additional knowledge of the specific situation.

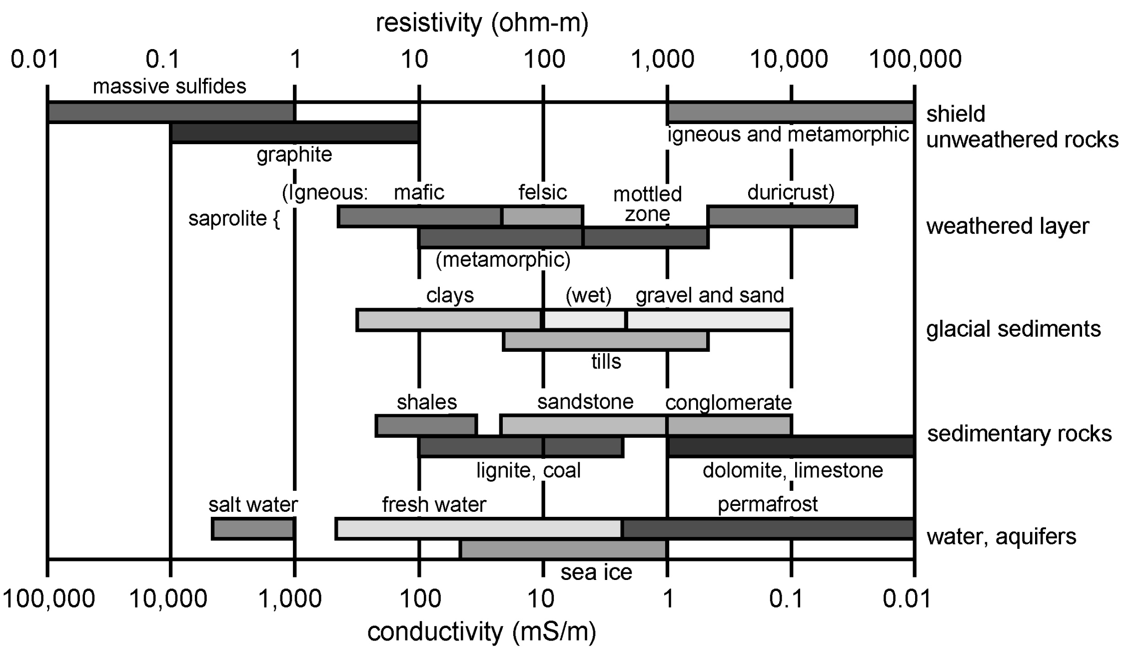


Figure 2-1 Resistivity of geological materials. (Modified from Palacky 1987)

The conduction of electrical current in geological materials is mainly electrolytic. The most common soil and rock forming minerals are insulators in the dry state, and thus the amount, distribution and properties of the water largely determine the resistivity.

For a rock mass this means that fractures, faults and shear zones constitute the dominating pathways for electrical current, whereas the solid rock normally is considered as an electric insulator. An exception is rocks with metallic content that may allow significant conduction through the crystalline structure.

Soils, on the other hand, are porous media consisting of a solid skeleton of particles, or grains, with pores in between. The grains are considered electrical insulators and the conduction is concentrated in the pore spaces that are typically filled or partly filled with water. Therefore the resistivities of soils are strongly influenced by the amount of water, which is determined by the porosity (Figure 2-2) and the degree of saturation. The resistivity of the water itself, to a great extent governed by the ion content, and the connectivity of the pore spaces are also important parameters. Another important factor influencing soil resistivities is the presence of clay minerals since these minerals bind water molecules and ions and thereby facilitate electrical conduction. 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 (e.g. Ward 1990; Revil and Glover 1997; Klein and Santamarina 2003). Therefore in the different models that have been used for describing resistivity of soils, there have been two categories depending on whether the soil has a clay content or not.

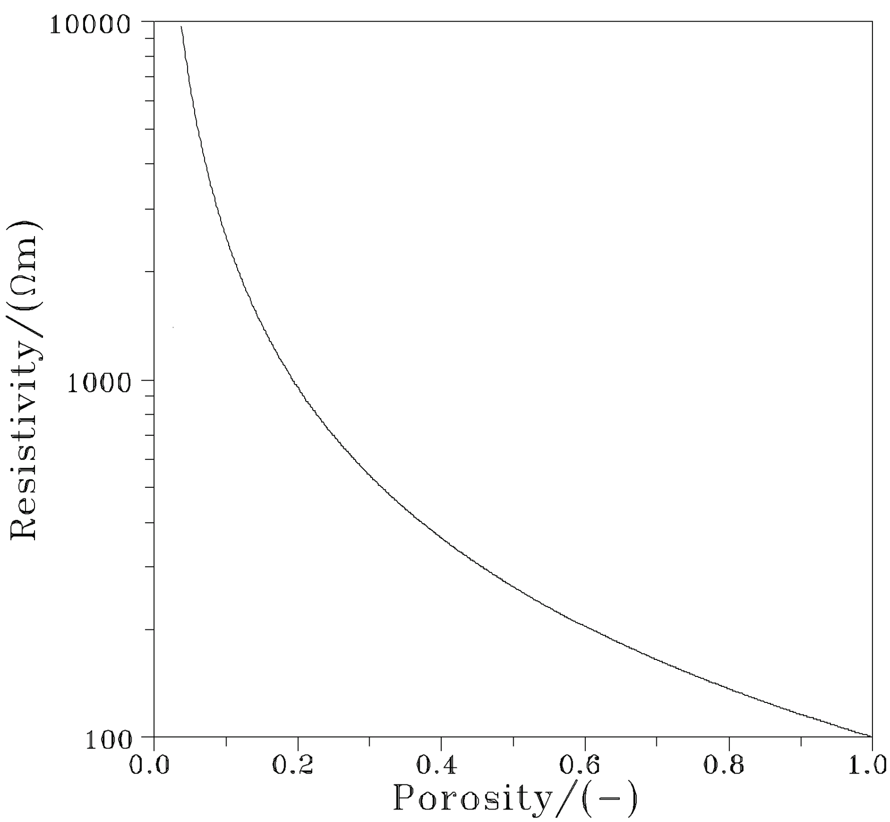


Figure 2-2 For clay-free soils and rocks, the resistivity depends strongly on porosity. (Modified from Dahlin 1993)

2.2 Resistivity Measurements

2.2.1 Measurement Principle

In the resistivity method an electrical current is introduced into the ground and the resulting potential distribution is measured. The most common resistivity systems use direct current, DC, or alternating currents, AC, with very low frequency. The method is also called DC-resistivity. Complex resistivity with alternating current at varying frequencies has not been used in this study and is not covered here. Some techniques use line electrodes or buried electrodes, but the most common method involves point electrodes on the surface. Typically one pair of steel electrodes is used to inject current and another pair is used to measure the potentials (Figure 2-3). This type of four-electrode measurement avoids erroneous influence on measurements from contact resistance at the interface between the electrode and the ground.

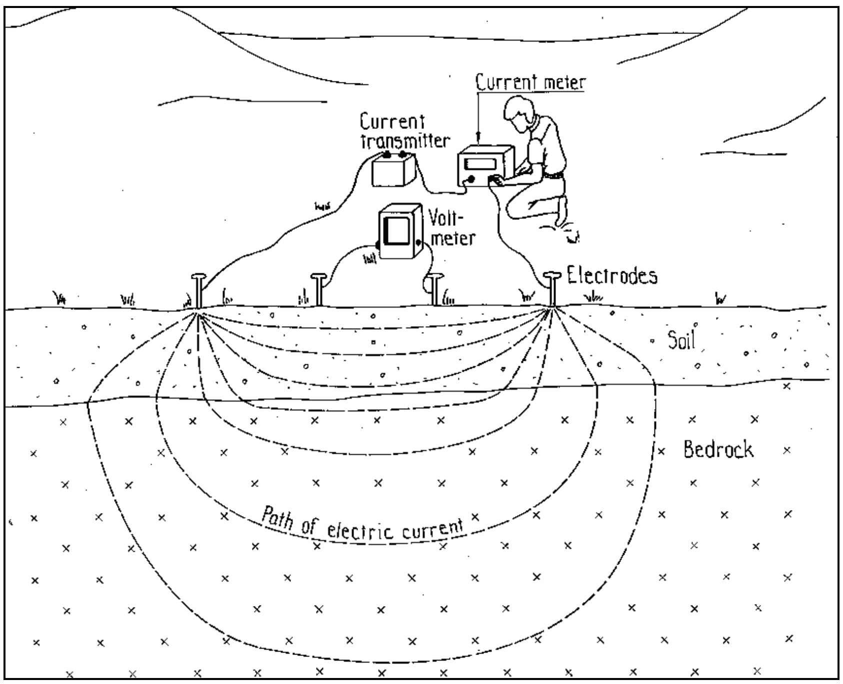


Figure 2-3 Sketch of the arrangement of a four-electrode surface resistivity measurement. A current is transmitted between two current electrodes and two potential electrodes are used to measure the potential field (modified from Robinson and Coruh 1988).

The measured voltage from a four-electrode arrangement can be thought of as a weighted mean value of the conductivities of all current paths between the potential electrodes. From such a measurement, information about the average electrical resistivity of specific subsurface volume is received. By altering the distances between the electrodes, different volumes of the subsurface are sensed and additional information about resistivities at different depths is obtained. This relationship between electrode spacing and depth penetration is fundamental for the method. However it is impossible to tell the resistivity of a certain layer directly from such a measurement. The current will be channelled into regions of lower resistivity and deflected from regions with higher resistivity. Without information about the subsurface structure, the true resistivities remain unknown. Therefore, a special methodology referred to as inversion or inverse modelling is used to estimate the true resistivities. This method involves a repeated procedure of fitting a subsurface resistivity model to a set of measurements. Inversion will be discussed in detail in section 2.3.2. First the basic theory of the resistivity method will be covered.

The resistivity, ρ, is a material property parameter that describes the ability of a material to conduct electrical currents. It is the inverse of the electrical conductivity, σ (Equation 2-1).

$$\rho = \frac{1}{\sigma} \qquad \text{(Equation 2-1)}$$

Consider the geometrically ideal situation with a current flow through a homogeneous media in a well-defined uniform cross-section between two potential electrodes (Figure 2-4). The resistance, R, is then described by Ohm's law (Equation 2-2) as the measured voltage, U, divided by the current, I.

$$R = \frac{U}{I} \qquad \text{(Equation 2-2)}$$

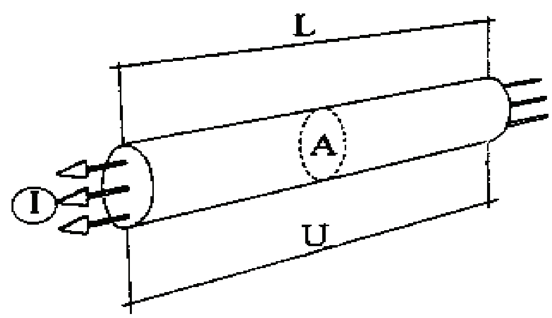


Figure 2-4 Current flowing through a homogeneous conductor with resistivity ρ, length L and cross-sectional area A.

However, the resistance is also proportional to the cross-sectional area, A, and the distance between the electrodes, L (Equation 2-3).

$$R = \rho \frac{L}{A} \qquad \text{(Equation 2-3)}$$

Combining these relations, solving for the resistivity and introducing a geometrical factor, K, lead to a new expression (Equation 2-4).

$$\rho = \frac{A}{L} R = \frac{A}{L}\frac{U}{I} = K\frac{U}{I} \qquad \text{(Equation 2-4)}$$

From this it is clear that the resistivity can be calculated for a measured voltage at a known current if the geometry is known. This may be applied to the original problem of four-electrode measurements on a plane surface over a conductive homogeneous subsurface and the geometric factor can be conveniently recalculated for this situation by equation 2-5:

$$K = 2\pi \left(\frac{1}{r_{11}} - \frac{1}{r_{21}} - \frac{1}{r_{12}} + \frac{1}{r_{22}} \right)^{-1} \quad \text{(Equation 2-5)}$$

The inter electrode distances r_{11}, r_{21}, r_{12} and r_{22} are defined in Figure 4. The geometric factor is specific to the way the electrodes are arranged and depends on the distances between the electrodes. The expression is valid for any general four-electrode geometry with surface electrodes, but in practice the electrodes are almost exclusively placed on a straight line. The geometric factor is different for electrodes buried at depth, for example borehole electrodes (e.g Telford et al. 1990).

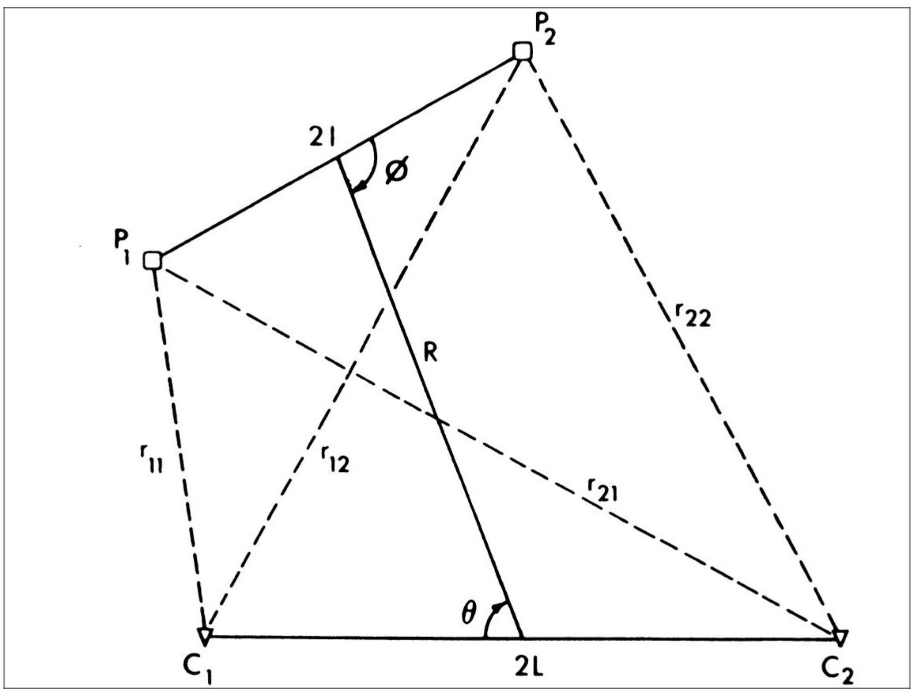


Figure 2-5 Sketch of the arrangement of a general four-electrode measurement with potential electrodes P1, P2 and current electrodes C1, C2 (0<θ, ϕ<π).
The distances between the electrodes are used to calculate the geometric factor, K (from O'Neill and Merrick 1984).

If the subsurface resistivity distribution is homogeneous the measured resistivity is the same as the true resistivity. However in practice this is never the case. Instead the measured resistivity should be seen as an artificial concept which does not generally coincide with the true resistivity. Therefore the term apparent resistivity, ρ_a, is used for the raw data from measurements.

2.2.2 *Electrode Arrays*

Figure 2-4 describes the arrangement of a general four-electrode measurement. This type of complicated configuration geometry is uncommon in practical measurements. Instead for practical reasons most configurations consist of electrodes placed along a straight line. Various different approaches for design of measurement configurations have been developed and tested throughout the development history of the resistivity method. Some commonly used electrode arrays, or measurement configurations, for resistivity surveying are shown in Figure 2-6.

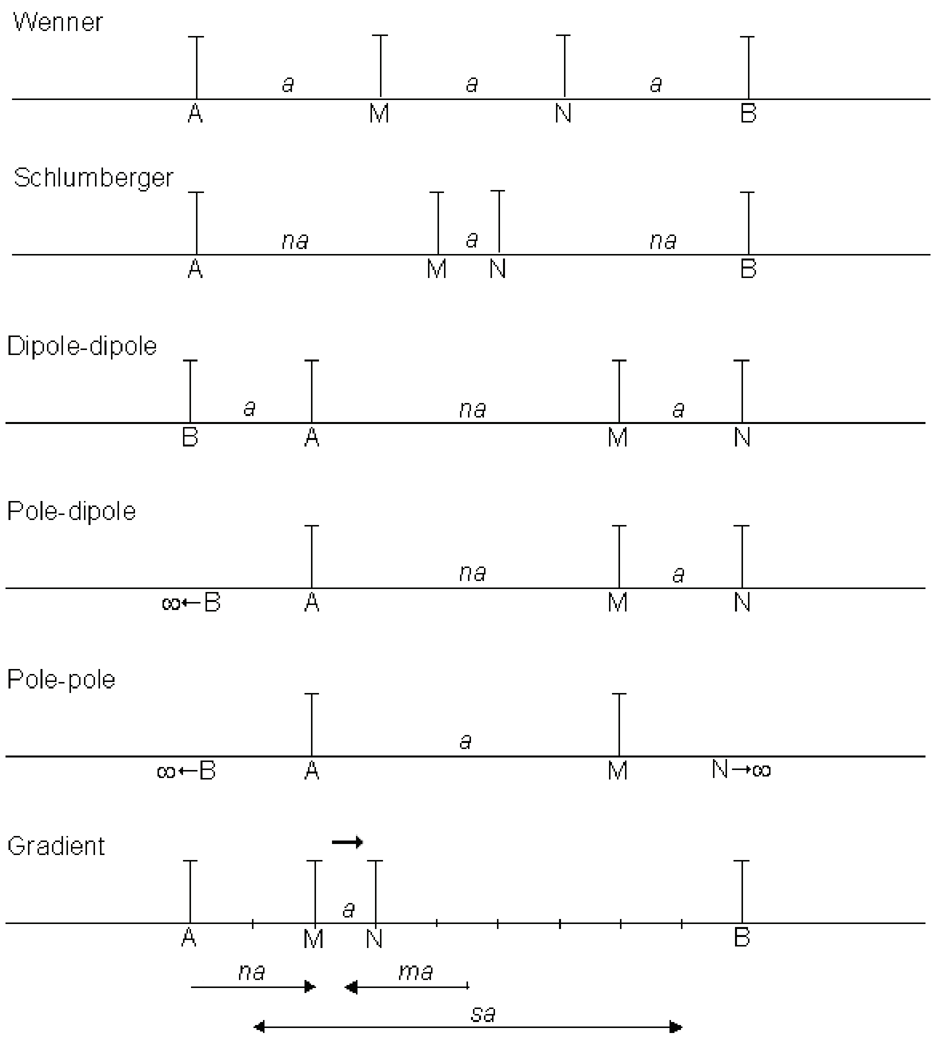


Figure 2-6 Common electrode arrays.
A, B = current electrodes, M, N = potential electrodes

Figure 2-7 displays a vertical cross-section of the three-dimensional sensitivity pattern of selected arrays in homogeneous ground. In non-homogeneous or anisotropic ground the sensitivity pattern will be different. The sections are taken through a vertical plane cutting through the electrodes. It should be noted that the sensitivity pattern for collinear arrays is rotationally symmetric around the line going through the electrodes in homogeneous isotropic ground, which means that the measurement is as sensitive to variation parallel to the electrode line as it is with depth.

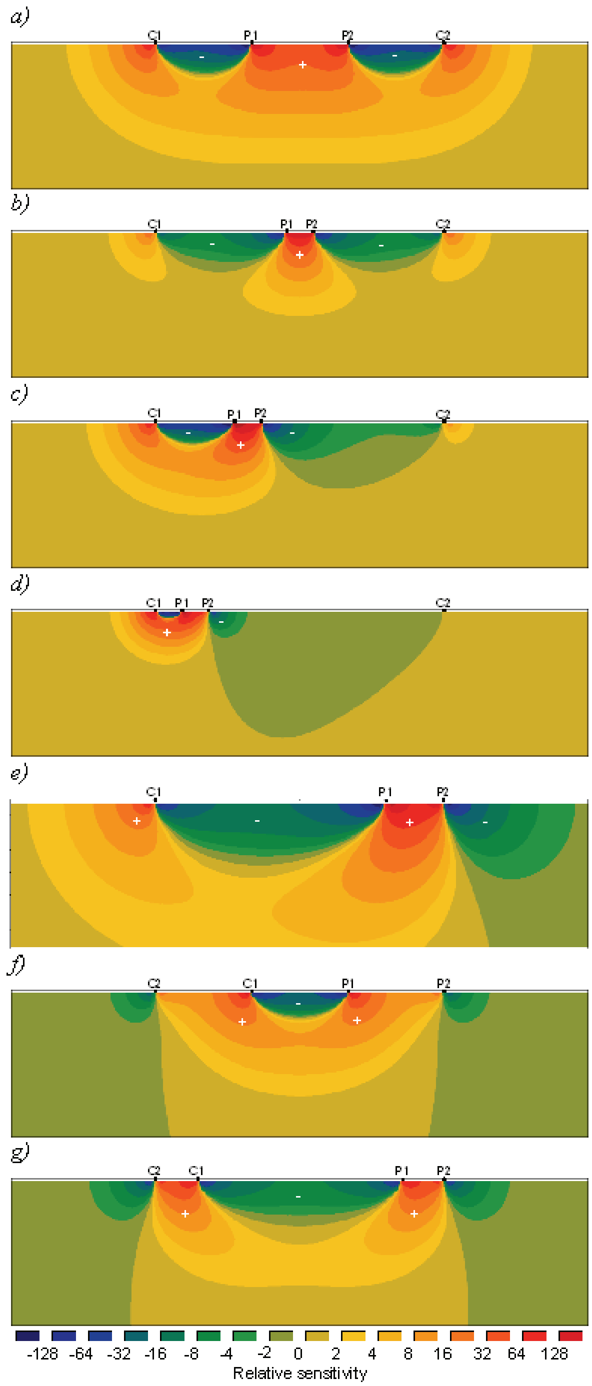


Figure 2-7 **Vertical section through 3D sensitivity function along the electrode layout for some electrode arrays:**
a) Wenner, b) Schlumberger (n=5) = gradient (s = 9, n = 5), c) gradient (s = 9, n = 3), d) gradient (s = 9, n = 1), e) pole-dipole (n=4), f) dipole-dipole (n=1), g) dipole-dipole (n = 5). C1, C2 = current electrodes, P1, P2 = potential electrodes. Regions marked with (+) have positive sensitivity and those with (-) have negative sensitivity. Vertical-horizontal plot ratio = 1. The absolute scale is the same for all diagrams, except for (d) - damped (x 0.1), and (e) + (g) – amplified (x 10).

The different electrode arrays have their strengths and their weaknesses. Arrays are typically described by their signal-to-noise ratio, their depth of investigation, their ability for lateral location of the target and their mapping abilities of horizontal layers or steeply dipping structures among other factors (Ward 1990). For example the dipole-dipole array has a good depth penetration and is considered good at mapping vertical structures, but has poor depth resolution and is more sensitive to noise in practical measurements since it has a lower signal-to-noise ratio. The Wenner array is good at mapping horizontal layers and is less sensitive to noise, but has a lower depth penetration and is less efficient in mapping vertical structures. The Schlumberger array has intermediate properties both regarding sensitivity to noise and mapping abilities of different types of structures. The pole-dipole array requires use of a remote electrode, which often makes it less practical for surveying, but has good resolution properties (Dahlin and Zhou 2004). Pole-dipole has the advantage of giving larger depth of investigation for a limited electrode layout, if the remote electrode is not considered, and therefore a higher resolution towards the end of the layouts. This may be a major advantage in dam investigation and monitoring.

The multiple gradient array (Dahlin and Zhou 2006) is an approach that combines the good properties from the different more established arrays and is suitable for modern multi-channel data acquisition. A number of studies have been done to evaluate, compare and search for new and optimised arrays (e.g. Barker 1989; Xu and Noel 1993; Beard and Tripp 1995; Olayinka and Yaramanci 2000a; Dahlin and Zhou 2004; Stummer et al. 2004; Wilkinson et al. 2006). The use of two or more arrays configurations for collecting data followed by combined evaluation of the data sets with joint inversion is a concept that has been attempted recently (de la Vega et al. 2003; Athanasiou et al. 2007). However, it should be mentioned that an increase in the number of data points does not automatically guarantee a better result. Joint inversion with bad quality data or with similar data, i.e. data from similar configurations, is not likely to be improved by an increase in the number of data points.

2.2.3 1D- 2D- 3D- Measurements

Historically, there have been two basic modes of resistivity surveying, and both modes are independent of the array type. Firstly, vertical electrical sounding, VES, uses the same midpoint for a specific electrode configuration. By systematically increasing the electrode separation, the current is forced deeper into the subsurface and the result is the apparent resistivity at increasing depths for a given location. The other mode is electrical profiling, where the midpoint is varied and all electrode separations are fixed. The result in this case is a data set of apparent resistivities at the same pseudo-depth along a line.

Single vertical electrical soundings, i.e. 1D measurements, or single electrical profiles are generally not recommended for dam applications due to the complicated dam geometry. The combined use of soundings and profiling is more adequate. It results in a collection of measurements at different depths along a line. This procedure is often referred to as continuous vertical electrical sounding, CVES, and has been described in detail in literature (e.g. Overmeeren and Ritsema 1988; Dahlin 1993; Dahlin 1996).

CVES involves measurements from electrodes placed along a line using a range of different electrode distances and midpoints, and is therefore advantageously performed using an automated multi-electrode system (Griffiths et al. 1990; Dahlin 1996). In such systems electrodes are inserted into the ground and separately connected to the measuring instruments through multi-core cables. The data collection then becomes very flexible as any electrode can be used according to a pre-defined measuring protocol and easily controlled by a computer. The resulting data represents a 2D section of the subsurface beneath the electrode line. This system is optimal for dam monitoring systems and for other types of long-term monitoring, as the electrodes are permanently installed and the measurements conveniently computer-controlled. Other systems have also been developed for efficient data acquisition in resistivity surveying. One example is a mobile system involving moving an electrode streamer cable during measurements (Sørensen 1996).

CVES, as described above, together with subsequent 2D interpretation, i.e. 2D surveying, is the most common way of resistivity surveying today. Furthermore CVES is the main focus of this guide. However, the combination of various separately measured 2D surveys combined in a grid, and interpreted in 3D, or 3D surveys based on 3D arrays, 3D surveying, is developing rapidly and its use has become more common recently (e.g. Bentley and Gharibi 2004; Gharibi and Bentley 2005). Such 3D investigations are appealing due to their ability to handle specific dam geometries and may therefore play an important role in future dam applications.

2.3 Resistivity Data Evaluation and Interpretation

As is often the case with geophysical surveys, interpretation of data from resistivity measurements needs to go through a number of steps in the search for the true resistivity model of the subsurface. These steps may sometimes be rather complicated.

2.3.1 Pseudosections

The conventional way of presenting apparent resistivity data from 2D resistivity surveys is to plot them in a section where the electrode separation or effective depth penetration is used for depth (Figure 2-8). On the x-axis is the distance along the surveying line and on the y-axis the pseudodepth is represented. As pseudodepth, the median depth of investigation can be used or a measure that is proportional to the separation between the electrodes. The median depth of investigation is the depth at which half the total contribution to the apparent resistivity value in the measurement comes from depths above, and half from depths below (Edwards 1977). Each dot represents a data point. Between points linear interpolation is customarily used for the plotting routine. As this section is built from apparent resistivity data it is referred to as a pseudosection and it differs largely from the true resistivity of the subsurface. Therefore inverse modelling is needed for further interpretation. Interpretation from pseudosections alone is not recommended.

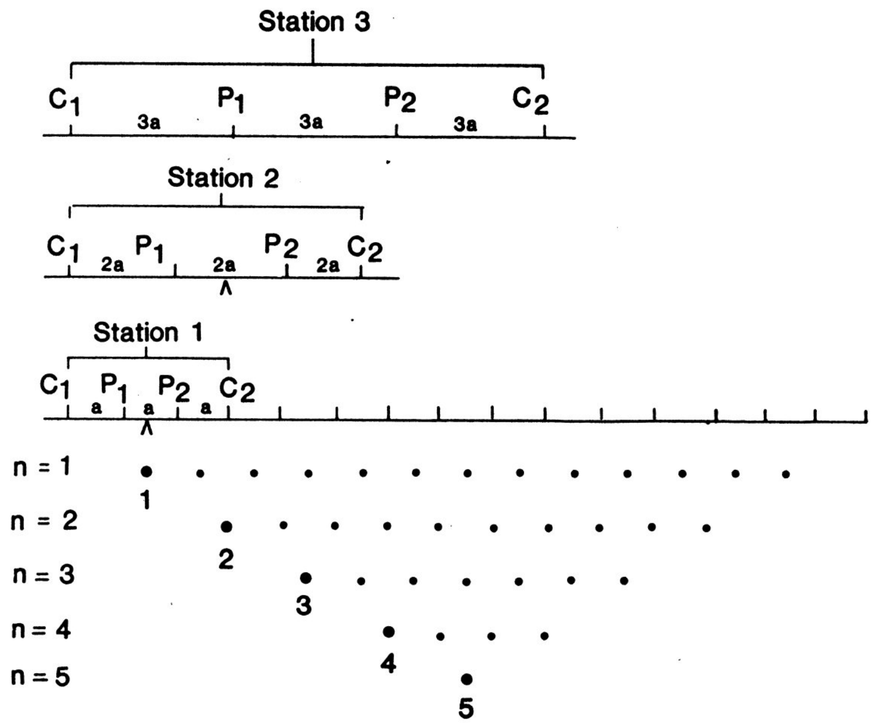


Figure 2-8 Principle for construction of a pseudosection for the Wenner array, with current and potential electrode locations at C1, C2 and P1, P2 respectively.
On the x-axis is the distance along the surveying line for the configuration midpoint, and on the y-axis is in this case is the electrode separation. Each dot symbolizes one data point (from Barker 1992).

The pseudosection is made to present raw data, and is also a tool for rapid visual assessment of data quality. Large inconsistent changes between adjacent data points in the pseudosection are often a sign of bad data quality in the measurements. Adjacent data points involve to a great extent the same measured subsurface volume and their respective potential readings should therefore vary in a systematic way provided the same electrode array was used for all data. Mixing of data with the same array but different n-factors and different a-spacings (e.g. for dipole-dipole, pole-dipole, multiple gradient array, see Figure 2-6 and Figure 2-7) in the same pseudosection can lead to an apparently noisy appearance and it may be necessary to make separate plots for each sub set of the data. Slight errors in data will not be identified by checking the pseudosection, but obviously incorrect data points, such as those resulting from instrumentation errors, failure of the relays in the switching unit, shorting of the cables in wet conditions, or mistakes during field surveying, may be identified. To achieve a final resistivity model, it is essential to remove such obviously incorrect data points before moving on to the next step, which is inverse modelling.

2.3.2 Inversion

In resistivity surveying it is in most cases desired to determine the subsurface resistivity distribution. As we have seen, measurements at the ground surface produces apparent resistivities of the subsurface. The goal of inversion is to estimate the true subsurface resistivities from a set of apparent resistivities, and it can be achieved by fitting the measured data to an assumed subsurface resistivity model. Today, inversion is performed automatically as an iterative process. This iterative process consists of an initial model guess, which is updated for every iterative step until an acceptable fit of the data is achieved or model criteria are met.

There are several commercial inversion software packages available (see section 5.3). For the 2D inversions presented in the examples in this report, a widely used commercial code has been applied (Loke and Dahlin 2002; Loke 2004). This code is based on theoretical considerations developed in the past decades, which are described briefly in this section. For more information on inversion the reader is referred to detailed sources. Important contributions in the 2D inversion of apparent resistivities have been published by, among others, Smith and Vozoff (1984), Tripp et al. (1984), Li and Oldenburg (1992), Loke and Barker (1995), Loke and Barker (1996a) and LaBrecque et al. (1996). Recently the use of 3D inversion (e.g. Park and Van 1991; Sasaki 1994; Zhang et al. 1995; Loke and Barker 1996b) has become more frequent in resistivity surveys and theoretical studies.

2.3.2.1 Forward Modelling

Central to any inversion method is a forward model, which calculates the data resulting from a given resistivity distribution in the subsurface. In 2D forward modelling the subsurface resistivity distribution is described by a 2D model extended in infinity in the third dimension. It is important to note, however, that the current sources, the current electrodes, are modelled as 3D sources. If not, they would obviously be mistakenly described as line electrodes. Therefore, the term 2.5D is sometimes used for this kind of modelling. Coggon (1971) describes how 3D point sources can be treated mathematically, by the means of Fourier transformation, to fit into the 2D modelling scheme. Such 2.5D modelling is further described by Dey and Morrison (1979) and Queralt et al. (1991) among others.

More explicitly, forward modelling finds a solution to the current flow equations in inhomogeneous ground for a given resistivity distribution and current source configuration. This solution includes the distribution of the potential field in the investigated 2D section, which allows a straightforward calculation of the apparent resistivities from the configuration of the potential electrodes. A more detailed mathematical formulation of the forward modelling problem (2D) is given in Appendix A.

2.3.2.2 Inverse Methodology and Formulation

In the automatic inversion routine a homogeneous starting model of the subsurface resistivity distribution is used with logarithmic averages of the measured apparent resistivities (Loke and Barker 1995). The subsurface is divided into a large number of rectangular cells, and the optimisation method attempts to determine the resistivity distribution of the cells that minimises the difference between the calculated and measured apparent values subject to certain constraints (Loke et al. 2003). The mathematical formulation of the inverse problem (2D) is given in Appendix B.

Regarding the methods of minimisation of the differences between model and data, Loke et al. (2003) describe the use of the L_1 and L_2 optimisation norms. The L_1-norm minimises the sum of the absolute values of the data misfit, whereas the L_2-norm minimises the sum of the squares of the data misfit. The L_1-norm optimisation is often preferable for inversion of embankment dam data. Apart from being more robust with regard to noisy data (Claerbout and Muir 1973), it tends to produce models with regions that are more blocky and separated by sharper boundaries. The latter factor is probably more realistic for measurements on a zoned embankment, where large resistivity contrasts are expected between different materials, i.e. between the fine-grained dam core and the fresh igneous rock of its foundation. Olayinka and Yaramanci (2000b) proposed another inversion scheme especially suited to a subsurface with a few homogeneous regions separated by sharp interfaces. This scheme uses a division of the subsurface into polygons, with the boundary coordinates and layer resistivities constituting the model parameters.

2.3.3 Time-lapse Inversion

For monitoring data or repeated measurements the apparent resistivities from two or more different measurement occasions can be analysed jointly using time-lapse inversion. Time-lapse inversion means that two data sets from different times are inverted together, where the first recorded data set would normally be regarded as a reference. In time-lapse inversion a smoothness constraint is applied not only to the spatial variation but also to the temporal variation between the data sets. This approach has been shown to focus the difference between the data sets on the actual change in the model and suppress artefacts due to the resistivity structure (Loke 2001). It takes into account the fact that in many situations the changes in the resistivity occur in a limited section of the subsurface while the rest of the subsurface has much smaller changes.

In dams, the resistivity varies in a cyclic manner over the year. The reason for this variation is discussed in section 3.5. When evaluating monitoring data from dams, a reference data set can be chosen as a median data set over the entire selected period, e.g. one or several years. However, the variation pattern is interesting for evaluation and using the median as a reference data set involves a risk that the variations are damped out by the inversion routine. Instead, a sliding damped data set can be used when analysing such data. In this case, the reference data set follows the actual data set, but with a strong damping that suppresses noise.

2.3.4 Considerations for Data Interpretation

As has been shown, many different materials may have similar resistivity (Figure 1). Therefore it is always unwise to interpret resistivity data by translating given resistivities as a certain type of material. This may be done only after having received reliable information on the material distribution in the field area from direct observation or other types of investigations to confirm the interpretations.

Calibration against field observations, borehole data and other information is of vital importance for the resistivity method and is essential for correct interpretation of a final model of true subsurface resistivities. However, the resistivity method can also be used as a tool for covering a large field area and form a basis for deciding where to invest in more detailed investigations.

For interpretation of a final 2D inverted resistivity model it is wise to always keep in mind some typical phenomena associated with the theories behind resistivity measurements that may affect the final model. A few such factors are listed below.

- **Depth resolution**: The resolving power of the resistivity method decreases exponentially with depth.

- **Resolution at the sides of the model**: At the sides of the final model there are fewer data points; the model may be strongly affected by boundary conditions and the weight the side blocks are assigned in the inversion. In many cases this problem can be overcome by increasing the length of the survey line so that it is certain that the area of interest is fully covered. On embankment dams, however, increasing the length of the survey line is not always easy. It is quite common that an embankment dam connects at one end to a concrete structure hosting the spillway or an intake to a power station and increasing the survey line is then not feasible.

- **The concept of non-uniqueness**: The principle of equivalence can be exemplified for the case of a homogeneous earth with an embedded horizontal high-resistivity layer. In this situation the high-resistivity layer with a specific resistivity and a specific thickness may, within the measurement resolution, produce the same result as a layer with twice the resistivity and half the thickness (Telford 1990).

- **Highly resistive or highly conductive top layer**: If the top layer is very resistive it might be difficult to get enough current into the ground. On the other hand, if the top layer is very conductive the current will be channelled into this layer and it might be difficult to reach the underlying structures with enough current. In both cases, the potential readings may become very small resulting in very low signal-to-noise ratios.

- **3D effects**: Inversion of 2D resistivity data assumes a 2D subsurface reality with no significant variations in the direction perpendicular to the survey line. This is rarely the case, but for many surveys it is a manageable problem. A four-electrode measurement involves an earth volume with the shape of a half-sphere for the case of a homogeneous subsurface. This means in principle that structures at a specific distance to the side of the survey line have the same influence on the measurements as structures at a similar depth. This phenomenon can also be seen in the sensitivity functions (Figure 2-7) that are rotationally symmetric along the line of electrodes for collinear arrays. For measurements along embankment dams, 3D effects are of great significance. However, for 2D resistivity surveys across the embankment dam it is normally valid to assume that the subsurface geometry in the direction perpendicular to the survey line, i.e. the cross-section of the dam, is reasonably invariable. Severe 3D effects are best avoided by undertaking a full 3D inversion. Computational power has for long limited the use of 3D inversion but recently it is becoming more and more established. However, 3D inversion requires data acquired in a pattern that may often be difficult to achieve on a dam.

3.0 RESISTIVITY MEASUREMENTS ON DAMS

The main aim of resistivity measurements on embankment dams is to verify the safety and integrity of the dam. This is done by detecting potential weaknesses, such as defective zones, anomalous seepages or internal erosion processes. In this section some basic principles concerning the use of the resistivity method for dam applications is discussed.

When applied for dam safety examination, the resistivity method can principally be used in two ways. Firstly, resistivity investigations at single occasions may detect spatially anomalous zones along the dam, and can be used to investigate suspected structural weaknesses. Secondly, by studying deviations in the time-variation pattern, long-term resistivity monitoring makes use of seepage-induced seasonal variations inside the embankment to detect anomalies not only in space, but more importantly, anomalies in time.

A special application is the use of resistivity measurements to find resistivity values as input data for SP investigations.

3.1 Investigations

The most common use of the method has traditionally been as single investigations. These investigations are performed within a limited time frame and are on the whole quite similar to resistivity surveys in many other engineering or environmental applications. The most common purpose is to check the integrity of the dam or to detect anomalous seepage in the dam or the foundation. In such investigations, resistivity profiling and/or resistivity soundings have been commonly performed but in recent year also 2D and 3D approaches have been applied (e.g. Ogilvy et al. 1969; Bogoslovsky and Ogilvy 1970; Arandjelovic 1989; Butler et al. 1989; Moldoveanu and Suciu 1989; Butler and Llopis 1990; Abuzeid 1994; Okko et al. 1994; Sirles 1997; Panthulu et al. 2001; Kim et al. 2004; Lim et al. 2004; Song et al. 2005; Sjödahl et al. 2005; Johansson et al. 2005b, Cho and Yeom 2007; Kim et al. 2007). The method has been applied in a similar manner on river dykes (e.g. Van Tuyen et al. 2000; Chen et al. 2004; Inazaki and Sakamoto 2005). Offshore measurements in the reservoir have also been tested (e.g. Corwin 1985). In most dam investigations the resistivity method has been used together with various other geophysical methods. Butler and Llopis (1990) emphasize on the importance of integrated multiple-method programs and also suggest the possible use of a monitoring strategy, where geophysical anomalies detected as a function of time can be correlated with the reservoir level.

Single investigation is less demanding than monitoring, and more flexible to carry out. It is unlikely that the results from a single investigation approach will be able to give answers to crucial questions about the safety of the examined embankment dam if carried out alone, but in combination with other methods it may be useful as a guide for continued investigations and contribute significantly to the total picture.

If investigation is repeated a number of times at different seasons or different reservoir levels the possibility to obtain useful information increases substantially. This approach falls in between single investigation and monitoring in power. It is essential that very high accuracy in electrode positioning between the different measurements is obtained, and ideally the electrodes should remain in place in between the investigations.

3.2 Monitoring

The monitoring approach is a more powerful method than single investigations. The fundamental objective behind evaluation of resistivity monitoring data is based on its time variation, as described in section 3.5. This requires a fairly long investigation period to be able to establish the normal resistivity-time variation in the dam. Factors, such as seasonal variation due to temperature changes and reservoir level changes among others, are to a great extent site specific and cannot be known in advance. Once established however, deviations from this normal background are taken to indicate anomalous conditions in the dam.

Repeated measurements on embankments over time have been performed. Some examples include Buselli and Lu (2001), who used repeated measurements on the downstream side of a tailings dam to locate contaminated seepage. Titov et al. (2000) evaluated dam integrity using measurements before and after a spring flood. Similarly, Engelbert et al. (1997) conducted resistivity measurement for locating canal seepage by comparing results respectively from an empty and a full canal. Johansson and Dahlin (1996) demonstrated seasonal resistivity variation inside an embankment dam by measuring repeatedly eight times over a period of 18 months.

The next level after repeated measurements is to perform regular monitoring. In an ongoing Swedish research program, resistivity monitoring of Hällby embankment dam by daily measurements commenced in 1996 (Johansson et al. 2005a) and five years later, in 2001, measurements commenced on a second dam, the Sädva embankment dam (Johansson et al. 2005a).

3.3 Geometry Considerations

For practical reasons 2D resistivity surveying is often performed along the embankment crest or along the slopes. Due to the complex geometry, inversion of 2D data from such investigations is not straightforward. Two types of 3D effects lead to geometric errors (Figure 3-1). The first is a result of the topography of the embankment slopes and the reservoir. The second, which is more significant, is a result of the zoning of the inner parts of the embankment dam. For an electrode layout along the dam crest this complex geometry results in violation of the 2D assumption, as, apart from direct topographical effects, there is also large variation in electrical properties in the direction perpendicular to the electrode layout direction (Sjödahl et al. 2006).

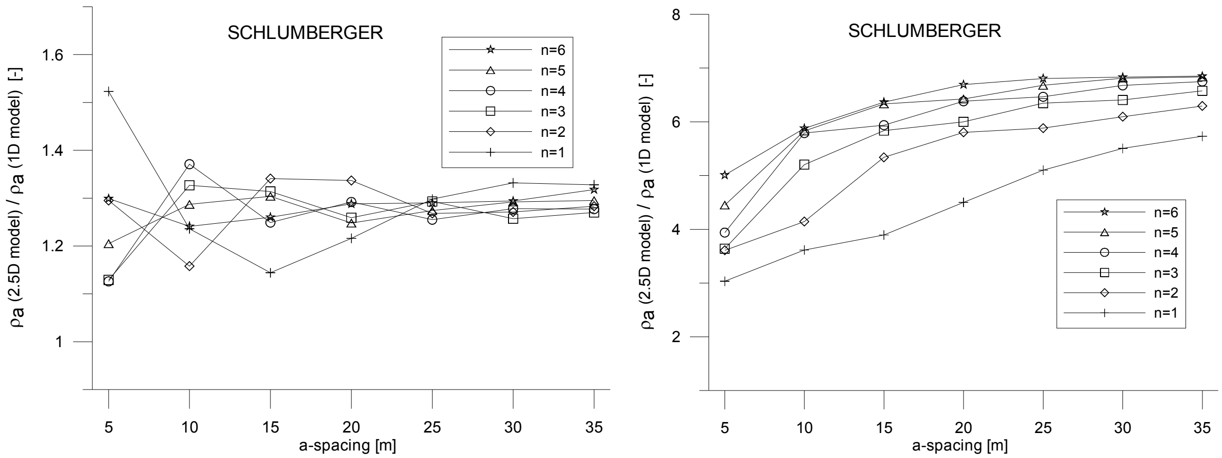


Figure 3-1 Influence on resistivity measurements along the crest due to the topography of the dam (left) and due to topography and internal design of a central till core rockfill dam (right).
Wenner-Schlumberger arrays with a-spacing of 5-35m in steps of 5m and n-factors 1-6; for both arrays a-spacing is the spacing between potential electrodes and n-factor the shortest distance between potential and current electrode divided by the a-spacing (from Sjödahl et al. 2006).

In spite of these 3D effects, 2D measurements along the embankment are performed. Measurement along the dam crest can give a good overview of the whole dam, and is used to find anomalous zones, which can subsequently be investigated more in detail using cross-section measurements, 3D surveying or other types of investigations. In the evaluation of such anomalies, special care has to be taken due to the violation of the 2D assumption. In general, absolute resistivity values as well as depth locations are likely to be distorted (Sjödahl et al. 2006).

Measurement along a survey line that crosses the dam can be used to study a specific part of the dam in more detail. This approach does not violate the 2D assumption, as long as the dam cross-section is reasonably constant along the dam, which is true in most cases. Furthermore, it is assumed that the inversion can handle topographical variations in the electrode layout direction.

Measurements on the downstream side may be carried out to check for seepage problems in the foundation, but are of limited use for checking the status of the dam itself. Measurement using boreholes is an attractive approach, as it would significantly increase the resolution at large depths. The technique could be used in a combination of layouts in one or more boreholes with surface layouts, or as measurements using layouts in two separate boreholes for investigating the region between the two boreholes. However, boreholes are generally avoided in the dam core on existing dams, and in addition steel or plastic casing is needed to stabilise the boreholes, complicating the task of carrying out the measurements.

An approach using 3D measurements is attractive because the problems associated with the complex geometry would be avoided. However, evaluation of 3D measurements is demanding, especially for monitoring data. Furthermore, 3D evaluation demands a 3D data acquisition approach, which makes the installations substantially more demanding. It is not clear that the improvement from 3D measurements, restricted to combinations of electrodes placed on the surface of the embankment dam, will be worth the effort that such an installation demands. A logistically attractive way to do a 3D survey would be to carry out the data acquisition as a number of parallel, and optionally also perpendicular, 2D lines that are merged and inverted in 3D (e.g. Papadopoulus et al 2005; Wisén 2005; Dahlin et al. 2007). Song et al. (2005) carried out such an attempt by performing 3D interpretation of combined 2D resistivity measurements along the crest, at three levels along the downstream slope and at both abutments perpendicular to the dam direction. However, when combining 2D measurements along the dam with 2D measurements across the dam, the asymmetry of the distortions in absolute values resulting from the violation of the 2D assumption only for the measurements along the dam, may lead to problems in fitting the different data into a joint 3D resistivity model.

3.4 Water Level Variations

A fluctuating reservoir level affects the measurements in different ways. The most obvious effect is that a change in water level will bring a pure geometric effect to the measurements. Numerical modelling has shown that this effect on the resistivity value may be several tens percent for a water level change of approximately half the reservoir height (Figure 3-2). Another effect of a change in water level is that the conditions inside the dam change. Soil saturation and hence also soil resistivity change. There is a dynamic factor complicating the analysis in this case. In case of rapid (daily or weekly) water level changes the effect will be quite hard to analyse, whereas for yearly and more even fluctuations, the effect can be compensated for. Secondary effects from a change in water level may also occur. A full reservoir exerts pressure on the embankment that may open up channels and increase seepage, which in turn will affect the resistivity in the adjacent areas, as discussed in section 3.5.

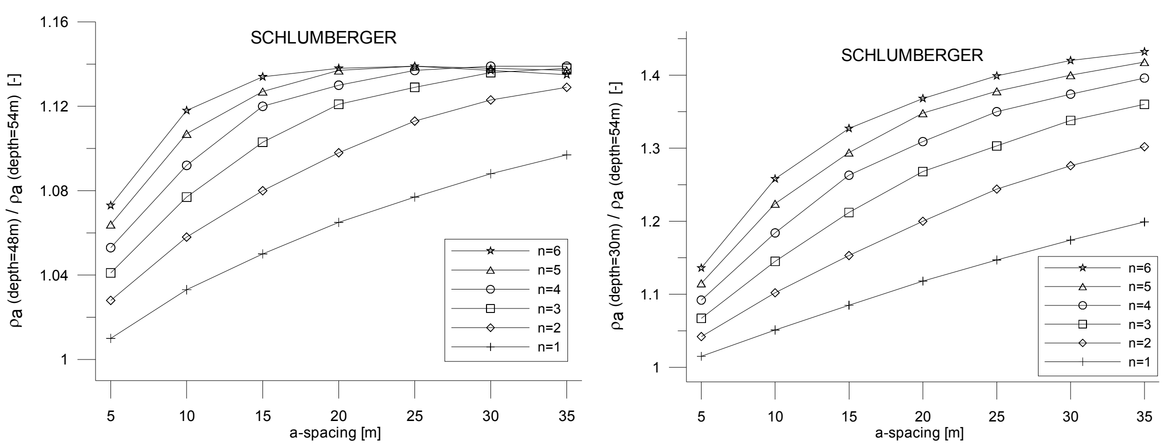


Figure 3-2 Influence on resistivity measurements along the crest from a lowering of the reservoir level from maximum level +54 m to level +48 m (left) and from maximum level +54 m to level +30 m (right).
Wenner-Schlumberger arrays with a-spacing of 5-35m in steps of 5m and n-factors 1-6; for both arrays a-spacing is the spacing between potential electrodes and n-factor the shortest distance between potential and current electrode divided by the a-spacing (from Sjödahl et al. 2006).

3.5 Temperature and TDS Variations

Seasonal temperature variations in an embankment dam have for a long time been used successfully for seepage detection. The seasonal temperature variation inside the dam is dependent on the seepage flow rate. This temperature variation depends mainly on the temperature of the reservoir water and the time it takes for the seepage water to travel through the dam. Seepage flow rates can therefore be evaluated from temperature measurements without knowledge of hydraulic conductivity in the dam (Johansson 1997). This is a great achievement, as the true in-field hydraulic conductivity is a difficult parameter to estimate.

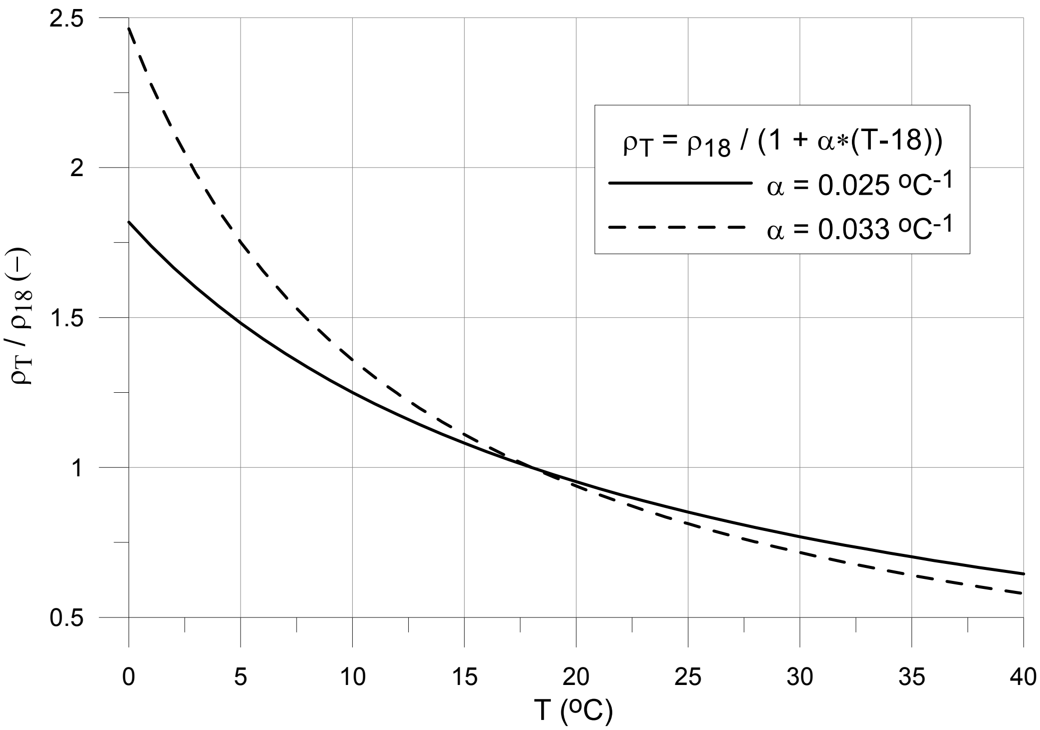


Figure 3-3 Influence from temperature on water resistivity, using the temperature coefficient of resistivity, α = 0.025°C-1 and α = 0.033°C-1.

There is a strong relationship between temperature and resistivity (Figure 3-3). Accordingly, the seepage will cause resistivity variations in the dam, depending on the seasonal resistivity variation in the reservoir water (Johansson 1997). Those variations may be recorded by repeated measurements. 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 3-4). 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.

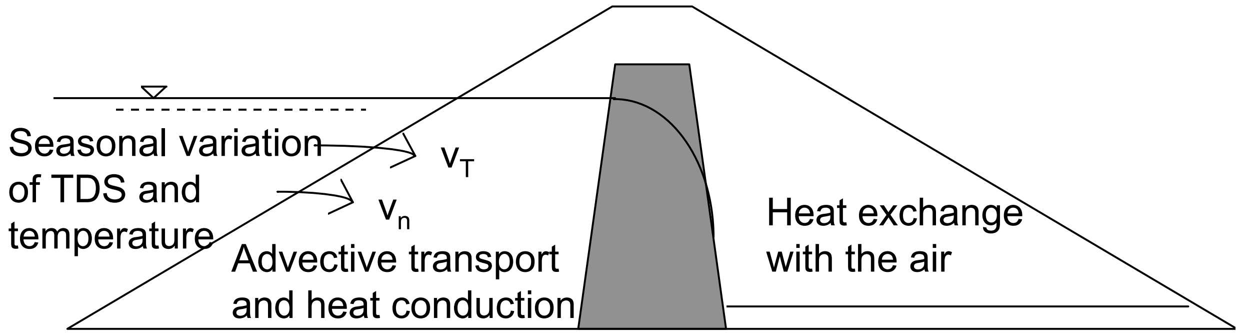


Figure 3-4 Cross-section of an embankment dam showing the important transport processes that affect the resistivity variation.
(From Johansson 1997)

The resistivity variation can be used to evaluate seepage in a similar way as temperature. Johansson and Dahlin (1996) did some initial tests on repeated resistivity measurements from the Lövön dam. The same evaluation approach was used by Sjödahl (2006), based on excellent data from the Sädva dam. The evaluation method is based on the principle described above for temperature variations and the assumption that the resistivity value inside the central parts of the dam can be measured with reasonable certainty of the data quality.

The temperature method is more certain, and has a much higher precision in its measurements than the resistivity approach. The advantage of the resistivity method is that it is non-intrusive, which is important on existing embankment dams. Another advantage is that the method is continuous along the dam, and collects information about the core where drillings normally are avoided. The resistivity method will thus give more spatial information than conventional pressure measurements that gives information in a point, or temperature measurements in standpipes at different levels which give information along a vertical profile or along the dam toe when using distributed temperature measurements in optical fibres.

Nevertheless, the seepage evaluation procedures of the resistivity and temperature method have a lot in common, and a basis for such evaluation is the variations in the reservoir water temperature. The temperature in the reservoirs of two monitored embankments, Hällby and Sädva in central and northern Sweden respectively, have been measured (Figure 3-5). The variations are cyclic with a period of one year. During the cold part of the year the temperature approaches 0°C and flattens out. In summer, maximum temperatures of approximately 20°C in Hällby and 15°C in Sädva are reached. The climate at Sädva is colder as it is situated farther north, and the sensor is situated on a larger depth which explains why the coldest temperature never goes down to 0°C but stops around 2°C. The sensor at Sädva is placed at great depth to ensure it is never above the surface, taking into consideration the high operational reservoir level fluctuations at Sädva. The sensors at both the Hällby and the Sädva dams are placed close to the main intake to a mini power plant, thereby assuring good mixing of the water and relevant values for both reservoirs.

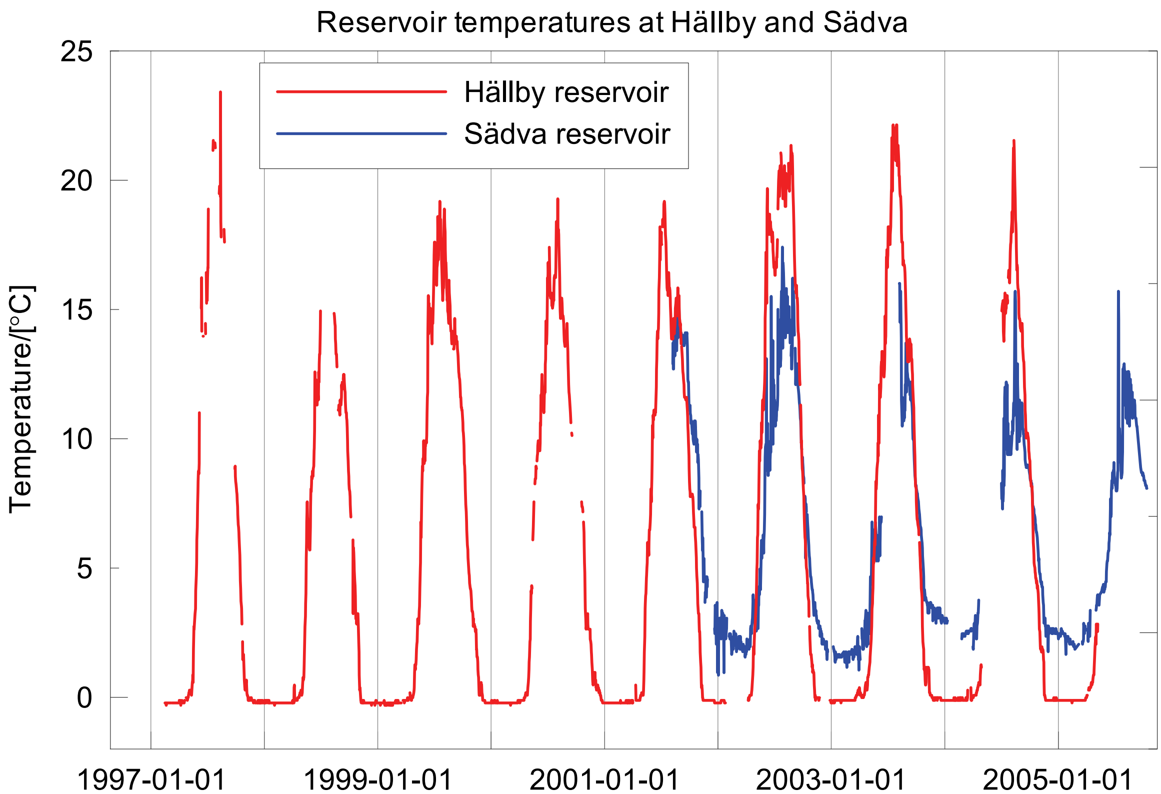
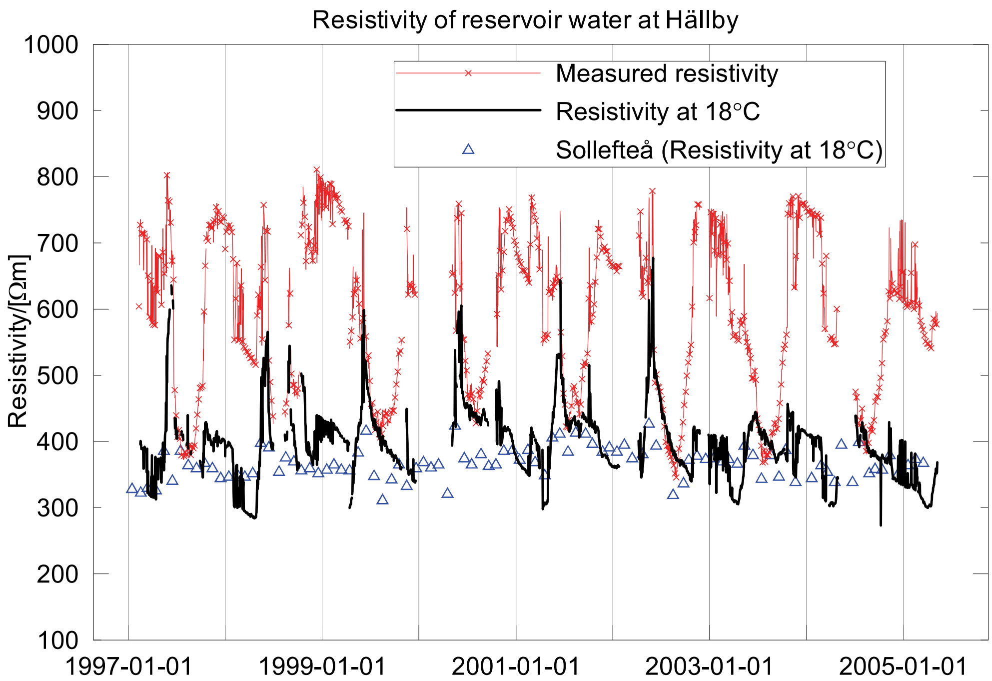


Figure 3-5 Temperature variations in the Hällby and Sädva reservoirs.

The resistivity in Hällby and Sädva reservoirs has been measured (Figure 3-6), and just as for temperature, the seasonal variations are obvious. The measured resistivities exhibit a high variation with top levels coinciding with low temperatures in wintertime. Adjusting for temperature effects by recalculating all resistivities to 18°C values (equation in Figure 3-3) reduces much of the variation. However, some variation remains, and this is explained by a seasonal variation in TDS.



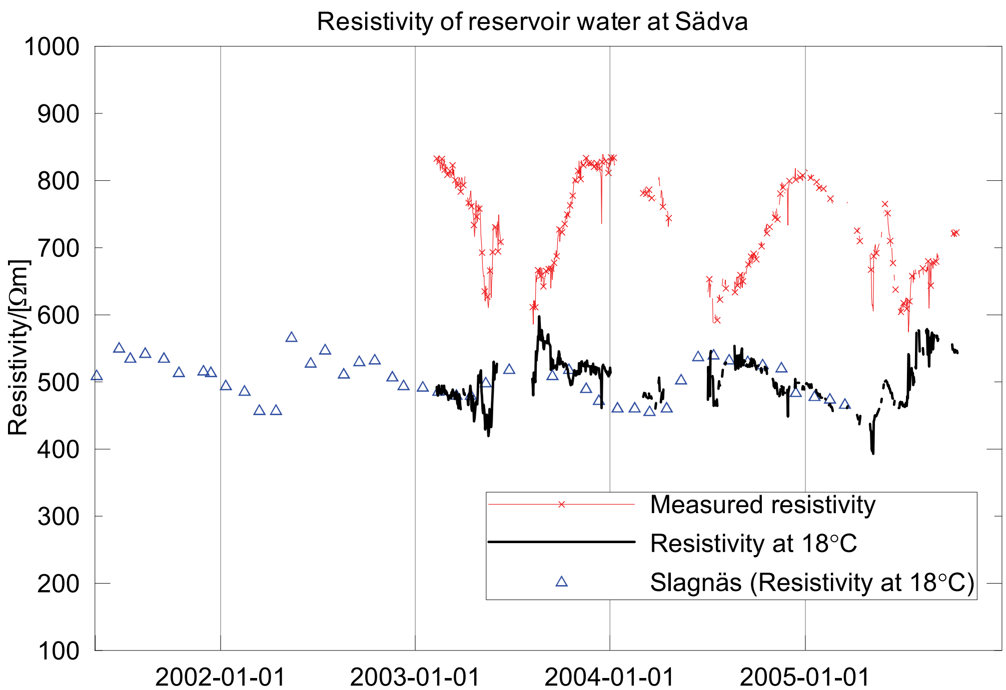


Figure 3-6 **Resistivity variations in the Hällby (top), and Sädva reservoir (bottom). Resistivity at 18°C has been corrected for temperature variations using a temperature coefficient of resistivity, α=0.025 (Keller and Frischknecht 1966). Monthly measurements (triangles) taken at Sollefteå and Slagnäs (SLU 2005). These locations are approximately 100 km downstream from each of the dams.**

Most noticeable in Figure 3-6 are the peaks around late spring/early summer, which are caused by low TDS-levels associated with snowmelt. Particularly at the Sädva reservoir the snowmelt is intense. The dam is located in the mountains and is the first reservoir in its river system, and therefore it receives large amounts of melting water. Consequently it is not surprising that there is a variation in the Sädva reservoir, also noted in the monthly measurements (Figure 3-6, bottom) taken by the Swedish University of Agricultural Sciences (SLU 2005). This variation in the monthly measurements is perceptible for the Hällby reservoir as well, but much less evident (Figure 3-6, top). In general, the measured data agree well with the monthly measurements taken by SLU about 100 km downstream, although the variation of the latter is much smoother. The variation can be expected to become smoother further downstream, and moreover the monthly sampling rate might miss some of the shorter peaks. Nevertheless, for the Hällby reservoir the resistivity variation is similar to prior measurements from the reservoirs at Lövön and Moforsen, two dams situated in the same region (Johansson and Dahlin 1996).

3.6 Soil and Fluid Properties

3.6.1 Typical Soil Resistivities

The electrical properties of earth materials vary within very wide intervals and are site-specific. The variation between different sites is to a large extent governed by the properties of the reservoir water. With water resistivities around a few hundreds of Ωm the formation resistivities of the rockfill and filter zones also become high. In dam cores constructed from glacial till, with a typical fines content of 15-40% (Vattenfall 1988), the importance of surface conduction is significant. For Scandinavian conditions with high resistive water it is likely that the glacial till in the dam core is the best conductor of all materials including the reservoir water.

3.6.2 Typical Fluid Resistivities

The influence of the properties of the reservoir water on the properties of the embankment construction materials is fundamental when it comes to resistivity investigations on embankment dams. The resistivity of the water is site-specific and typically in the interval 10-500 Ωm, even though cases outside this interval are perfectly possible as well. Water resistivity has a large influence on the material properties inside the dam, especially in coarse-grained soils as it governs electrical conduction in such materials. It is necessary to have knowledge about the site-specific conditions. What is the signature of a weak zone in the dam? It is likely that a leakage zone could be either low-resistivity or high-resistivity depending on the electrical properties of the water in the reservoir. Therefore in practice for dam investigations both high- and low-resistivity anomalies are searched for. Typically, variations in space along the dam are examined and less attention is paid to the actual absolute resistivity values in the embankment. Using a monitoring approach makes it easier as changes over time are analysed and the actual resistivity values are of lesser importance. Seasonal variations of reservoir water resistivity, due to for example snowmelt, may in some cases be used as a natural tracer.

3.7 Effect of Internal Erosion on Soil Resistivity

Internal erosion is the reason why weak zones can appear as high-resistivity anomalies. When internal erosion occurs, the fine particles of the soil are washed out from the core. This process affects the resistivity in two ways, each working against the other. Firstly the porosity of the core increases which leads to a decrease in the resistivity due to the higher water content. Secondly the reduction in the fines content in itself increases the resistivity. In theory it is difficult to predict the effect of internal erosion on the electrical properties of the dam core and this may differ from one dam to another depending on material properties and water resistivity. Laboratory tests performed by Bergström (1998) on some Swedish glacial tills used as impermeable seals on waste deposits indicate a significant increase in resistivity as the fines content is reduced (Figure 3-7).

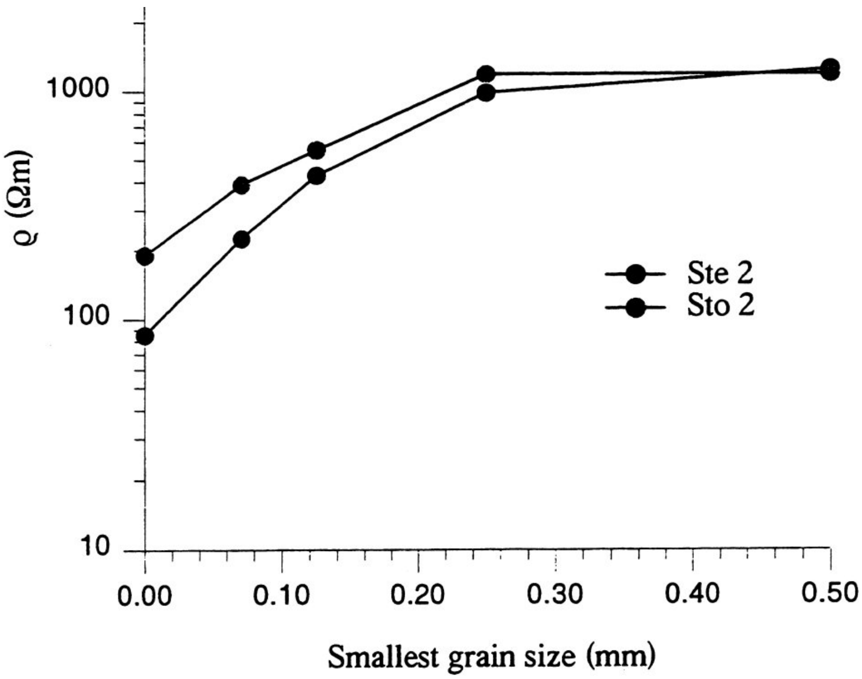


Figure 3-7 Importance of fines content on resistivity of soils.
Results from an experiment simulating erosion in a glacial till used for sealing waste deposits, but similar to a dam core. Ste 2 and Sto 2 are named samples from two different sites (from Bergström 1998).

In the experiment conducted by Bergström (1998) resistivity was measured on the same soil under water-saturated conditions with different levels of fines removed, thereby simulating the washout of fines as a result of internal erosion. The glacial till sample is similar to those used in the core of many Swedish dams, and could be categorised as slightly more coarse than average for that purpose, which then suggests that the effect may be even stronger for dam core materials. In this experiment the resistivity value increases approximately ten fold on the removal of fines smaller than 0.25 mm, and thereafter it flattens out.

Recent research based on theoretical and practical considerations, concludes that particle sizes up to 0.2 mm are readily transported to the filter face in the initial stage of a leak. If the leak increases in size, soil particles as large as 5 mm could be carried away by seepage flows (Foster and Fell 2001).

However, the increase in resistivity is small for removal of particle sizes larger than 0.2 mm. Thus according to the results from Bergström (1998), resistivity will be most sensitive in the initial phase of the internal erosion process.

Consequently, for embankment dams in typical Scandinavian conditions (with high-resistive reservoir water), it is likely that internal erosion will cause an increase in the resistivity of the core as washout of fines occurs. Burns et al. (2006) performed laboratory tests with a miniature resistivity array on a clay specimen that was exposed to piping and internal erosion. They mapped the growth of the developing pipe as a high-resistivity eroded zone, and conclude that the method may prove useful in monitoring large-scale embankments.

4.0 DATA ACQUISITION

4.1 Survey Design

It is important to design a field survey carefully according to the survey objectives and site characteristics. Ideally 2D surveying should be carried out with the electrode layout perpendicular to the geologic strike direction, or in the case of an embankment, electrode layouts perpendicular to the crest of the dam. With such layouts, the 2D interpretation approach provides a good approximation. However, often it is not feasible to use such layouts on embankment dams due to difficult access and electrode contact problems on, for example, the downstream side of the dam. Thus, an electrode layout along the top of the dam core is often the most practical and in many cases the only possible option for performing resistivity measurements on existing dams. On some dams measurements can also be conveniently carried out along the downstream toe and on berms.

When 2D surveying is carried out along the crest of the dam it is important to be aware that 2D inversion of the data leads to very strong violation of the basic assumptions. Since measurements are carried out along the extension of the structure, the properties vary strongly in the direction perpendicular to the electrode layout in contradiction to the assumptions. The zonation of the dam with material of different electrical properties leads to higher current density in the more conductive zones, mainly the dam core and reservoir water, and less current density in the highly resistive parts of the embankment. Numerical modelling presented by Sjödahl et al (2006) illustrates this clearly (Figure 4-1). This variation in properties results in so called 3D effects, which lead to an apparent strong increase in resistivity towards depth compared to the resistivity of the dam core. In this example the reservoir water is assumed to have very low conductivity (high resistivity), as is the case in northern Sweden, and in cases with more conductive reservoir water the current distribution would shift towards the reservoir.

The high current density in the dam core means that surveying along the core of the dam will be sensitive to variation in electrical properties of the dam core, which is precisely what is required. Hence, surveying along the dam crest can be used to locate anomalies in space and time, but it is important to be aware that both the resistivities and the depths of the inverted models will be distorted. If the berms and the downstream toe are available for electrode layouts this can provide valuable additional information. Electrode layouts on the upstream side in the reservoir are another option, but are more demanding logistically with need of a boat(s) and possibly divers. Data from underwater layouts also require accurate water depth data for each electrode in the interpretation.

In cases where it is possible to do surveys perpendicular to the dam it is recommended to do so at sections selected on the basis of variations indicated in the survey(s) along the dam or indications from other methods. If it is feasible to carry out many closely spaced 2D lines perpendicular to the dam, the data can be merged to carry out 3D inversion, which should increase the detection ability and improve the definition of a weak zone.

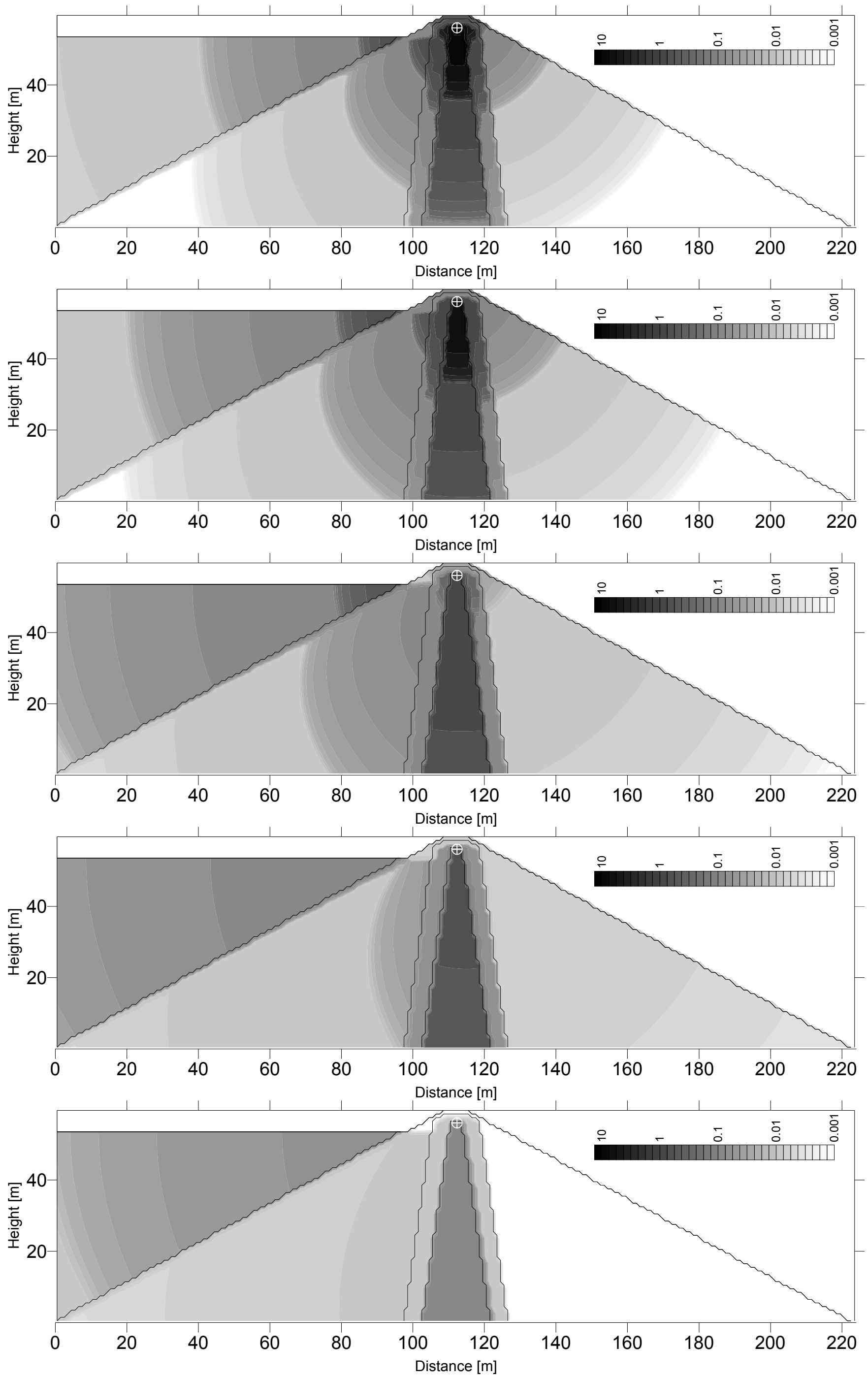


Figure 4-1 **Current density in the cross-section in the center between the current electrodes (mA/m2 at 1A transmitted current).**
Distance between current electrodes increasing from above: 20m, 40m, 100m, 200m and 400m (from Sjödahl et al. 2006).

4.2 Equipment and DA Software

Resistivity measuring equipment consists of a current transmitter and a voltmeter. Simple steel spikes may be used as electrodes. Cables are needed to connect the instruments to each electrode. Multi-electrode systems characteristically use multi-core cables with one take-out for each electrode. These systems also need an electrode selector, a switching device that is controlled by the computer to select the appropriate electrodes for each measurement. There are systems with built in computers, but also systems that use an external PC. For field measurements, there is a variety of instruments or packages of instruments on the market. Systems used as permanent installations for dam monitoring have some specific requirements.

4.2.1 Instrumentation

Multi-electrode data acquisition equipment for electrical imaging designed for engineering and environmental applications is generally suitable for dam investigations. Such equipment typically consists of a resistivity instrument, often with capability to measure induced polarisation (IP) as well, a relay switch (electrode selector), multi-electrode cables, stainless steel electrodes and various connectors (Figure 4-2; Figure 4-3). Most modern instruments have a built-in computer that can handle the entire data acquisition process and memory capacity to store days of measured data. Sometimes there is an option to control the system from an external computer as well for better control of the data acquisition process via the larger screen of the PC. For some systems the relay switch is integrated in the instrument, whereas for some it is an external unit that is connected to the instrument with a cable. There are also systems with distributed electrode switches, i.e. relays at each electrode (Dahlin 2001). ABEM Lund Imaging System, AGI Sting and IRIS Syscal are examples of commercially available data acquisition systems.

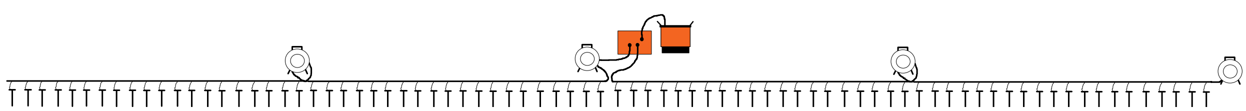


Figure 4-2 Sketch of a resistivity data acquisition system with 4 electrode cables linked together on a line, and the relay switch and instrument connected at the midpoint.

The instrument consists of a transmitter capable of transmitting direct current (DC) pulses of typically up to around 400V. Maximum current output lies around 1A, but there is a power limit that is often in the range 100-200W. It should be noted that these currents and voltages are dangerous, and it is essential that the field crew is fully aware of this. The operator must always keep all parts of the equipment including instrument, electrode selector, electrode cables, electrodes etc. under control and away from unauthorized persons and stray animals while the system is operating in order to avoid accidents!

Figure 4-3 Picture showing an example of a commercially available data acquisition system, consisting of instrument, relay switch, electrode cables, stainless steel electrodes, cable jumpers and connection devices.

The input side comprises one or several voltage measuring channels, which should have input impedance at least in the range 10MΩ. Instruments with multiple channels have the advantage of offering much more efficient data acquisition process, whereas single channel instruments often leave the field crew to spend a good part of the day in the field waiting for the instrument to take measurements. The time to take the actual measurements depends on the measuring protocol, selected integration times, stacking, etc. One measurement will typically take a few seconds, and with stacking of data and several hundred or even thousands of different data points measured on an electrode spread it can take long time.

It is essential to use good quality electrode cables that withstand the harsh climatic and mechanical conditions that are common in dam investigations. Electrodes usually are made of stainless steel, which has acceptable electro-chemical properties for resistivity measurements. It is fundamental to provide sufficiently good electrode contact, which may require substantial work in form of hammering down and watering of electrodes. The most common source of data quality problems in electrical imaging is when the contact resistance between electrode and ground is too high.

Layouts used for 2D electrical imaging typically consist of several tens of electrodes (most often in the range of 28 to 81 electrodes). Obviously, using a larger number of electrodes has the advantage of giving larger survey depth while maintaining high near surface resolution. Even if the objective is to look deep, good near surface resolution is of interest as it leads to improved model definition at depth. Switching between different combinations of electrodes is done automatically via the relay switch, according to pre-defined measurement protocols. These measurement protocols can be designed to measure with any of the common electrode arrays, or use non-traditional arrays. It is, however, crucial to design these protocols to provide a good data cover, sufficient depth penetration and adequate signal-to-noise ratio. In the case of multi-channel instruments some of the traditional electrode arrays, such as for example Wenner, are not suitable as they do not lend themselves to multi-channel data acquisition approaches. Each measurement protocol consists of hundreds or even thousands of different electrode combinations that each give rise to one data point in the resulting data file.

Measurement lines are extended via a so called roll-along procedure, in which part of the electrode layout is moved and more data points are added. In order to get an even data cover for the longest electrode separations, the portion of the array that is moved should not be too large, and a quarter of the total layout is often suitable for 2D imaging. The roll-along procedure can be repeated.

The instruments use commutated DC pulses with measuring cycles that must be designed to filter out telluric currents, electrode charge-up effects, power grid noise, etc (see section 4.3 below) in order to get data of adequate quality. Each individual data point is generally stacked and evaluated statistically to secure data quality.

IP data of adequate quality can be measured with a standard layout for resistivity imaging in cases with favourable site conditions, such as low electrode contact resistances and modest noise levels (Dahlin et al. 2001). Problems with capacitive coupling in the multi-electrode cable arise if the electrode contact resistance is high, and in areas with conductive ground, inductive coupling may be a problem. One way forward in such cases is to use separate cables for current transmission and potential reading (Leroux and Dahlin 2003; White et al. 2003).

There are data acquisition systems designed for towed array surveying available (for example Århus PACES system and Geometrics OhmMapper), but these are not likely to function well in many cases in dam applications due to high contact resistances and noise problems apart from the limited depth of investigation. For levees that are rather low and elongated with grass cover these methods may, however, work well.

The data acquisition systems described above can, with some modifications, also be used for monitoring of embankment dams. An important addition is lightning protection that should be designed with individual protection for each electrode input connected to the system, as well as for power supply and modem telephone connection. Since the seasonal variation is the main interest in monitoring it should normally not be necessary to measure more often than once a day, which in turn means that a single channel instrument should be adequate unless it is a very large electrode installation.

4.2.2 Electrodes

For resistivity a single measurement surveying standard steel spikes is usually the electrode choice, although a lot of hammering and watering may be needed on embankment dams. In resistivity monitoring with permanent installations careful design and installation of electrodes is crucial, and should be given high attention. The interface between electrodes and ground must offer good and stable conditions for electric conduction to ensure that current can be passed into the ground easily. Proper installation of electrodes is important to avoid high electrode contact resistances and troublesome noise levels. For poor installations high contact resistances will lead to lower current levels and lower signal-to-noise ratios.

Often self-potential (SP) measurements are also to be carried out by the monitoring equipment. The typically very small potential readings from such measurements make the method very vulnerable to polarisation effects in the interface between electrode and ground. Therefore special non-polarisable electrodes are normally used for SP measurements. Non-polarisable electrodes consist of a metal electrode embedded in a solution consisting of a salt of the same metal, often with a gelling agent added for stability. Commonly used electrodes are copper-copper sulphate, lead-lead chloride or silver-silver chloride electrodes (Corwin and Conti 1973; Petiau and Dupis 1980; Corwin 1984; Milsom 1996; Friborg 1997). However, apart from being more expensive these electrodes may in some cases restrict the monitoring capacity, as non-polarisable electrodes are normally not used as current electrodes. It may be that certain types of non-polarisable electrodes could function as current electrodes without damaging their low noise properties for SP, but no results of any study investigating this have been found. A concept of in-situ built electrode was presented by Thunehed and Triumf (2001) for SP monitoring at a dam site in northern Sweden.

Figure 4-4 Installation of electrodes at Hällby. Left: Resistivity electrodes (steel plates). Right: Non-polarisable SP electrodes (copper-copper sulphate in bentonite-filled pre-packaged cloth bags).

Multicore cables are recommended to connect each electrode to the instruments. This is the most convenient way for installations, as special designed pre-made cables can be ordered in advance. Cable take-out intervals at the planned electrode separation and distance to the first take-out are chosen to fit the local requirements. Special care must be taken when connecting the electrodes to the cable take-outs to ensure good contact and lasting performance. Preferably the electrodes can be connected to polyurethane (PUR) covered stainless steel wires (Figure 4-4) to be joined to cables splits (pig-tail splits) on a PUR covered multi core cable. It is essential to seal any contact point between different metals, such as copper of the cable and stainless steel of the electrode, from contact with water to avoid corrosion and loss of function.

Another important issue for installation of permanent systems is the electrode spacing. A shorter distance between the electrodes gives more electrodes and increases resolution, as the measurements are denser. Furthermore, shorter electrode spacing resolves the upper layers better, which in turn may remove uncertainties at larger depths. The drawback is that more electrodes demand more capacity from the cables and instruments, which increases the costs not only from the electrodes themselves but also for the other parts of the system.

In Sweden installations with 3 m electrode spacing for a 30 m high dam have turned out to be a reasonable compromise. Stainless steel plates have served well as resistivity electrodes (Figure 4-4), and the selected electrode dimensions of 250x250x1 mm ensure sufficient surface contact.

4.2.3 Data Acquisition Software

Data acquisition software is generally specific for each equipment manufacturer and at least for surveying with mobile equipment usually built into the instrument. It is beyond the scope of this guide to go into details of different software, but it is of course crucial that the operator is well versed with the software used and chooses suitable data acquisition parameters for the survey in question. Some general points can be raised.

The measurement sequence including choice of electrode arrays and data density is generally defined in protocol files (in ASCII format), which are simply a list of the different electrode combinations to measure. Typically, one line specifies C1, C2, P1, P2 for one measurement in the case of single channel measurement, and for multi-channel measurements more columns are added for the other channels. The protocol files refer to an electrode cable geometry that at least for some systems is also defined in a file in ASCII format. Measuring protocols for standard cable geometries and electrode arrays are delivered with the equipment, and could be a good choice for an operator who is not an expert in designing measuring protocols. In some cases, however, tailor made protocols are required, especially in the case of monitoring installations where each layout tends to be unique.

In order to maintain good data quality it is essential to ensure proper electrode contact, as mentioned before in this guide. The data acquisition should have provisions for and always be set to test that the electrode grounding is adequate before actual surveying starts. This is done either by trying to transmit a current at the requested level, or by measuring the contact resistance, for all electrodes in the layout.

It is of paramount importance to set the data integration properly so that power-line noise, for example, is suppressed efficiently. The instrument should thus be set for either 50 Hz or 60 Hz depending on the power grid frequency, so that the instrument integrates over a number of full power line frequency periods. In cases of operation close to a railway the integration time may need to be set to integrate over full multiples of 16 $^{2}/_{3}$ Hz.

Data acquisition parameters such as measuring current, measuring delay (time from current-on until actual measuring starts), integration time, data stacking etc. should be adapted to site conditions. It is generally recommended to do some test measurements and analyse the results before deciding on the set-up for the survey. It is also essential to keep an eye on the data stability and quality during the entire survey, and make adjustment such as for example improving the electrode contact if needed. If negative data values turn up it is generally a sign of problems that must be addressed before measuring proceeds, by checking that all electrodes are properly connected and grounded, that the electrode cables have been rolled out in the right direction and connected in the right places etc.

4.3 Error Sources

Noise sources in resistivity investigations are plentiful. Examples of noise in urban environments include metal objects in contact with the ground, such as cables, metal pipes and fences. Other sources are active noise from the 50 Hz power grid and telluric noise.

Geometric errors are introduced in the measurement if the electrodes are placed incorrectly as the geometric factor will be wrong. For 2D surveying a slight error in the placement of an electrode along the line have much graver consequences for the results compared to a misplacement of an electrode off the line (Zhou and Dahlin 2003).

Measurement procedures can be adjusted to minimise the disturbances from noise. As has already been discussed, different arrays have different sensitivity to noise. In survey areas where much noise can be expected, measurements with less sensitive arrays could be preferred. Monitoring techniques will reduce noise that is not time-dependent. The use of permanently installed electrodes eliminates variation in electrode misplacement errors over time.

Assuring good grounding conditions is essential in order to minimise effects from noise. Bad grounding conditions lead to high electrode contact resistances, which in turn results in transmission of lower current levels. Low current levels lead to small potential readings and hence low signal-to-noise ratios. High contact resistances can also lead to capacitive coupling in the electrode cables, which may completely ruin the data quality.

During measurements, repeated readings from the same configuration should be used to check data stability. A high variation coefficient from the same configuration is a sign of poor signal-to-noise ratio. Charge-up effects are another source of noise in resistivity measurements. In this case electrical charge is stored at the interface between the ground and the electrodes, which affect the next measurement. For this reason a measurement sequence should preferably not include an electrode that measures the potential immediately after it has been used as a current electrode (Dahlin 2000).

Typical noise sources that have been seen at dam sites are steel sheet walls, concrete structures, metal objects, grounding cables, other cables and metal pipes for instrumentation among others. These noise sources can in many cases be expected not to vary much with time, and therefore can be eliminated or reduced when interpreting long-term monitoring data. However, it should be recognized that variation in water content may lead to changes in coupling between a metal object and the soils materials of an embankment. It is important to know as much as possible about potential sources of disturbance, as they may significantly mislead interpretation of resistivity values. A complementary survey with a magnetometer or metal detector can be valuable for identifying such sources of disturbance.

4.4 In-field Data Quality Control

It is essential to keep an eye on the data acquisition process in the field to ensure good data quality. Basic data quality assurance is, as mentioned, done via stacking and statistical evaluation of the individual data points. However, even if data is highly repeatable there may be serious errors inherent in the data due to one or more of the sources outlined above. Hence, in-field data quality control is a very important part of the data acquisition process. A basic requirement of the data acquisition software, whether built-into the instrument or running from an external computer, is that it displays the data as it is being measured. A simple way to do this is to list the measured resistances or apparent resistivities together with a statistical measure of the stability of the data on the screen.

The following chapter describes different useful tools for data quality assessment, like graphical tools for viewing data and editing away bad data points. Ideally, it should be possible to plot data on-line in the field in different ways, for example by viewing the measured samples of the individual measuring cycles and plotting data in pseudosections.

When carrying out a field campaign in a remote area it is mandatory to do sufficient data quality assurance by for example pseudosection plotting and preliminary inversion while at the site. In this way one can avoid having to travel back to the site to re-do the survey because of poor data. Furthermore, a preliminary evaluation of the data on-site can be valuable for guiding the continued investigation on the basis of the preliminary results; for example, by locating key areas for follow up by additional measurements.

5.0 DATA PROCESSING, INVERSE MODELLING AND INTERPRETATION

Processing of resistivity data includes data quality assessment, inverse numerical modelling and presentation and analysis of the results. Checking data quality is usually performed by plotting the pseudosection. Checking of data also includes removal of apparently erroneous data points, and in some cases weighting of data in relation to reliability can also be performed. Subsequently, inverse numerical modelling is carried out on the data set, and the final model or alternative models are presented and analysed. For standard resistivity investigations this is usually done manually in steps as explained above. However, for long-term monitoring it becomes too time-consuming and automatic routines are necessary. Such automatic routines need to be robust and simple, but still have the capacity to perform the individual steps of the data processing scheme.

5.1 Data Quality Assessment and Noise Removal

Data quality assessment can be done by examination of the pseudosection, see the example in Figure 5-1. The pseudosection is described in section 2.3.1. It gives an initial indication of the resistivity distribution in the ground, but inverse modelling is needed for interpretation. The pseudosection can, however, be used for presentation of raw data and assessment of data quality. Erroneous data points, due to e.g. poor electrode grounding or instrument malfunction, can be detected. Bad data points due to e.g. noise from man made structures such as metal pipes, will however not always be detected by visual control of the pseudosection.

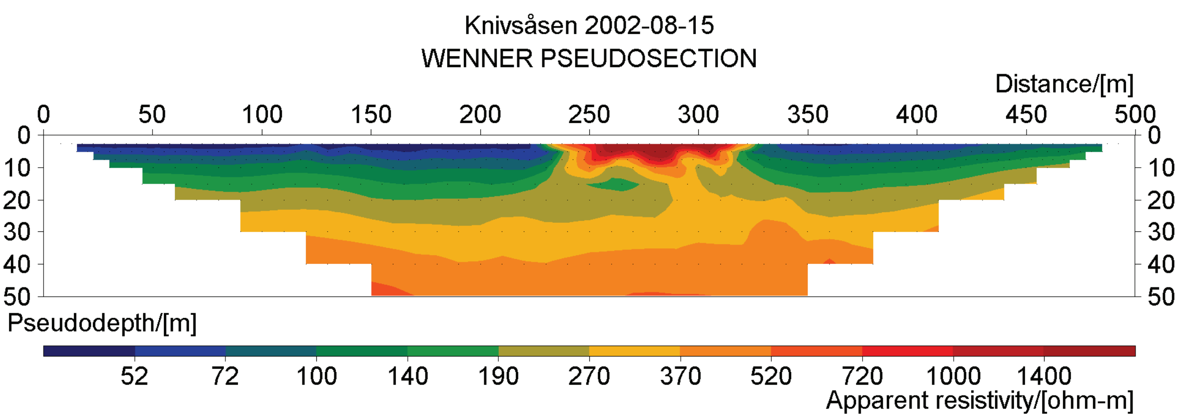


Figure 5-1 Example of Wenner array pseudosection.

It is possible to edit away bad data points in different ways. One way is to open the data file in suitable spreadsheet software and sort the apparent resistivities in increasing order and simply delete data with unrealistically large or small values. This method only works for rather extreme outliers in the data, and care must be taken not to remove valid data; however, used together with pseudosection, plotting it can be useful.

A better way is to use software where data can be plotted as a profile for each electrode spacing and n-factor, and bad data can be removed by clicking on them. The "Exterminate bad datum points" feature in Res2dinv (Loke 2004) is an example of such a tool for editing away noisy data points

(Figure 5-2). The Aarhus Workbench[1] is another option. It may, however, be more difficult to identify which are the noisy data points for arrays with a mix of different separations and n-factors than for e.g. Wenner data. It is common that such plots have an apparently noisy character even for very good data quality. Newer versions of the abovementioned software have facilities plot multiple gradient array data in a way that facilitates editing, provided the array type is properly specified. See example in Figure 5-3.

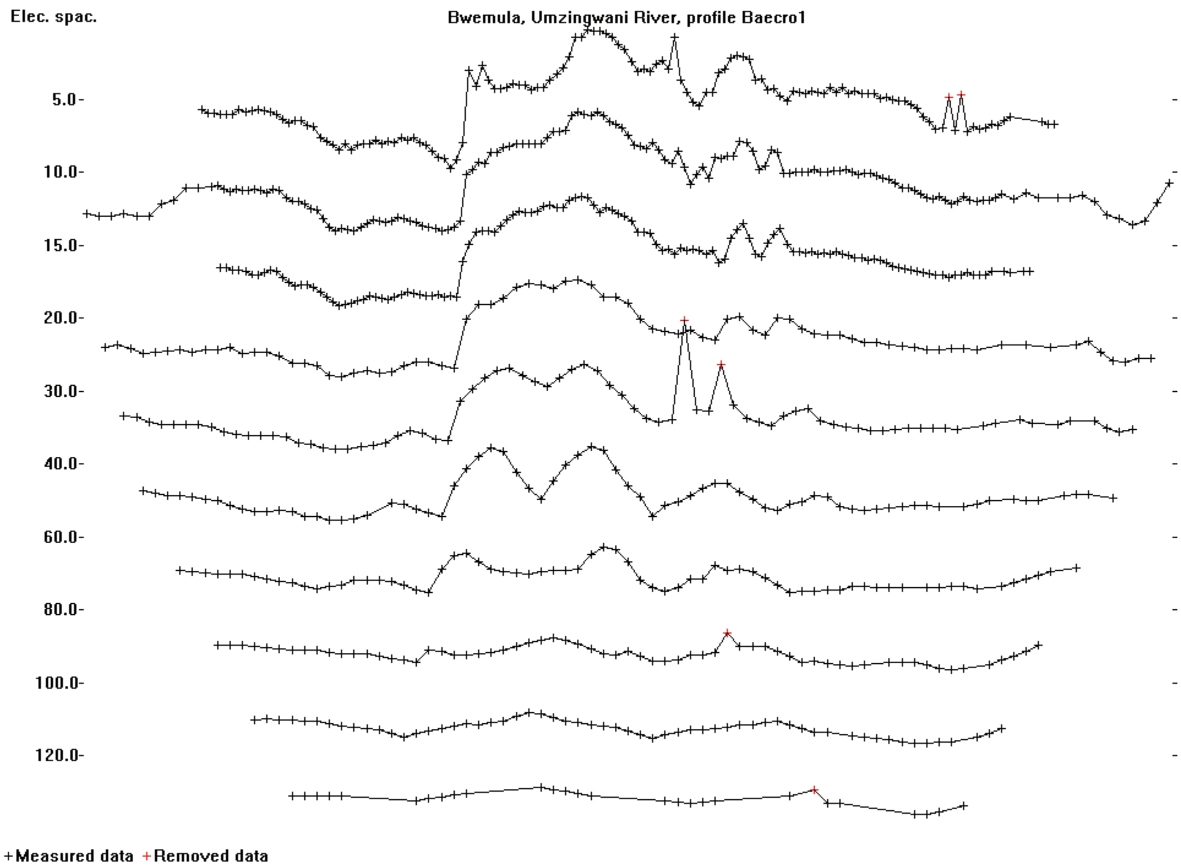


Figure 5-2 **Bad data points can for example be edited away by clicking on them using the "Edit bad datum points" in the inversion software Res2dinv.**

[1] http://www.hgg.au.dk

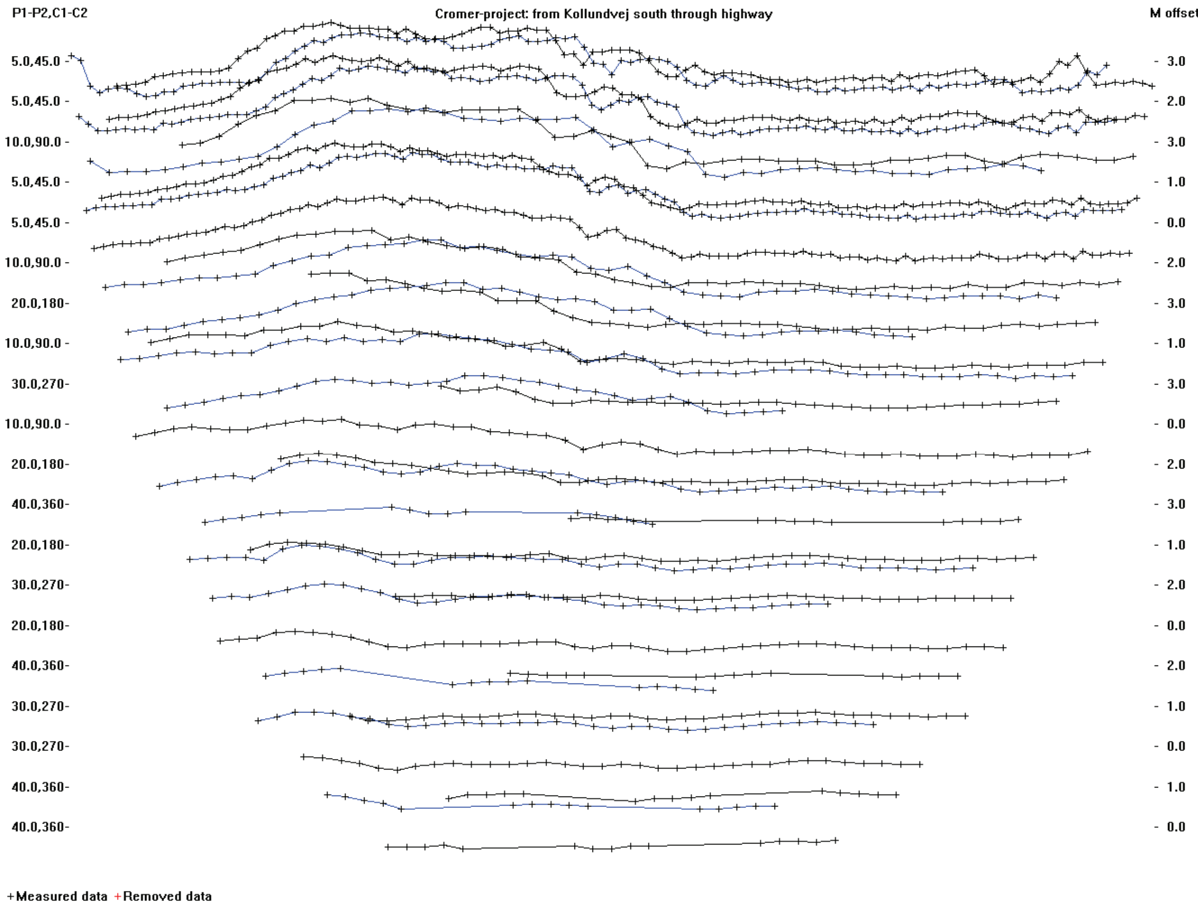


Figure 5-3 Example of edit data screen for multiple gradient array data.

The reciprocity principle can be used to assess the data quality of the measurements. In a four-electrode configuration a reciprocal measurement is carried out by switching places between the two current electrodes and the two potential electrodes. According to the reciprocity principle the measured potentials from normal, R_{normal}, and from reciprocal measurements, $R_{reciprocal}$, should not be affected by switching positions of the electrodes. By carrying out measurement both ways, the errors in percent, e_{obs}, can be evaluated directly (Equation 5-1).

$$e_{obs} = 100 \cdot \frac{\left| R_{normal} - R_{reciprocal} \right|}{\left(R_{normal} + R_{reciprocal} \right) / 2} \qquad \text{(Equation 5-1)}$$

For monitoring systems it is recommended to carry out such measurements, at least initially, to establish that the data quality is of satisfactory quality. This may be repeated at different seasons to check how the data quality is affected by factors such as variation in ground moisture content and freezing. It gives valuable information and at the same time it is easy to carry out with automated systems. Error levels may be affected by, for instance, different grounding conditions for the electrodes and noise disturbance from capacitive coupling in cables (Dahlin 1993).

5.2 Time Series Data Filtration

Automatic routines for data quality control and removal of erroneous and bad data is necessary for monitoring data. It can be demanding to make such routines efficient. The easiest algorithm simply removes extremely high and extremely low values. However, it is in the nature of resistivity data to vary within five to six order of magnitudes and that makes it complicated not to remove the correct data and vice versa. Another idea is to have a special predefined range for each measurement configuration, within which the data may vary. Such routines may be introduced after a few measurements have been performed and should preferably be revised and refined after a longer period.

One approach is to process data by means of a time base filtering, where for example median filtering (7-day or 15-day based), an infinite impulse response (IIR) filtering (predictive filtering) or finite impact response (FIR) filtering (sliding filter) are possible options. Median filtering simply means taking the median value of all daily measurements for a certain data point from e.g. a week. A low-pass filtering method using the IIR routine has been tested on Swedish data as well, based on Equation 5-2:

$$\rho_{n+1}^{f} = \frac{\rho_n^{f} + f \cdot \rho_{n+1}^{m}}{1+f},$$ (Equation 5-2)

where ρ_{n+1}^{f} and ρ_n^{f} are the filtered value from time step *(n+1)* and *n* respectively, and ρ_{n+1}^{m} represents measured raw data for time step *(n+1)*. The factor f may be 0.2, for example. In addition, a maximum threshold for the impact of a new data value (e.g. 0.4 of the present filtered value) acts as a de-spiking filter. In order not to shift the filtered data series towards higher dates, the filter is run forwards and backwards, and the average is taken as the filtered data. In the Swedish case the filter factors were determined by trial-and-error through plotting raw data and filtered data together, and adjusting the filter factors until sufficient noise rejection was obtained without suppressing the natural variation in the data.

The success of this approach is dependent on good start values at each end of the time series. If a heavily distorted start value is used, it will shift a large portion of the filtered series. To avoid this, an approach that can be described as a median-mean may be adopted to find suitable start values, in which the initial data points (from e.g. a couple of weeks) are sorted and a mean is taken after excluding a number of data points in each end of the sorted table. However, if a longer break in the data series should occur particular care needs to be taken to assure a good filter function.

5.3 Inverse Numerical Modelling

Inverse modelling is needed to interpret the true resistivities of the subsurface. This can be performed by commercial inversion packages, such as Res2dinv[2] (Loke and Dahlin 2002; Loke 2004), EarthImager2D[3] and SensInv2D[4], which perform 2D smoothness constrained inverse modelling.

[2] Geotomo Software; http://www.geoelectrical.com

[3] Advanced Geosciences, Inc.; http://www.agiusa.com

There are also software packages available that can be obtained for free for academic and non-commercial use, for example DC2InvRes[5], Res2d[6] and DCIP2D[7]. In the inversion with 2D inversion software 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 so that the differences between the model response and the measured data (the model residuals) are minimised. This can be done either minimising the absolute values of the differences (inversion with L_1-norm or robust inversion), or minimising the squares of the differences (inversion with L_2-norm or smoothness-constrained least-squares inversion).

Inversion with 3D models is also available. However, apart from being more computationally demanding, it requires field data with a surface cover, or at least a considerable number of relatively closely spaced 2D lines that can be combined for the inversion. Examples of commercially available 3D inversion software are Res3dinv[2], EarthImager3D[3] and SensInv3D[4].

The smoothness-constrained (L_2-norm) method is a commonly used version of regularised least-squares optimisation. This method minimises the sum of squares of the spatial changes in the model resistivity and the data misfit. It gives good results where the subsurface geology exhibits a smooth variation, such as a gradual change in fine material content in a soil or a gradual change in chemical composition and data quality is good. However, in cases when a sharp transition in the subsurface resistivity is expected, e.g. the contact between a fine-grained dam core and fresh igneous rock of the foundation, this method tends to smear out the boundaries and create overshooting and undershooting on each side of the boundary. An alternative method is the L_1-norm optimisation method that tends to produce models with regions that are more blocky, i.e. piecewise constant and separated by sharp boundaries. This might be more consistent with the known geology in some situations (Loke et al. 2003). A major advantage of the L_1-norm is its better robustness against noise. This may be important when handling monitoring data, as robustness against noise is particularly valuable for automatic routines.

Time lapse inversion, described in section 2.3.3, is an interesting approach for treatment of monitoring data. It means that data sets from different points in time are inverted together, where the first recorded data set would normally be regarded as a reference. In time-lapse inversion, a smoothness constraint is applied not only on the spatial variation but also on the temporal variation between the data sets. This approach has been shown to focus the difference between the data sets on the actual change in the model and suppress artefacts due to the resistivity structure (Loke 1999; Loke 2001). The model obtained from the inversion of the initial data set is used as a reference model to constrain the inversion of the later time-lapse data sets.

In dams, the resistivity can be expected to vary in a cyclic manner over the year, and hence some average of the variation over the year might be used as a reference data set. This, however, has the

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[4] Geotomographie GmbH; http://www.crosswellinstruments.de/html/geoelectric.html

[5] Thomas Günter; http://resistivity.net/

[6] Bing Zhou, University of Adelaide; http://www.adelaide.edu.au/directory/bing.zhou#Files

[7] University of British Columbia Geophysical Inversion Facility (UBC-GIF); http://www.eos.ubc.ca/research/ubcgif/

disadvantage of damping the data from different seasons unevenly in cases of large seasonal variation and thereby making evaluation more problematic. Instead, a sliding damped data set can be used when analysing the data. In this case, the reference data set follows the actual data set, but with a strong damping that suppresses noise (Johansson et al. 2005a).

5.4 Presentation and Analysis of Result

Data from 2D surveying can, as previously mentioned, be presented as raw data in pseudosections and as a final resistivity model after inverse numerical modelling. For monitoring data, the variation in time is important, and parts of the dam can be studied in detail by special presentation of the result.

Using pseudosections for direct evaluation is generally not performed in most applications. Apparent resistivities might be misleading as different electrode arrays have different sensitivities on different locations and depths. However, evaluating apparent resistivities can be an important tool for data quality analysis. Moreover, in connection with monitoring over long time series and in situations where absolute values are less important it might be useful to also evaluate apparent resistivities. Apart from studying pseudosections, data from single measurement points, which represent single points in the pseudosections, can be plotted over the full monitoring period.
A resistivity model, i.e. the final inverted model, of the subsurface is fundamental for resistivity investigations. For monitoring data a large number of resistivity models are produced over a given period. Presenting the mean or median inverted model together with some measure of the distribution of the variation (e.g. Equation 5-3; Equation 5-4) is then of interest, as this gives a quick overview of the situation and the variation inside the embankment. The mean or median model section serves only as an overall inspection and a source of information in the decision of where possible detailed examinations should be carried out.

It is clear that the relative variation (Equation 5-3) is a rough measure on the variation, which has the advantage of not being affected if some data may be missing as long as the extremes are included.

$$V_r = (\rho_{max} - \rho_{min}) / \rho_{median}) \qquad \text{(Equation 5-3)}$$

Alternatively the variation coefficient (Equation 5-4) can be used.

$$V_c = \sqrt{\frac{\sum_{i=1}^{n}\left(\rho_i - \overline{\rho}\right)^2}{n-1}} \bigg/ \left|\overline{\rho}\right| \qquad \text{(Equation 5-4)}$$

If there is a longer period of missing data it will affect the variation coefficient, but not the relative variation unless the maximum or minimum value is absent. In any case, these are simple statistical tools, but still useful for the purpose of quickly analysing the complete model section. The variation section can be used to select points for a detailed presentation of data, in order to analyse the change in resistivity over time at a certain point in the model section.

So, to summarise, the rough evaluation technique described here, involves first looking at the inverted model sections using the median and the relative variation as very simple statistical tools and then checking in more detail those zones that turn out to be interesting.

5.5 Interpretation of Results

Interpretation of the inverted models should be done with the aid of as much complementary data as possible. This depends on ambiguities in the inversion process caused by equivalence, suppression, 3D effects etc, and ambiguities in the interpretation of resistivity values in terms of material type. Access to good documentation of the embankment, surrounding structures and the foundation is important for a correct interpretation of the results. Monitoring records of reservoir water levels, temperature and electrical conductivity are also essential, especially for interpretation of monitoring data. Furthermore, results from monitoring with other methods such as temperature in standpipes or along the dam toe, can provide valuable additional information for the interpretation.

Supplementary information can also be provided from investigation with other geophysical methods. Magnetic gradiometers or metal detectors (e.g. Geonics EM61) can provide important information on the location of non-documented or poorly documented metal objects that may affect the measurements. Seismic methods investigate different material properties, and can be a very useful combination with resistivity imaging. Ground penetrating radar (GPR) may also be a useful complement in some cases. For monitoring, one or a combination of these methods can be used for a baseline survey in the initial phase of the programme, to serve as a foundation not only for the interpretation of the results, but possibly also as input for the design of the monitoring set-up.

Induced polarisation (IP) can be measured along with resistivity. It has not been used to any significant extent on dams so far, but has a potential of adding different information that may prove to be valuable for detecting anomalous behaviour of an embankment. Streaming potentials (SP) have been given a role in embankment dam investigations due to the immediate link to flow in porous media, and should when appropriate be combined with the resistivity investigations.

6.0 EXAMPLES AND LESSONS LEARNED

In the following section field measurements from three Swedish dam sites are presented. The first one covers a dam safety investigation at Enemossen tailings dam, where resistivity measurements were one method in a broader investigation approach. The other two examples cover long-term monitoring of the embankment dams at Hällby and Sädva. These are particularly interesting, as experience from such long-term monitoring is rare. Permanent monitoring systems were installed at Hällby in 1996 and in Sädva in 1999. Long time-series with daily measurements have been recorded at both these dams.

6.1 Enemossen

A dam safety investigation was conducted at the Enemossen tailings dams close to the Zinkgruvan mining site in southern Sweden (Sjödahl et al. 2005). The investigation comprised temperature, resistivity, induced polarisation (IP) and self-potential (SP) measurement together with standard visual inspections of the dams. The aim of the study was to examine the extent of the damage around earlier reported sinkholes and to examine the overall integrity of the dams.

Large volumes of ore are mined at the Zinkgruvan mine, and the majority of the tailings are stored at the Enemossen tailings facility. Enemossen covers an area of 0.60 km^2 and contains a volume of seven million m^3, which is stored in two embankment dams with total length of 1340 m and a maximum height of 27 m. The oldest parts of the dams were built in 1976, and as the mining activity expanded, the dams were raised five times resulting in an unusual layout of the core (Figure 6-1).

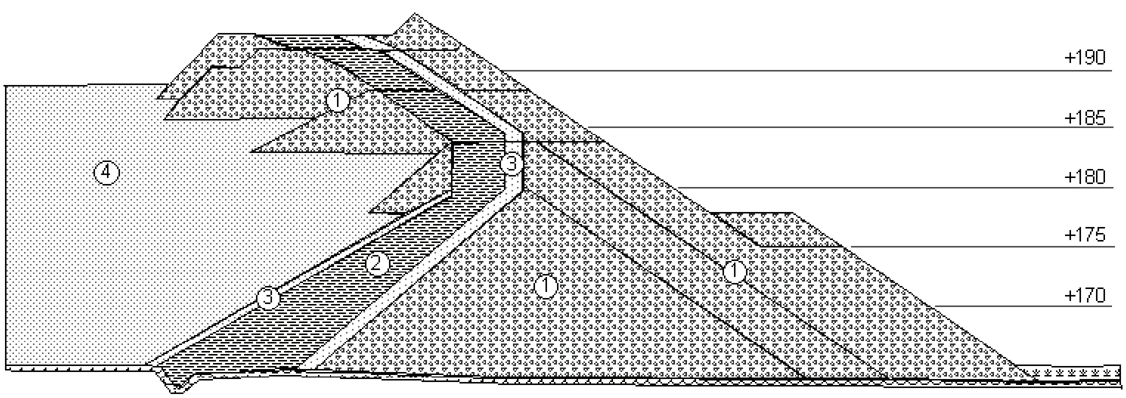

Figure 6-1 Cross-section of the X-Y dam at Enemossen. (1) Support fill (downstream and upstream), (2) Core, (3) Filter, (4) Tailings. Level refers to meter above sea level.

The tailings are discharged into the containment area as a slurry through a system of pipes and the resistivity of the outflow mix of tailings and water is approximately 10 Ωm. This low resistivity for Scandinavian conditions is explained by the high level of dissolved solids (TDS) in the tailings water. As a consequence, possible leakage zones are likely to stand out as low-resistivity areas.

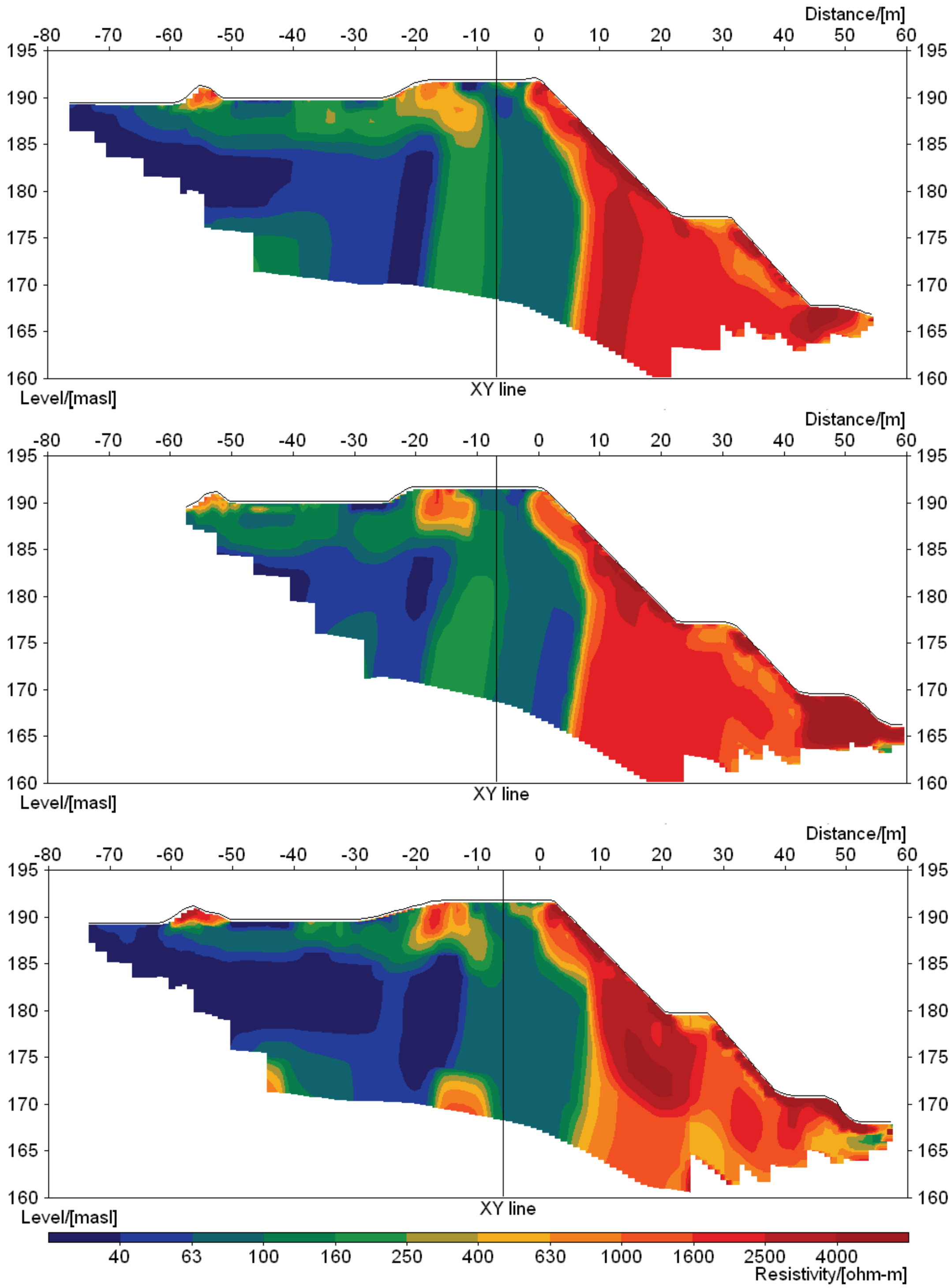

Figure 6-2 **Inverted resistivity cross-sections from the X-Y dam.**
Top: chainage 0/471 m (mean residual 3.1%). Centre: chainage 0/492 m (mean residual 3.3%) Bottom: chainage 0/310 m (mean residual 1.7%). Level refers to meters above sea level and chainage to length along the dam in meters. The XY line refers to the crossing of the longitudinal measurements along the dam crest.

Longitudinal 2D measurements along the dam crest provided an overview of the dam and based on results from those measurements and information about reported problem areas, three cross-sections on the X-Y dam were selected for detailed measurements (Figure 6-2). In general the resistivity distribution along the three cross-sections shows many similarities and fits well with what could be expected from the cross-section diagram of the dam (Figure 6.1) and a basic knowledge of the resistivities of dam construction materials.

Some characteristic features are generally recognised. All sections illustrate the low resistivity of the tailings, with the ground water surface also identified thanks to the well-sorted character of the fine sand. The coarse rockfill in the constructed pier on top of the tailings (at –55m) as well as in the upstream and downstream support fill are observed as highly resistive zones. Furthermore, the inclined shape of the low-resistive dam core at the top is identified. Apart from the similarities, a few differences were also distinguished in the cross-sections. One is the low-resistive zone beneath the upstream fill immediately upstream of the core; this zone is more prominent in the section at chainage 0/310 m. This could be related to anomalous seepage and fits well with the occurrences of previous sinkholes. A lower resistivity is also seen in the downstream fill at this chainage, which may be caused by a higher content of fine material.

The overall conclusion from the investigation was that none of the detected resistivity anomalies needed any immediate further investigation. The area around the latest reported sinkhole at chainage 0/500 m is similar to other parts of the dam, even though the downstream part of the core has a lower resistivity in the cross-section of 0/492 m. In general, known problem areas at Enemossen are associated with low resistivities. However the resistivity measurements alone did not provide enough information to confidently come to a decision about the status of the dams.

6.2 Hällby

Hällby was the first Swedish embankment to get a permanently installed resistivity monitoring system. Daily measurements started in 1996, making these a unique long-term monitoring data series (Johansson et al. 2005a).

The embankment dam at Hällby is divided into a left and a right flank with a centrally placed power plant and spillway structure (Figure 6-3). The left dam is 120 m and the right dam is 200 m long. Both dams have a maximum height of around 30 m and are constructed as a zoned rockfill embankment dam with a vertical central core of glacial till and filter zones. The reservoir at Hällby stores a maximum volume of 625 million m^3, and the reservoir level variations are less than 0.8 m.

The dam is classified into the highest consequence class in RIDAS, the Swedish guidelines for dam safety. A sinkhole was observed on the left dam in 1985, located close to where the dam connects to the intake structure. This sinkhole at Hällby was repaired by grouting. After additional drilling on the right dam it was decided to grout the area close to the spillway on the right embankment dam as well (Bronner et al. 1988).

The monitoring installation comprises full instrumentation for resistivity measurements. Except for the resistivity system, until 2003 the dams were sparsely monitored with only a few piezometers and a drainage system measuring leakage from the left dam. In 2004 the drainage system was updated and new piezometers were installed. Furthermore, starting in 2004 both the left and the right dam were reinforced by a seven-meter wide zone of coarse rockfill placed on top of the entire length of the downstream face of the embankment. At the same time the dam core was also raised and therefore all land-based electrodes at Hällby have been reinstalled.

The electrode installations were made somewhat imprudently. The electrodes on the right dam crest were placed above an unsuspected thermal insulation layer, and the electrodes along the upstream slopes were not positioned properly. However, the measurements from the left crest and the right downstream toe have been functional, though the data has shown considerable noise. On reinstalling the electrodes during 2004 and 2005 (Figure 4-4; Figure 6-3) the same type of successful installation as in Sädva (Johansson et al. 2005a) has been aimed for.

Detailed analysis of the monitoring data can be performed by examining resistivity over time in certain areas of the model section. In Figure 6-4 a few selected depths at two locations on the left dam, chainages –61.25 m and –43.75 m, are presented in this form.

The area around chainage –61.25 m has been very stable over the full monitoring period and is considered a healthy part of the dam, whereas around chainage –43.75 m some deviation from the assumed pattern of variation has been observed at a depth of 19.9 m. The area closest to the intake between chainage 0 m and chainage –40 m is not covered by the method due to large depths.

Figure 6-3 Hällby dam during the reinstallations of electrodes in 2005. The top of the right dam crest is excavated and new electrodes are being placed out, every second being a non-polarisable electrode (white bags). The downstream slope has been reinforced with additional rockfill. In the background are the spillways, the intake to the power station (high building) and the left embankment dam.

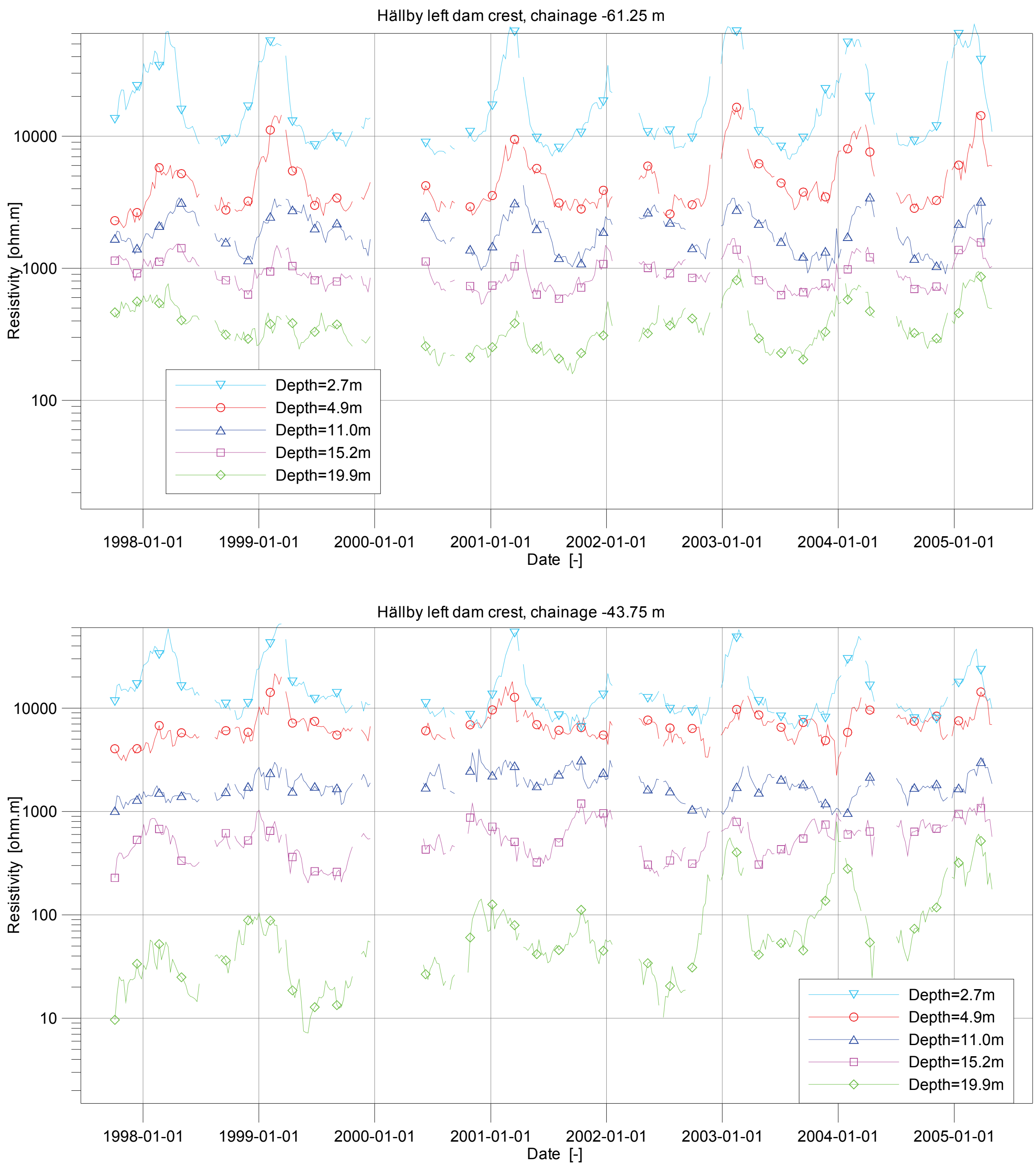

Figure 6-4 Time series of inverted resistivity data at five different depths from two different locations on Hällby left dam.
Top: chainage –61.25 m at the healthy part of the dam. Bottom: chainage –43.75 m showing tendencies expected from internal erosion at large depths.

In general, for both locations, the variation is high close to the crest, which is explained by extremely high winter resistivities due to ground freezing. For chainage –61.25 m the amplitude of the variation becomes lower at larger depths. This is the typical appearance for most of the examined parts of the dam and consistent with theory as the impact from seasonal temperature variation in the reservoir or in the air decreases with depth below the surface for a healthy dam. At chainage –43.75 m, however, there are significant variations at large depths. Furthermore, there are signs of increasing variations and increasing absolute resistivities for the deepest depth.

These large variations in resistivity may be a sign of higher seepage flow, and the increased resistivity may be a sign of material change due to washout of fines and internal erosion. The increased variation in combination with increased resistivity is possibly a sign of increased seepage due to the internal erosion.

Without other observations from additional investigations it is not possible to verify if internal erosion and increased seepage are the reason for the observed anomalies. However, these signs have not been observed in any other part of the dams and this area is next to a known problem area. The high variation at the bottom of the dam has spread from right to left over the last two to three years and the zone at the same depth (19.9m) between chainage –10 m and chainage –20 m is a known problem area where sinkholes have been reported in the past. Unfortunately there are so far no other measurements in this specific area. The seepage monitoring system for the left dam indicates no significant change, although a small trend may be seen. An increasing pore pressure has been observed in the pressure sensors located closer to the intake structure at chainage 0 m. None of these observations are, however, strong enough to confirm an internal erosion process.

6.3 Sädva

Regular daily resistivity monitoring started at the Sädva embankment dam in 2001. Electrodes and cables along the dam crest were installed in 1999. Based on the problems experienced at Hällby, a new improved installation was designed that has generated high quality resistivity measurements (Johansson et al. 2005a).

The Sädva dam is located in the upper part of the Skellefteälven River just south of the Arctic Circle. It has a reservoir storage volume of 625 million m3. The dam and power plant were commissioned in 1985. The total length of the dam is 620 m, sub-divided in a 210 m long main dam across the old river channel and a 410 m long dyke along the old river channel. The maximum height of the main dam is 32 m, and the dyke is considerably lower, averaging around 10 m. The dam is a rock fill embankment dam with a slightly inclined central core made of fine-grained glacial till. The main dam is founded on bedrock, while the dyke is founded on moraine except where it connects to the main dam. Annual water level fluctuations are around 16 m (+460.7 - +477.0 m.a.s.l.), which is half the height of the dam. These high water level variations constitute a complication in the evaluation of the resistivity measurements, but at least the seasonal pattern is roughly the same from one year to the next. The reservoir reaches maximum levels in the late summer to early autumn and declines initially rather slowly during autumn and then more rapidly during the winter to reach the lowest levels in early spring. It fills up again very rapidly during late spring to early summer due to the vast snowmelt.

The high reservoir fluctuations affect the resistivity measurements at Sädva. Numerical modelling has shown that water level changes in the order of half the reservoir height may affect apparent resistivities by up to 50 percent or more (Sjödahl et al. 2006).

The same kind of evaluation of the monitoring data as done for Hällby has also been carried out for Sädva, and the difference between the two dams is obvious. Firstly, the data quality has improved significantly resulting in smoother data with less noise. This is a consequence of the improved installation. Secondly, the variations are smaller and also consistent along the length of the dam, which may be a sign of a healthier dam with generally lower seepage flow rates. The only exception is a zone immediately next to the spillway where both the resistivities and the resistivity variations are higher. However since no other observations indicate problems in this zone, it has been interpreted as an effect from the concrete spillway structure. More analyses are required to achieve a high degree of confidence concerning the reason for the diverging measurements in this zone.

The homogeneous conditions in the main dam are evident from the time series for five monitored depths at chainage 82 m (Figure 6-5). The appearance is typical for most parts of the main dam with the characteristic seasonal variation. All depths inside the dam demonstrate similar conditions, with only small changes in resistivities and in the size of the seasonal variations between different depths.

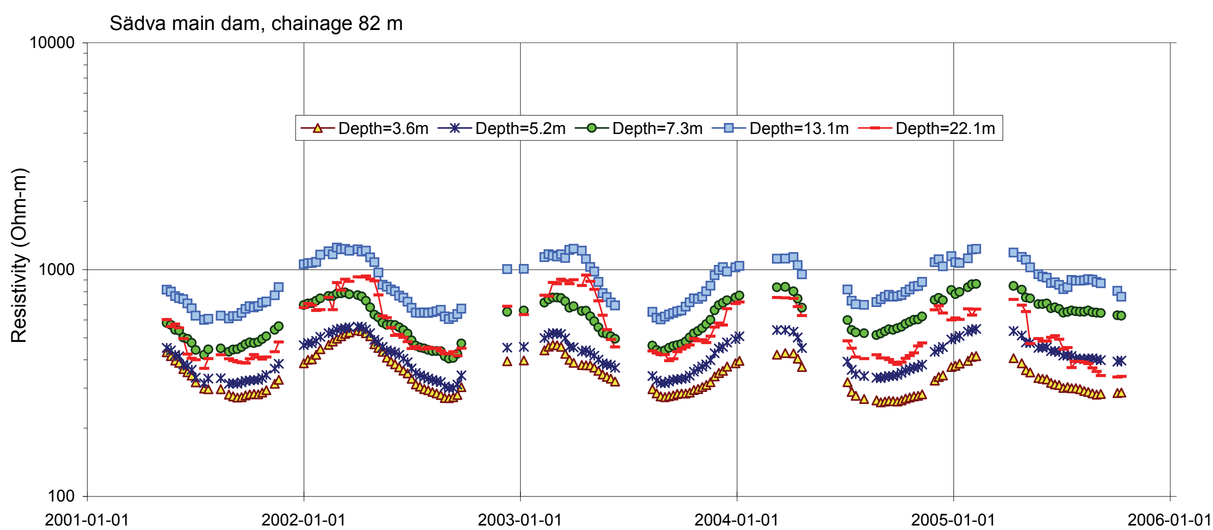

Figure 6-5 Time series of inverted resistivity data at five different depths at chainage 82 m from Sädva main dam over the period from 2001-05-12 to 2005-11-25.

The conditions along the dyke are not as homogeneous as for the main dam. The resistivities in the dyke are generally higher than in the main dam and also varying more along the length of the dam (Figure 6-6 top). The most obvious inhomogeneity is the large difference in the foundation around chainage 450 m, which is probably due to a variation in rock type or rock quality in the underlying rock. Clearly higher relative variation also occurs in the same area and this suggests the possible presence of a seepage path through the foundation (Figure 6-6 bottom).

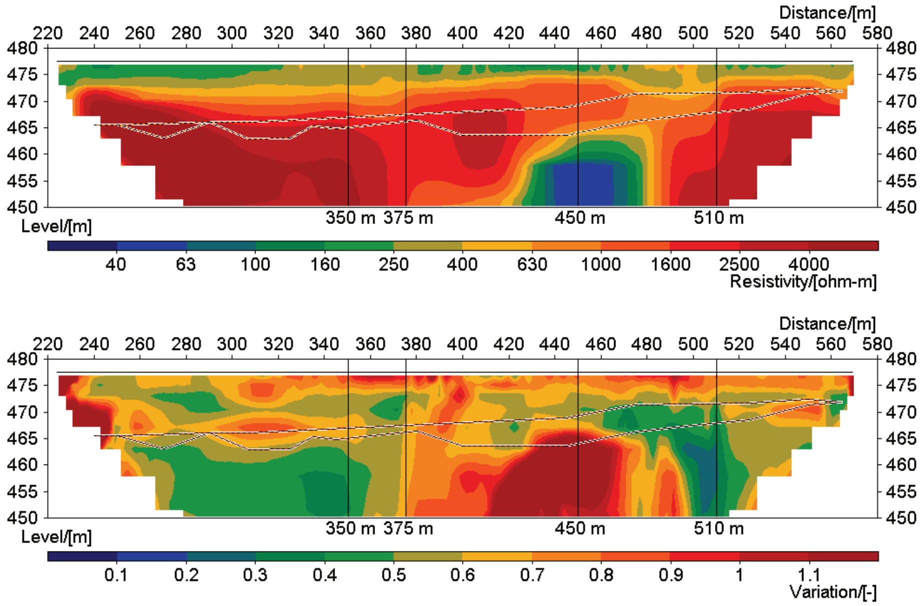

Figure 6-6 Sädva dyke longitudinal model sections with foundation and bedrock level indicated (solid lines).
Median inverted model of resistivity distribution (top) and relative variation of inverted resistivity models (bottom), over the period from 2001-09-20 to 2005-11-25. The four investigated areas at 350 m, 375 m, 450 m and 510 m are marked out. The investigated depth of 20 m corresponds to the level 458 meter above sea level.

Four different areas were selected for qualitative evaluation. The areas are all situated at the same depths but at different distances along the dam at chainages 350 m, 375 m, 450 m and 510 m. They are marked by vertical lines in Figure 6-6. A depth 20 m, corresponding to the level 458 meter above sea level, was selected. It is below the lowest reservoir retention level, implying that the soil will be saturated throughout the year. The dam geometry is also almost identical in all areas, so a similar resistivity variation may be expected at all four areas provided the seepage flow regimes are similar.

The seasonal variation is examined in detail for each of the four areas (Figure 6-7). The seasonal variations in the selected areas ranges from 12% at chainage 510 m to around 75% at chainage 450 m. By comparing different areas along the embankment, the most sensitive areas can be identified. These may be potential leakage areas. Such areas can then be given extra attention in the future monitoring. Early detection of a trend of increasing seepage is of great value for the overall safety of embankment dams.

A quantitative seepage evaluation method was also tested for the area around chainage 450 m. This method is based on principles put forward by Johansson (1997) and later more thoroughly described by Sjödahl (2006). A total seepage flow in the order of one litre per second was estimated for the whole area around chainage 450 m, which is reasonable. However considering the extent of the simplifications and assumptions, the quantitative evaluation method must be seen as an initial test at this stage. More work is needed to refine the method. Nevertheless there are in fact few or no reliable methods capable of quantifying the seepage flow through embankment dams, and a result merely in the right order of magnitude is valuable for dam safety purposes.

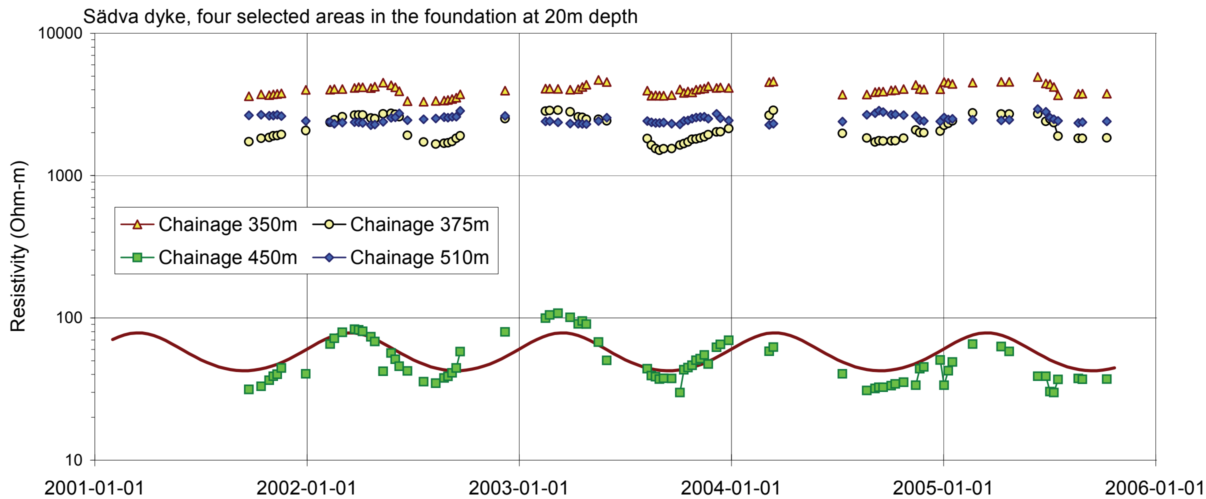

Figure 6-7 Seepage evaluation in the foundation of Sädva dyke.
The four selected areas are located at 20 m depth. Data from the low resistivity area around chainage 450 m exhibit higher variation than the other areas. The line represents an approximate method to quantify the seepage by trying to fit a calculated response from an assumed seepage flow rate of 3.0x10-5 m3/(s,m).

6.4 Discussion on Field Examples

At Enemossen a dam status investigation was conducted using mobile resistivity surveying equipment with no repeated measurements in time. As opposed to long-term monitoring, this type of one-time survey is at present the standard approach to resistivity surveying of dams.

The survey at Enemossen was instructive, highlighting a few special aspects. One aspect was the ability to measure along lines crossing the dam. Cross-section measurements are not often carried out due to practical problems of extending the line into the reservoir and sometimes also due to problems of attaining adequate electrode contact in the highly resistive downstream support fill. When carried out however, cross-section measurements are informative since the 2D inversion will not be disturbed by severe 3D effects. Thus the results obtained will reflect the true subsurface resistivities and not be only a qualitative comparison in space or in time.

Another important experience from the Enemossen survey was that it emphasized the fact that electrical properties are highly site specific. At Enemossen, the reservoir resistivity was approximately 10 Ωm, whereas in the reservoirs at Hällby and Sädva the resistivity was in the order of several hundreds of Ωm. Due to this difference a leakage area might stand out as low resistivity in one situation and high resistivity in the other. Thus information about the background resistivity of the reservoir is essential for dam leakage investigations.

The investigations at Hällby demonstrate the strength of the monitoring approach. From the long-term measurements an anomalous zone was identified. The conclusion that this anomaly is associated with internal erosion and anomalous seepage is plausible but cannot be confirmed by the resistivity monitoring data alone. Nevertheless it is clear that without monitoring, i.e. with only a single investigation, the anomaly would never have been discovered.

The experience from Hällby also demonstrates the importance of combining different measurement techniques to support interpretation. This is a fundamental rule in all geophysical investigations and applies here also. The dilemma on embankment dams is that intrusive investigations are normally strongly avoided. Furthermore many Swedish dams are sparsely monitored and therefore it may be difficult to acquire adequate reference data.

Finally the experience at Sädva confirms the advantages of the monitoring approach compared to single measurements and emphasizes the importance of appropriate electrode installations. With good data quality there is a possibility that the method may progress from qualitative appraisal for finding anomalies in time or space to a quantitative method for evaluating seepage flow rates through dams, although at present such evaluation involves many assumptions and simplifications.

7.0 SUMMARY AND GENERAL RECOMMENDATIONS

The resistivity method is an established method widely used in many engineering and environmental applications. The method is described, from a theoretical as well as practical viewpoint, in this guide.

In the past the method has been used for dam applications with a varying degree of success. One obvious advantage is that the method is non-intrusive. Other advantages are the ability to cover large areas rapidly and its suitability to long-term monitoring. Of fundamental importance is the physical coupling between the resistivity parameter and seepage or seepage paths.

The rapid development of data acquisition and data processing has bolstered the possibility of using the method effectively for dam applications. Long-term monitoring with spatially denser data points can now be achieved and is necessary to achieve satisfactory measurement resolution in the challenging conditions posed by the three-dimensional dam geometry. For dam applications it is natural to distinguish between single measurements and repeated measurements, as the evaluation methodology and potential target of the investigation may differ between the two approaches. In general for both approaches it is important that the method is used together with other methods to secure good reference data.

Single time resistivity surveys are performed with standard mobile equipment. These can be used for the detailed investigation of known problem areas in an embankment dam. Survey design depends on type of damage suspected. Single investigations can also be used for standard dam safety investigations. In such cases measurements along the dam are recommended to cover a larger area and if possible to combine these with cross-section measurements for more detailed information at selected areas, based on the information obtained from the initial measurements. Single investigations may also be performed in conjunction with SP surveys to provide resistivities for SP data interpretation.

Resistivity monitoring is performed with permanently installed electrodes. In addition to qualitatively identifying anomalies in space, such measurements also provide a time series, which on further analysis may provide data for a quantitative evaluation of seepage in specific regions. The monitoring approach is based on two principal ideas that may both be recognized by studying the time-series. Firstly the washout of fines due to internal erosion will affect the resistivity in the dam. Secondly seasonal resistivity variations in the reservoir, originating from variations in temperature and ion content, will affect the resistivity in the inner part of the dam as the seepage water propagates through the dam.

The monitoring approach is without doubt much more powerful than single investigations, in that it provides more reliable data and allows one to draw conclusions from the characteristics of the variations. The drawbacks are that monitoring is more expensive as it requires a permanent installation. Moreover a certain reference period, preferably one year, is needed before the method of analysing time series can be used to its full potential.

The expected result from a single investigation is at best a qualitative comparison of different regions along the dam. With monitoring data, the qualitative comparison can be done between different time steps, which may identify any progressive changes. Long time-series may be able to provide approximate seepage estimation, using similar reasoning as in the analysis of temperature data. Work is in progress in Sweden for improving these evaluation methods.

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APPENDIX A. FORWARD MODELLING

The constitutive law governing the current flow in the subsurface is Ohm's law (equation A-1).

$$\mathbf{J} = \sigma \mathbf{E} \qquad \text{(Equation A-1)}$$

where J is the current density, σ is the distribution of electrical conductivity in the subsurface, the inverse of the resistivity, and E is the electric field. The electric field is the gradient of a scalar potential *U* (equation A-2).

$$\mathbf{E} = -\nabla U \qquad \text{(Equation A-2)}$$

When no sources or sinks are applied, the divergence of the current density equals zero (equation A-3).

$$\nabla \mathbf{J} = 0 \qquad \text{(Equation A-3)}$$

Combining equation A-1 and equation A-2 gives equation A-4.

$$\mathbf{J} = -\sigma \nabla U \qquad \text{(Equation A-4)}$$

Rewriting equation A-3 and equation A-4 gives equation A-5.

$$\nabla(-\sigma \nabla U) = 0 \qquad \text{(Equation A-5)}$$

Equation A-5 is Poisson's equation when no current sources are present. In the presence of a point source, or current electrode, the divergence of the current density can be described by a Dirac delta function and a point current I (Coggon 1971). In equation A-6, I is the amount of current injected at r_s.

$$\nabla \mathbf{J} = I\delta(\mathbf{r} - \mathbf{r}_s) \qquad \text{(Equation A-6)}$$

Using these descriptions of sources Poisson's equation becomes:

$$\nabla(-\sigma \nabla U) = I\delta(\mathbf{r} - \mathbf{r}_s) \qquad \text{(Equation A-7)}$$

For the 2.5D approximation the potential is in three-dimensions because of the 3D point source, but resistivity, the model parameter, is constant in the strike direction, or y-direction that is perpendicular to the layout direction. This allows for simplifications, and technically, the calculations are simplified into pseudo-2D by placing the source at y=0 and applying the Fourier cosine transform with respect to the y-coordinate (e.g. Coggon 1971; Zhou 1998; Zhou and Greenhalgh 1999).

The Poisson equation (equation A-7) for full 3D or the Fourier transformed simplified equation for 2D is then typically solved numerically by dividing the subsurface in a number of discrete cells and solving by matrix inversion techniques. The most common numerical methods are the finite differences or the finite element method, and some commercial software allows a choice between either of these methods.

Two types of boundary conditions are used. At the surface a Neumann boundary condition is applied (the potential gradient in the normal direction is zero) due to the infinite resistivity of the air. At the other boundaries a Dirichlet boundary condition can be applied and the potential set to zero. This is true only sufficiently far away from all possible positions of the current electrodes, which must be considered when constructing the mesh. A more efficient and also more common method is therefore to apply a mixed boundary condition (Dey and Morrison 1979) along the non-air boundaries.

APPENDIX B. FORMULATION OF THE INVERSE PROBLEM

Inverse numerical modelling (inversion)

The inversion procedure is applied to solve the following equation (equation B-1),

$$\left(\mathbf{J}_i^T \mathbf{R}_d \mathbf{J}_i + \lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W}\right)\Delta \mathbf{r}_i = \mathbf{J}_i^T \mathbf{R}_d \mathbf{g}_i - \lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W} \mathbf{r}_{i-1} \qquad \text{(Equation B-1)}$$

where $\mathbf{g}_i$ is the data misfit vector representing the difference between the logarithms of the measured and calculated apparent resistivity values, $\Delta\mathbf{r}_i$ is the change in the model parameters for the ith iteration and $\mathbf{r}_{i-1}$ is the model parameters vector for the previous iteration, containing the logarithm of the model resistivity values. **J** is the Jacobian matrix of partial derivatives and **W** is a first-order roughness filter (deGroot-Hedlin and Constable 1990). The damping factor λ determines the relative importance given to minimising the model roughness and data misfit. $\mathbf{R}_d$ and $\mathbf{R}_m$ are weighting matrices introduced to modify the weights given to the different elements of the data misfit and model roughness vectors. By adjusting the form of these weighting matrices, the L_1- or L_2-norms can be used in the data misfit and model roughness minimisations. A more detailed description of the inversion method is given in Farquharson and Oldenburg (1998).

Time-lapse inversion

For evaluation of repeated resistivity data using time-lapse inversion the optimisation equation (equation B-1) is modified such that it also minimises the difference between the logarithm of the model resistivity values of the later time data set and the initial time data set. The modified equation used is given by equation B-2,

$$(\mathbf{J}_i^T \mathbf{R}_d \mathbf{J}_i + \lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W})\boldsymbol{\delta}\mathbf{m}_i^k = \mathbf{J}_i^T \mathbf{R}_d \mathbf{g}_i - \lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W} \mathbf{m}_{i-1}^k - \beta_i \lambda_i \mathbf{V}^T \mathbf{R}_t \mathbf{V}\left(\mathbf{m}_{i-1}^k - \mathbf{m}_{i-1}^0\right) \qquad \text{(Equation B-2)}$$

where $\mathbf{m}^0_{i-1}$ and $\mathbf{m}^k_{i-1}$ are the model parameter vectors for the initial data set and the kth time data set. The additional term, $\beta_i\lambda_i\mathbf{V}^T\mathbf{R}_d\mathbf{V}(\mathbf{m}^k_{i-1} - \mathbf{m}^0_{i-1})$, on the right-hand side of the above equation constrains the change in the model for the kth time data set such that the difference between the model resistivity values for this data set and the model for the initial time data set (which serves as a reference model) are also minimised. β is the relative weight given to this cross-model constraint and **V** is the cross-model weighting matrix that determines the characteristic that we wish to introduce in the differences in the model resistivity values. For example, if a simple damped or Marquardt (Lines and Treitel, 1984) cross-model constraint is used, then **V** is the identity matrix **I**. $\mathbf{R}_t$ is the weighting matrix that modifies the weights given to the different elements of the model difference vector such that the L_1 or L_2 norm can be used (Farquharson and Oldenburg, 1998). If it is known that the time changes in the model resistivity values vary temporally in a smooth manner (for example a chemical plume that spreads by diffusion), then the L_2 norm constraint can be used. Alternatively, if it is known that the changes are expected to occur abruptly in relation to the monitoring interval, the L_1 norm constraint is more appropriate.

APPENDIX C. CHECKLIST FOR FIELD MEASUREMENTS

The following list may be used as a help when planning and packing for a field campaign. However, do not forget to review the list critically and to modify it for the different requirement in every case:

- Resistivity instrument (with controlling computer if needed).
- Relay switch / electrode selector (unless built-into the instrument).
- Interconnecting cables(s).
- Electrode cables.
- Cable joints (if applicable).
- Sufficient quantity of electrodes.
- Sufficient quantity of cable to electrode connectors (cable jumpers).
- At least an additional double amount of electrodes and jumpers if operating in areas with dry ground giving contact difficulties.
- Batteries for power supply of the equipment including sufficient spares (often regular car batteries, and better gelled lead-acid batteries that are easier to handle and do not leak).
- Polyurethane covered hammers (two or more) for hammering down electrodes.
- Remote electrode cable(s) if pole-pole or pole-dipole array is used.
- Plastic bottles for water with added salt and viscosity increasing polymer, to improve electrode contact in dry ground. A drill mud polymer (such as Johnson Revert or similar) added to the water can increase the viscosity to prevent draining away during measurement in permeable soils. Mix salt and polymer with water to suitable viscosity, it may be wise to do this in buckets before pouring the mixture into plastic containers of convenient size.
- Spray paint and pegs to mark out profile lines.
- Non-metallic tape to measure distance from profile line to reference objects, or to measure electrode spacing if smaller spacing than the take-out spacing are to be used.
- A set of walkie-talkies if cables with long electrode take-out spacing are used (i.e. more than 2 meters between each take-out).
- Levelling equipment and / or GPS receiver.
- Tool and spares kit.
- Pocket multimeter with continuity check function for error detection.
- Sun shade / parasol for instrument (and operator) if hot weather can be anticipated.
- Rain protection for equipment (and operator) if rain or wet snow can be anticipated (small plastic bags over the electrode cable multi pole end connectors are recommended to avoid water entering when connecting and disconnecting).