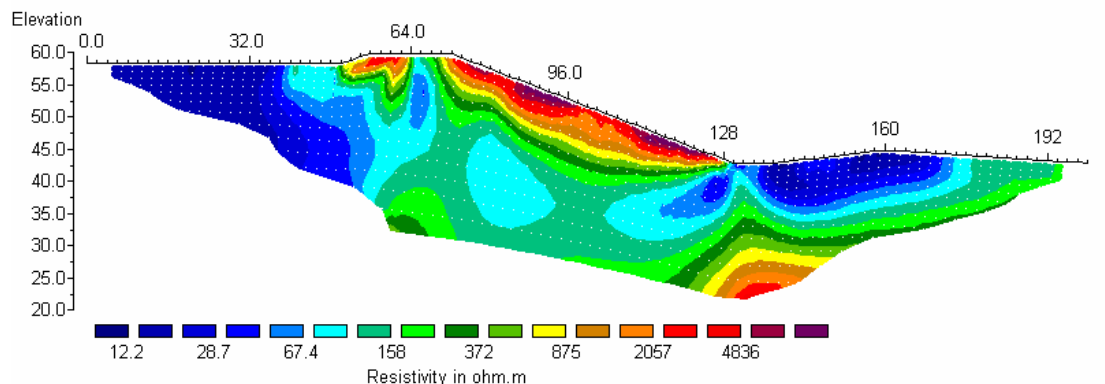


Monitoring of Tailings Dams with Geophysical Methods



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2006:07 | ISSN: 1402-1757 | ISRN: LTU-LIC-- 06/07 -- SE

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Never put off till tomorrow
What you can do today

Lord Chesterfield, 1749

Abstract

Several dam failure accidents have occurred during the last years and mine tailings dam failures are occurring at relatively high rates. Studies of past earth dam failures show embankment dam problems and failures are often related to internal erosion in one way or another. Geophysical methods have the potential of detecting internal erosion processes and anomalous seepage at an early stage of their development. The methods have been tested to monitor and investigate earth dams; however the methods have not been used very much in mine tailings dam.

The present study has been conducted to test the applicability of geophysical methods, mainly electrical resistivity and self-potential (SP), for detecting anomalous seepage through mine tailings dams and monitoring the physical condition of the dam. Field measurements of resistivity and self-potential have been performed in the Kiruna, Aitik and Kristineberg tailings dams to look for streaming potentials, inhomogeneities and time variations of electrical properties and self-potentials. SP and resistivity measurements have also been carried out with fixed electrodes in the Kiruna and Kristineberg dam at a roughly monthly interval during one year starting in November 2003 and ending in October 2004. Laboratory measurements of resistivity have been carried out on different soil samples from the tailings dams to look for eventual changes in electrical properties with change in grain size and water content.

The electric resistivity survey in the Kristineberg provides a good image of the subsurface resistivity distribution associated with filling materials and water table in the dam. The results of the electrical resistivity survey from 2004 on the Kristineberg tailings dam are fairly similar to those obtained from in 2003. The SP distribution in the dam also reveals that there are no significant changes in SP values from 2003 to 2004. The resistivity from the fixed potential electrodes closed to the current electrodes indicates a seasonal variation in the apparent resistivity representing the freezing and thawing effect within in the dam. The SP measurements from the fixed electrode at the Kristineberg dam, shows fairly stable values during summer and more unstable during the winter probably due to change in contact resistance.

The result from the 2002 SP measurements in the Kiruna dam reveals a general pattern of positive SP values at the downstream side, which is in agreement with the expected result of streaming potentials developed over the dam core. The dam was raised during the summer 2003 and new SP measurements were repeated thereafter during the autumns of 2003 and 2004 in the same areas as for the 2002 measurements. The results from 2003 measurements deviate from 2002 measurements; with in general, more negative potentials along the downstream slope. The potential distribution obtained from the 2004 measurements is compatible with the results obtained before the raising of the dam. The SP data from the fixed electrode shows unsteady physical conditions within the dam after increasing the height of the dam. The apparent resistivity from fixed electrode survey is much influenced by the variations of the pool level of the tailings pond.

Some positive SP anomalies on the downstream slope of the IJ-dam at Aitik have been identified that could be related to the seepage through the dam. A distinct positive anomaly at

the coordinate 7451330 north that continues to the toe of the downstream slope of the dam is generated from a known seepage of the water.

The laboratory measurements on soil samples from the dams reveal a decrease in resistivity as finer particles are added to the samples that contained coarser fractions. Internal erosion may thus be reflected by an increase in resistivity.

This work has demonstrated the potential of using resistivity and self-potential methods for monitoring the physical condition, and the time changes in the condition of mine tailings dams.

Acknowledgements

Many people have helped me during the years I have been working with this thesis. I would hereby like to express my gratitude to them.

My supervisor, Professor Sten-Åke Elming for giving me this opportunity, for arranging funding for this work, for providing guidance and support, for valuable discussions and not least for critical reading and correcting this manuscript, which has improved it in many ways.

My assistant supervisor, Dr.Hans Thunehed for providing much guidance and support for this work, for discussions and for helping in the filed works. He has also provided a critical reading of this manuscript and valuable suggestions for its improvement.

Professor Dattatray Parasnis, for his devoted time to discussions and suggestions.

Swedish Institute for providing partial financial assistance of this study.

Maj-Len Knutsson, for taking care of me in this foreign country and helping me in many ways. She had the patience to listening to my poor Swedish from the beginning and she always asked “Hur är det?” when I met her.

Roger Lindfors for his help with fixing equipments for field work and his assistance in the laboratory work. Timo, Malte and Stefan for their help the in the field measurements.

My colleagues at Division of Ore Geology and Applied Geophysics and also Applied Geology, for their friendliness and interesting talk during coffee break.

My friends at Porsögården 14, (Elin, Jonas, Frida, Harry, Sofia, Martin, David, both Anna, Annika, Magnes, Peter ...) introducing Swedish life and cultures to me and avoiding my loneliness.

Anders and Karin for their hospitality, encouragement and all support.

Professor Uday kumar, Aditya Parida and their families for their kindness, encouragement and fun. They made my work and life a lot easier in Luleå.

Kancha and Helena for their help and warmth. They always welcome me to their home during my stay here in Luleå.

Finally, I would like to express gratitude to my mother and father for their support, inspiration and understanding.

Ganesh Mainali
February, 2006
Luleå, Sweden

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1. Introduction

Instability problems of large dams and the possibility of a dam failure threaten the safety of people and industrial property as well as cause substantial environmental effects. Several dam failure accidents have occurred during the last years. Mine tailings dams failures are occurring at relatively high rates. The rate of failure has actually increased in recent years since a previous peak that occurred in the early-mid 1930's. Many of these failure events have resulted in massive damage in the form of human casualties, destruction of property, pollution of the environment and economic loss to the mining industry. During last 10 years, 21 major tailings dam failures in the world have been reported, including Aitik tailings dam failure in Sweden. Dam safety has increased in importance all over the world due to the recent failures that have occurred and the increased consciousness among the people and society and media interest. In Sweden, the hydropower companies have dealt with the dam safety issues for decades, while mining companies were turned into increased attention from the middle of the 1990's due to increased height of the tailings dam. Most of the mining companies have developed their own guideline for dam safety.

Studies of past earth dam failures show three major causes: (1) seepage and internal erosion in the embankment (2) seepage and erosion of the foundation and (3) erosion of the overtopping (ICOLD, 1995). Saturation of embankment soils, abutments, and foundations due to seepage generally result in reduced soil strengths leading to sloughing, sliding, and instability. When water flow through poorly compacted soil, e.g. in an embankment dam, internal soil erosions will take place. During internal erosion, the fine grains in the core of a dam are flushed away by seeping water and as a consequence the hydraulic conductivity in the remaining material will increase. High velocity flows through the dam embankment can cause progressive erosion and piping of the embankment or foundation soils. Thus internal erosion caused by seeping water constitutes a significant threat to the stability of embankment dam. Statistics from the International Commission on Large Dams (ICOLD, 1995) show that embankment dam problems and failures are often related to internal erosion in one way or another. The seepage rate depends mainly on the hydraulic conductivity of the core which is strongly dependent upon the core material and its compaction. The identification and investigation of internal erosion is not easy as it can be much localized. The usual way to indicate or monitor internal erosion is by e.g. visual inspection, pore-pressure measurements and measurement of seepage water volumes in dikes below the dam. It is crucial for dam safety to be able to detect internal erosion by non-destructive methods at an early stage of development. To describe the condition of dams, in part for safety reasons, dams need regular inspection and monitoring. Supervision and regular monitoring of the tailings impoundment with suitable techniques are probably the most important requirements to obtain a high level of dam safety.

As the physical properties of the materials in the dam may be expected to change due to internal erosion and seepage of the water; geophysical methods have the potential of detecting internal erosion and anomalous seepage. The use of geophysical techniques is generally appealing due to their non-destructive and often cost-effective advantages over other methods. Geophysical methods have also been used in the study of dams, (e.g. Butler et al; 1990; Al-Saigh et al; 1994; Carlsten et al; 1995; Panthulu et al; 2001; Titov et al; 2000 and Sjödhall et al; 2004). Most studies have been performed on hydro-electrical dams since the conditions on mine tailings dams have been considered more complicated due to the electrically conductive water filling the pore volumes and the possible presence of ore minerals in the dam body. Geophysical methods may thus play important roles in monitoring the integrity of the dam

and detecting anomalous seepage conditions on the dams at the early stage of their development.

The principle objective of the present study is to test the applicability of geophysical methods, mainly electrical resistivity and self-potential for detecting anomalous seepage through mine tailings dams and monitoring the condition of the dam. In order to achieve this, field measurements of resistivity and self-potential have been performed on tailings dams to look for streaming potentials, inhomogeneities and time variations of electrical properties and self-potentials. Laboratory measurements of resistivity have been carried out on different soil samples from the tailings dams to look for eventual changes in electrical properties with change in grain size and water content.

1.1 Tailings

Tailings are fine-grained waste material from the mining industry. The ore is in the process ground-up to a size less than 0.01-0.1 mm, i.e. silt fraction. The metal content is removed and the remains are waste materials deposited in slurry form (Vick, 1990), i.e. the tailings. During this process, ores are first milled and finely ground, and then treated in a hydrometallurgical plant. Since the extracted metal represents only a small percentage of the whole ore mass, the vast majority of the material mined ends up as fine slurry. The tailings contain all other constituents of the ore but the extracted metal, among them heavy metals and other toxic substances. Moreover, the tailings also contain chemicals added during the milling process.

1.2 Tailings dams

1.2.1 General

A tailings dam is the confining embankment designed to enable the deposited tailings to settle and to retain tailings and process water. Due to typically low concentrations of the useful mineral in the ores, large amounts of tailings are produced, requiring extensive tailings ponds to contain them. The most critical element of tailings facilities is usually the dam. The most common causes of failure are related to the forces of water resulting in, e.g. internal erosion of the dam material or overtopping of the dam.

Tailings dams are an expensive asset to a mining company, and so generally the embankments are built with material that is available locally to the proposed construction site. In areas where borrow materials are not available (particularly in required quantities), the embankments are constructed and raised by the sand fraction of the tailings. So the coarser particles (sandy fraction) are used for dam construction, while the fines are deposited in the pond. A high percentage of fines in the tailings results in long settling periods, sometimes several years. In handling large amounts of inhomogeneous wet slurries, water management is a key safety factor. Deficient water management is one of the main causes of accidents and hazards emanating from tailings facilities.

Most mining processes are wet and the tailings leave the treatment plant as slurry, i.e. tailings mixed with process water. This makes it convenient to pump it from the plant to a place for sedimentation and storage. The use of tailings dams to create an impoundment for storage is the most common way of handling tailings. When the tailings have settled within the

impoundment, the water will either be recovered for use in the treatment plant, released after proper treatment into a tributary river or stream or, in arid climates, evaporate. As the tailings fill the impoundment, the surrounding dams are continuously raised (ICOLD, 1996).

The tailings dam will be exposed to different kind of loads; water pressure combined with the load from the tailings itself. There is always also a risk for liquefaction of the saturated tailings and liquefied tailings are capable of doing a lot more harm than plain water in case of a failure. The size and capacity of a tailings impoundment must increase with the mine production of tailings.

1.2.2 Historical background

To facilitate the understanding of the safety issues of tailings dams, it is first necessary to give a brief historical review of how the tailings dam technology developed. The reader is referred to Vick (1999) from which much of the following account has been drawn.

Minerals of economic interest were initially separated from crushed rock according to differences in specific gravity. During the 19th century the mining technology was rather primitive and it was only profitable to mine rich ores, resulting in comparatively coarse waste and correspondingly small volumes. The remaining waste was traditionally disposed in a convenient location like the nearest lake or stream. Froth Flotation technique greatly increased the ability to mine low-grade ore bodies shortly after the turn of the century. This process required the ore to be crushed to a finer particle size in a wet process, requiring water. As a result, the tailings became finer, larger by volume due to the low grade ore and left the process as slurry. The growing volumes and the decreasing particle size contributed to spread the tailings in the environment over greater distances, particularly in streams. Accumulated tailings regularly plugged irrigation ditches and contaminated downstream growing areas. Conflicts soon arose as the dumped tailings started to block irrigations channels and contaminate croplands, which gradually lead uncontrolled dumping of tailings to an end. To retain the ability to mine, industry fostered construction of some of the first dams to retain tailings. The purpose of the first dams, often constructed across the stream where the tailings used to be dumped, was pollution control.

Mechanized earth-moving equipment was not available to the early dam builders so construction of conventional earth fills dams was impossible for any mining operation at this time. As a result, miners by trial and error developed a method where the deposited tailings constituted part of the dam and only small volumes of fill material were required to be put in place. Today, this method is called the “upstream method” (see section 1.2.3.1). This construction procedure, now almost always mechanized, remains in use at many mines today. Due to the lack of proper spillways etc. some of these first dams did not survive for long and failures started to take place. The first documented tailings dam failure was in 1917.

After the seismic failure of the Barahona tailings dam in Chile in 1928, the upstream method was replaced by the downstream construction (see section 1.2.3.2). This method resembles the design of the conventional water retaining dam. By using cyclones, that separate the fine fractions from the course, it is possible to create zones within the dam with different functions. The coarser fraction is used for the downstream part of the dam and the fines settle along the beach to create a progressively finer, and therefore less permeable, zone. During the 1940's the availability of high-capacity earth moving equipment and mechanical shovels, was

possible to construct tailings dams of compacted earth fill in a manner similar to conventional water dam construction practice.

The development of tailings dam technology came out was an empirical basis, as it was learned by trial and error of construction practices and equipment available at the time. It was not until the 1960's, however, that geotechnical engineering and related disciplines adopted, refined, and widely applied these empirical design rules. The 1965 earthquake-induced failures of several tailings dams in Chile received considerable attention and proved to be a key factor in early research into the phenomenon of liquefaction. Earthquake-induced liquefaction remains a key design consideration in tailings dam design. Over the past 30 years, environmental issues have grown in importance, as attention has largely turned from mine economics and physical stability of tailings dams to their potential chemical effects and contaminant transport mechanisms. Formal design criteria are established for tailings dams and these are becoming increasingly standardized internationally.

1.2.3 Construction Methods

Design methods for tailings dams differ somewhat from water retention dams. Earth fill water retention dams normally built for hydropower, water supply, flood control and irrigation purposes to store only water, whereas tailings dams are designed to retain impoundments of tailings. Water retention dams are usually built to full height during one period of construction while tailings dams usually are not constructed initially to completion, but raised sequentially as the impoundment fills. Construction and design conditions will therefore change over time. The fundamental dam engineering principles for tailings dam design are: (1) locating the dam to minimize the catchment's area, (2) maintaining a wide beach to control internal seepage from the free water pond, (3) enhancing internal drainage by constructing pervious initial starter dikes and (4) exploiting pervious foundation conditions.

The beach is the area between the crest of the dam and the free water pond where the coarser particles from the tailings settle during deposition. Starter dike is the initial dam stage from which the subsequent raises of the dam are constructed.

The fundamental principles described above were understood during the beginning of the 20th century. From that time, for tailings dams, three typical construction methods have developed (Vick, 1990), which are upstream, downstream and centerline constructions. All these construction methods will be described below.

1.2.3.1 Upstream construction

Upstream design is a very common method of constructing and raising tailings dams. One main reason for this is that it can be far cheaper than the centerline and downstream methods, as the quantity of construction material required is reduced.

Figure 1.1 shows the basic design principles of the construction of an upstream embankment. Initially a starter dam/dike is constructed, normally of borrow material as no tailings is produced yet. Tailings are then discharged from the crest of the dam along its periphery to create a tailings beach where the tailings can settle as the slurry run towards the pond. When the impoundment is full, or rather before that, the second dike is constructed on the settled

and consolidated tailings beach. This process continues as the tailings dam increases in height (Figure 1.1 b-d).

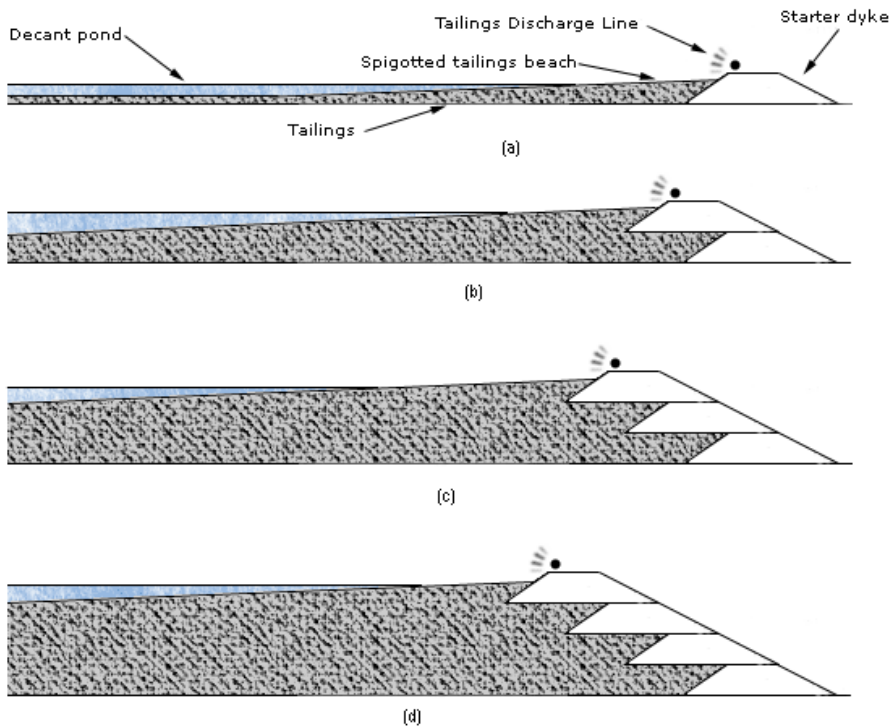


Figure 1.1. Upstream tailings dam construction scheme.

Upstream construction method is the oldest and most economical so most of the tailings dams in the world were built using this method. The saturation of the soil influences the scale of liquefaction as the pore water pressure of the soil increases. Upstream construction often results in a low relative density and generally high degree of water saturation.

1.2.3.2 Downstream construction

The design requirements for the downstream construction method are similar to conventional water storage dams. As in upstream construction, downstream construction (Figure 2.2) also begins with a starter dam constructed of compacted borrow materials, however, this starter dam may be constructed of pervious sands and gravels or with predominately silts and clays to minimize seepage through the dam. Tailings are then discharged behind the starter dam. When the impoundment is full, or rather before that, the next raise is placed on the downstream slope of the existing dam (Figure 1.2 b-d). This enables the incorporation of internal zoning for control of the hydraulic gradient within the dam. Significant volumes of water can therefore be stored along with the tailings.

The downstream method of construction provides a degree of stability not found in upstream construction due to the ability and ease of compaction, the incorporation of phreatic surface control measures and the fact that the dam raises are not structurally dependent upon the tailings deposits for foundation strength. A major disadvantage of this method is the large volume of fill material required to raise the dam

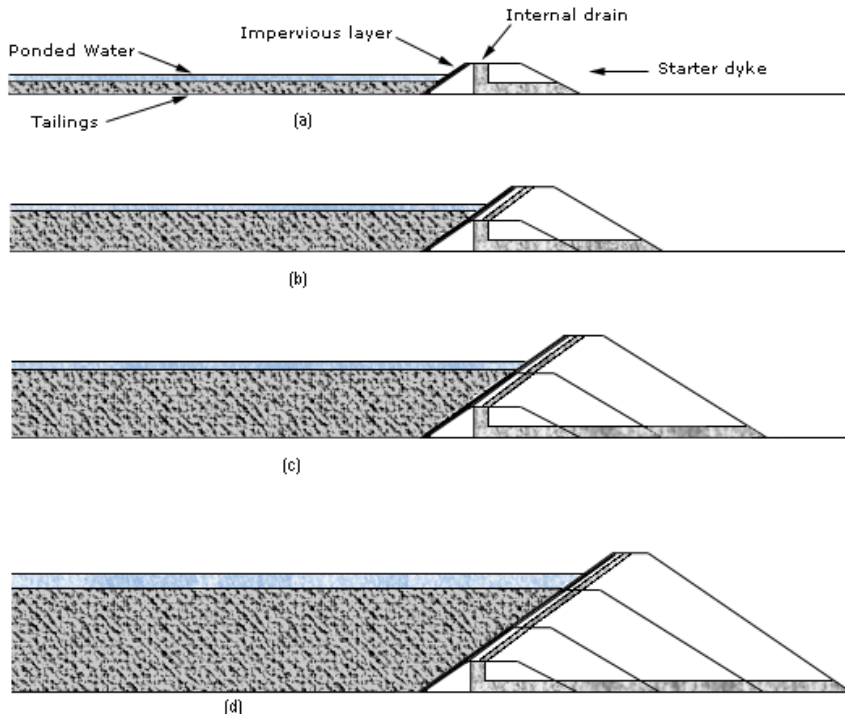


Figure 1.2. Downstream tailings dam construction scheme.

1.2.3.3 Centerline construction

Centerline construction method (Figure1.3) is a compromise between the upstream and downstream methods in many aspects; it shares the advantages of both methods and mitigates the disadvantages. The volume of fill material needed is intermediate between upstream and downstream methods as well as the cost. Initially a starter dam is constructed, normally of borrow material as no tailings are produced at this stage. Tailings are then discharged peripherally from the crest to form a beach. When the impoundment is full, or rather before that, the progressive raises are placed on the beach and the downstream slope of the existing

dam (Figure 1.3 b-d). This enables the incorporation of structural measures for control of the hydraulic gradient within the dam, similar to the downstream construction. Storing of significant volumes of water along with the tailings are not recommended due to the need of an adequate beach, even though this beach does not need to be as wide as for the upstream construction.

The seismic resistance is generally acceptable as the main part of the fill material can be compacted. The rate of raise is normally not restricted by pore pressure dissipation for centerline construction. Although this embankment type is not amenable to permanent storage of large volumes of water, short term storage of water due to heavy precipitation events or mill shutdown will not adversely affect the stability of the dam.

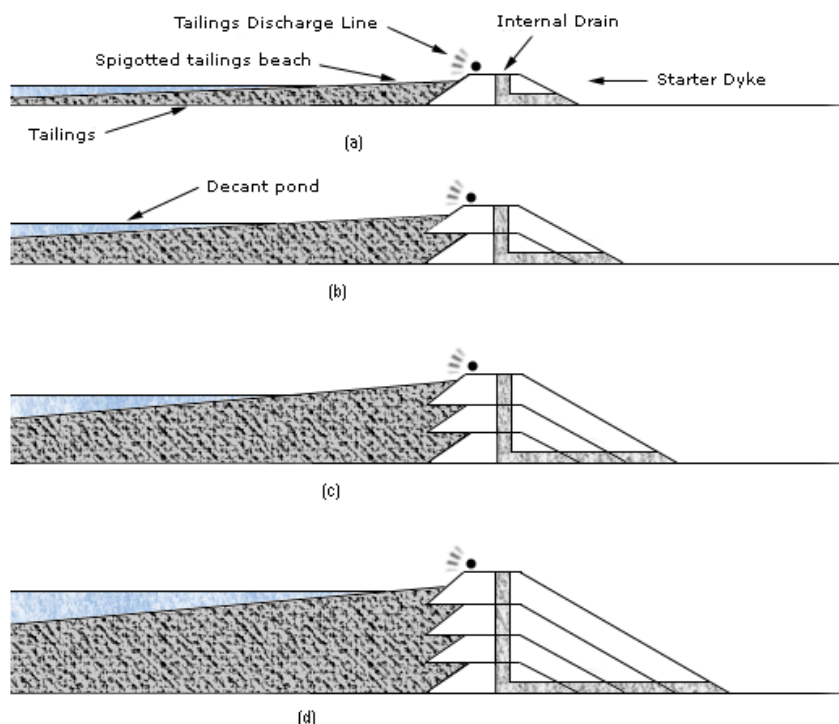


Figure 1.3. Centerline tailings dam construction scheme.

1.2.4 Swedish Tailings Dams

Mining has been practiced in Sweden for hundreds of years, and is still a viable industry with greater ore production than ever before. On a world scale, the Swedish ore production is relatively small, but within Europe Sweden is one of the biggest metal ore producers. In addition to waste rock, Swedish mines produce huge amount of tailings which are deposited

in tailings impoundments with the use of tailings dams. In 2005, nine tailings dams (Figure 1.4) were in operation in Sweden, (Bjelkevik , 2005a).



Figure 1.4. Mines and tailings dams in operation in Sweden 2005 (after Bjelkevik , 2005a).

In Sweden, the development of construction methods for tailings dams has developed from the basic knowledge of water retaining dam. The design of the Swedish tailings dams differs somewhat from conventional tailings dams internationally, as most Swedish tailings dams are originally constructed with a core of moraine similar to water retention dams. Most of them constructed in stages according to centerline or downstream method with a core, filter and support fill. Moraine has very often been used as construction material as there was easy accessibility to suitable moraine at most of the tailings dam sites.

The trend of using tailings as construction materials has been continuously rising during last 10 years. The reasons for that are the availability of moraine in the vicinity has decreased, more of volumes of materials are needed for increasing the height of dams and the process of getting permits for borrow materials is getting more complicated. As a result several tailings dams are now raised using tailings and waste rock. The construction method has therefore changed to upstream or centerline. (Benckert, 2003).

Events like incidents and failures that have occurred in Swedish tailings dams have been studied by Bjelkvik (2005b). Failure and incident in this case are defined as: Tailings dam failure is an event resulting in the tailings dam structure failing to retain what it is designed and constructed for, causing an emergency situation due to the spill of tailings and/or water. An incident is an unexpected event that happens to a tailings dam that poses a threat to the overall dam safety and needs response quickly to avoid a likely dam failure. The studied reported that there were 27 incidents and 3 dam failures during the period of 1990 to 2004 and the three main causes of the events that occurred in Swedish tailings dams are structural, internal erosion and water related causes.



Figure 1.5. Location of the investigated dam sites, Kiruna, Aitik and Kristineberg as shown with small black square.

1.3 Study area

The study area includes three tailings dams at the Kiruna, Aitik and Kristineberg mines, which are located in northern part of Sweden. The location of investigated dam sites is shown in Figure 1.5.

1.3.1 The Kiruna tailings dam

The iron ore mine in Sweden's northernmost city is operated by LKAB, a state-owned mining and mineral processing company. For more than a century LKAB has mined the ore in Kiruna. It started as an open-pit mine, and by the 1960s, underground mining was underway and today operations continue deep underground. Current plans for expanding the mine actually include relocating parts of the city. With an ore body 4km long, 80m thick and reaching a depth of 2km, LKAB's Kiruna is the world's largest, most modern underground iron ore mine. The Kiruna ore body was formed at around 1900 Ma following intense volcanic activity with the precipitation of iron-rich solutions on to a syenite porphyry footwall. The ore contains a very pure magnetite-apatite mix, containing more than 60% iron and an average of 0.9% phosphorus. Since mining began here over 100 years ago, LKAB has produced over 950Mt of ore, yet only one-third of the original ore body has been extracted.

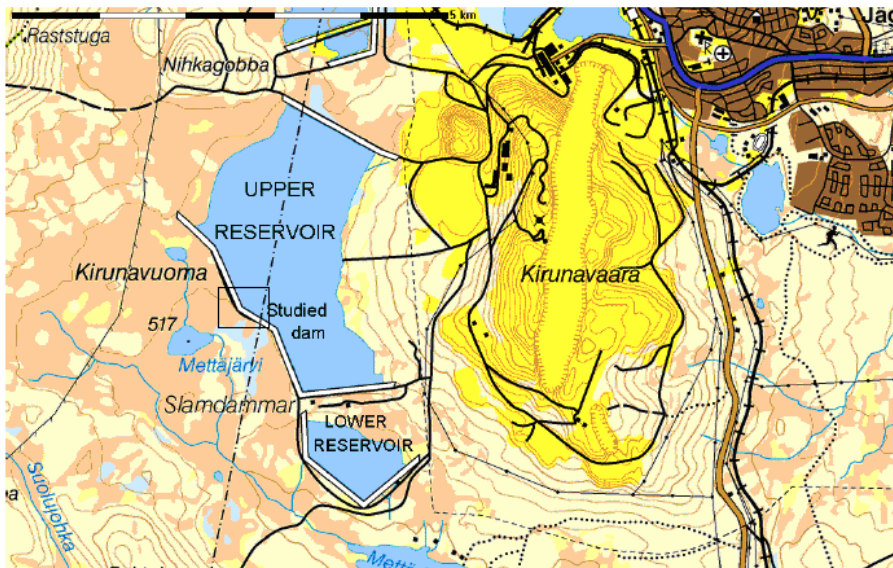


Figure 1.6. Map of the Kiruna mine area showing the impounding reservoirs and the location of the investigated dam.

The wet handled fine-grained waste rock (tailings) is transported by pumping in pipelines or by gravity in flumes to tailings ponds, from which water is re-circulated back to the ore treatment processes in a closed system. The entire length of the Kiruna mine tailings dam of this study is about four kilometers. The location of the dam is shown in Figure 1.6. The dam

was investigated with mobile self-potential (SP) survey and with fixed electrodes for repeated SP and resistivity measurements. The tailings dam at Kiruna consists of a central core of compacted, low permeability moraine surrounded by sandy filters and supporting rock fill (Figure 1.7). The surface of the dam is covered by very coarse materials.

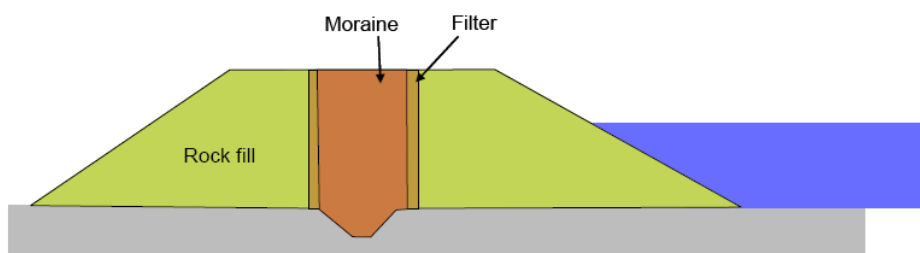


Figure 1.7. Schematic representation of principal design of tailings dam at Kiruna.

1.3.2 The Aitik tailings dam

The Aitik mine, owned by the Boliden Mineral AB, is considered to be the largest open pit copper mine in Europe. About 18 Mt of copper ore is mined annually. Production commenced in 1968 and by 2012 it is expected that the northern side of the mine will reach a depth of 400 meters. Gold and silver are also produced in this mine. Substantial amount of the tailings generated during operation is deposited in a tailings pond west of the mine. The tailing pond occupies an area of 13 square km (Figure 1.8). The clarification pond is located west of the tailings pond. The area of the clarification pond is 1.6 square km and is used for final cleaning of the water before discharge to the environment, or re-circulated to the mill and there used as process water.

The Aitik earth dams were not built in the same manner as the Kiruna tailings dam or hydro-electric dams. Instead of using an impervious core with layers of supporting fill material, the dams were built as composite masses of local moraine, waste rock and slurry sand. In the upper reservoir, the suspended sediments in the slurry settle to form sandy layers on the bottom. In order to raise the dam higher, material is added to the crest and extended into the reservoir such that the layers of sediments form a portion of the new dam's foundation. This process is repeated whenever the dam needs to be raised.

The principle design of the tailings dams of upper reservoir is shown in figure 1.9. The dam was raised several times using downstream and upstream construction methods. The lower dam i.e. IJ-dam (dam for clarification pond) has a central core of compacted material. Self potential measurements have been performed on the dam of the clarification pond (IJ-dam) and five soil samples including moraine have been collected for laboratory measurements from the upper tailings dam. Self potential measurements have been performed on the dam of the clarification pond (IJ-dam). The study area is shown in figure 1.8.

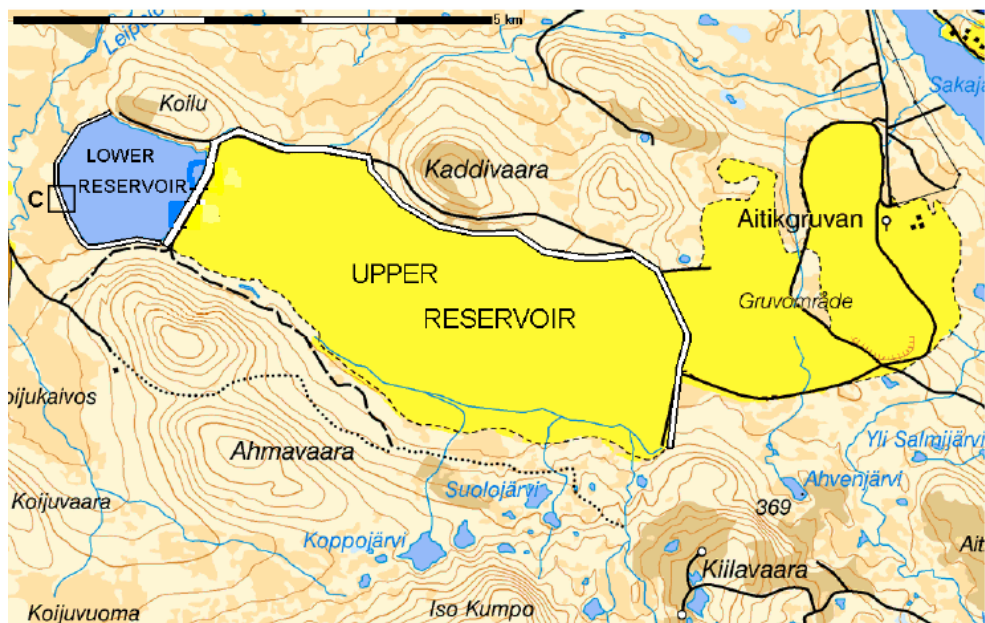


Figure 1.8. Map of the Aitik mine area showing the impounding reservoirs and the location of the investigated dam. C indicates the study area at the lower dam (IJ- dam).

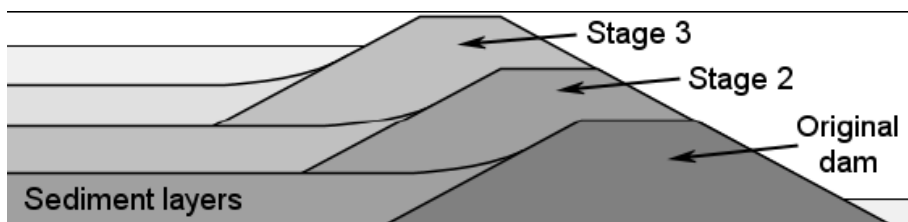


Figure 1.9. Schematic representation of principal design tailings dam of upper reservoir at Aitik. Layers of sediment accumulate on the bottom of the tailings pond and form a portion of the dam's foundation.

1.3.3 The Kristineberg tailings dam

Kristineberg is situated in the northern part of Sweden in the Västerbotten County at the border of Malå and Lycksele municipality. The Kristineberg mine, also owned by the Boliden

Mineral AB, is Sweden's deepest mine, reaching about 1170 meters depth. The Kristineberg deposit, containing zinc, copper, lead, gold and silver, was discovered in 1918 and mining was begun in 1940. The ore is now transported 100km east to Boliden for processing; however before 1991, Kristineberg had its own refinery that processed ore from several mines that were once active in the surrounding area in addition to what was produced locally. The Kristineberg mine tailings reservoir is located in a small valley and is controlled by an earth dam at one end. This dam is old and the construction type is same as the Aitik tailings at the beginning. The dam has been raised a number of times using a range of different construction materials and techniques. That has resulted in complex geometry and properties of the dam. The downstream slope of the dam was soil and grass-covered and the upstream face consisted primarily of larger rocks fragments. A gravel road is running along the width of the crest.

A ca 300 meter wide section of the dam (Figure 1.10) was investigated using resistivity and SP methods and five soil samples were taken from different part of the dam for laboratory measurements. The downstream slope of the dam is covered by moraine and measurement conditions are therefore favorable for both SP and resistivity.



Figure 1.10. Map of the Kristineberg mine area showing the impounding reservoirs and the location of the investigated area.

1.4 Layout of the thesis

The thesis comprises of six chapters. Introduction and research objectives, tailings dam's properties and study area are mention in the first chapter. Chapter two and three deal with self-potential survey and resistivity survey, respectively. Laboratory resistivity measurements on samples are described in the fourth chapter followed by resistivity and self -potential measurements using fixed electrodes in the chapter five. Results of the measurements are described in each corresponding chapter. Final conclusions drawn from the study are presented in the last chapter.

2. The Self-Potential Surveys

2.1 Introduction

The self-potential (SP) method is based upon measuring the natural potentials developed in the earth by electrochemical actions between minerals and subsurface fluids or by electrokinetic process involving flow of ions fluids. There are generally natural potential differences between any two points on the ground which are associated with electric currents in the ground. These potential differences consist of two parts, first constant and unidirectional and second time-varying or fluctuating. The former part of the potential difference can arise due to various electrochemical processes in the ground and the time varying potentials are results of magnetotellurics.

Ranging normally from a fraction of a millivolt to a few tens of millivolts, self-potentials some times attain values of the order of a few hundreds millivolts and much more. Such large anomalous potentials are often observed over sulphide and graphite ore bodies, magnetite and several other electronically conducting minerals (Parasnis,1997).The self-potential (SP) survey is one of the oldest and simplest methods in geophysical exploration, and it is used for solving many problems in applied geophysics. The SP method was first used by Robert Fox whose aim was to detect underground copper sulphide deposits in Cornwall, England in 1830.

In recent years the SP method has found increasing use in geothermal, environmental and engineering applications to help delineate sources associated with thermal flow and groundwater. The SP method has been used in different geological and engineering problems such as mining exploration (Sato and Mooney, 1960; Lögn and Bolviken, 1974; Corry, 1985), hydrogeology (Rao,1953; Bogoslovsky and Ogilvy, 1974; Schiavone and Quarto, 1984), engineering and environmental geophysics (Bogoslovsky and Ogilvy, 1977; Corwin, 1990), dam and embankment seepage (Ogilvy et al.,1969, Bogoslovsky and Ogilvy, 1970a,b, Butler,1984;), and geothermal studies (Corwin and Hoover,1979).The major environmental and engineering applications of the SP have been investigations of subsurface water movements. Specific uses include the mapping of seepage flow through containment structures such as dams, dikes and reservoir floors; and the mapping of flow patterns in the vicinity of landslides, sinkholes, wells, shafts, tunnels and faults. SP anomaly amplitudes generated by such environmental and engineering sources tend to be lower than those seen in mineral or geothermal exploration.

2.2 Origins of self-potentials

The Self-potential or spontaneous potentials arise from different electrochemical processes, however the mechanisms are not fully understood. The varieties of sources cause difficulties in the interpretation, as all electrical potentials can be superposed. There is no particular way to separate an SP-anomaly into component based of their electrochemical origin. Thus the target of interest is defined by the anomaly sources and other sources are called noise. The main mechanisms involved in SP are briefly described below.

2.2.1 Electrofiltration potential

The electrofiltration or streaming potentials arise when water or other fluids flow through

sand, porous rock, moraines, basalts, etc. The basic theory of electro-filtration is that when a liquid moves with respect to a solid surface that normally exhibits negative charges, e.g., clay minerals, then the positive charges from liquid e.g. water will be attracted and accumulated at the solid surface. The result gives a diffuse layer that has an excess of positive charges with respect to negative charges in the vicinity of the solid surface. This phenomenon is known as the electrical double layer (Figure 2.1). When a pressure gradient forces the liquid to flow relative to the solid, the excess positive charge within the diffuse layer will be dragged along with the fluid flow creating an electric convection current (I_{conv}). This convection current will cause the mobile charges to deplete upstream and accumulate downstream, creating an electric potential difference. This will result in an imbalance between the positive charges in the upstream part (the low pressure) and negative charges in the downstream part (the high pressure). This charge separation results in a streaming potential that will drive a conduction current (I_{cond}) back through the fluid.

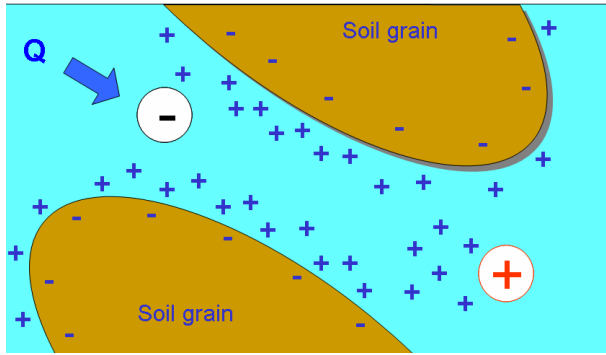


Figure 2.1. Schematic representations of the pore wall double layer geometry. As the liquid flows some of the counter ions in the diffuse portion of the double layer will be shared off and carried with the fluid, creating an electric current.

In steady state for a capillary or porous medium with a non-conducting matrix, these two currents, I_{conv} and I_{cond} are balanced by each other,

According to the Poisson's equation, a Gouy-Chapman diffuse layer and the parabolic velocity profile characteristic of Poiseuille's flow, convection and a conduction current (Morgan et al., 1989) can be expressed by:

$$I_{conv} = -\pi \epsilon \frac{\zeta}{\eta} G \Delta P \quad (2.1)$$

$$I_{cond} = \pi \sigma_w G \Delta V \quad (2.2)$$

where ΔV and ΔP are the potential difference (streaming potential) and the pressure difference driving the flow, σ_w is the fluid conductivity, ϵ is the dielectric permittivity of the fluid, ζ is the zeta potential (the voltage at the closest plane to the solid surface where charge movement occur), η is the viscosity of the fluid, and G is the geometrical factor.

From equations (2.1) and (2.2) we will get

$$\Delta V = -\frac{\epsilon\zeta}{\eta\sigma_w}\Delta P \quad (2.3)$$

$$\frac{\Delta V}{\Delta P} = -\frac{\epsilon\zeta}{\eta\sigma_w} \quad (2.4)$$

This is the Helmholtz-Smoluchowski equation. The ratio $\Delta V/\Delta P$ is referred to as the streaming potential coefficient C .

It is seen that the streaming potential coefficient C depends upon the conductivity, the dielectric permittivity, the zeta potential, and the viscosity of an electrolyte along the flow path. Estimation of the value of C for any area can be derived by plotting the electrical potential versus the elevation where the pressure difference between measuring points can be assumed from the elevation difference between them and where the groundwater surface follows the topography of the area. This C value is referred to as the apparent streaming potential coefficient. Laboratory experiments show that if there is a groundwater flow, there should be a streaming potential in the order of 10-150mV between two points separated by an elevation of 10m (Bergström, 1998) or $C \approx 1 - 15$ mV/m.

However, in the field the porous media or matrixes around an electrolyte are not completely non-conducting. Thus the value of an apparent streaming potential coefficient will be less than the value estimated in the laboratory. In case of a surface conductivity σ_s , equation (2.3) becomes

$$\Delta V = -\frac{\epsilon\zeta}{\eta\left(\sigma_w + 2\frac{\sigma_s}{r}\right)}\Delta P \quad (2.5)$$

where r is the pore or capillary radius.

The magnitude of the streaming potential depends on the resistance of the return current path, thus if the solid is not insulating, part of the conduction current will pass through it, reducing the streaming potential. The subsurface resistivity distribution will therefore play a large role in the shape and magnitude of streaming potential anomalies.

Wherever groundwater is in motion, which is practically everywhere, there will exist SP anomalies due to streaming potentials. For the case of running water in contact with earth and rock the developed surface charge is typically negative, resulting in negative potential values

upstream and positive values downstream. Naturally there is a correlation between topography and SP, with high points generally having negative SP anomalies.

Streaming potentials generated by subsurface water flow are the source of the great majority of SP anomalies of engineering interest. Since the streaming potential or electrokinetic provide information directly related to subsurface flows in porous medium, self-potential methods used in groundwater investigations and in geotechnical engineering applications for seepage studies. In order to be able to distinguish true streaming potential anomalies when interpreting Self-potential measurements, an awareness of all of the possible SP-generating electrochemical mechanisms is required.

2.2.2 Mineral potentials

The minerals potentials are probably the most common cause of strong local SP-anomalies. Mineral potentials occur above all kinds of electrically conducting mineral bodies. They are often called sulphide potentials since they are generally strongest on sulphide mineralization e.g. pyrite and chalcopyrite. SP values caused by mineral bodies are typically greater than those associated with streaming potentials. The potentials are almost invariable negative over the top of the deposit and quite stable in time.

The origin of minerals potentials is not completely understood. Many theories have been developed in an attempt to explain the phenomenon. Early theories attributed mineralization potential to oxidation of parts of the mineral body above water table, but such an explanation can not be used in the case of graphite. Later, Sato and Mooney (1960) proposed a more detailed theory of mineralization and developed a new model where electrons are lost in the lower portion of the ore body and gained in the upper part by a number of possible chemical reaction pairs and the ore body acts only as an electron conductor. The different electrochemical reactions at the upper and lower parts of the ore body create potential drops across the mineral-electrolyte interface that can be solved for by assuming chemical equilibrium.

A problem with this approach is that no current flow can exist under chemical equilibrium. This can only occur if there is no current flow, in which no SP anomaly would be registered. The voltages at the interface are not only dependant on the chemical reactions, but also on the current flow, just as when the voltage of a battery drops and current is drawn from it. Thus the interface voltages depend both on the chemical reactions involved and on the subsurface resistivity distribution.

Kilty (1984) used non-equilibrium thermodynamic equations to expand the Sato and Mooney model. According to his model there are four separate voltages to consider: the potential drop in the ore body (V_o), the potential drop in the ground and the interface voltages at the upper (V_u) and lower (V_i) parts of the ore body. The voltages can be related as $IR = V_u - V_i - V_o$ where I is the current flow and R is the resistance of the current path outside of the ore body. The mineral potential value is a part of the potential drop IR .

2.2.3 Diffusion potentials

Diffusion potential is due to the difference in mobilities of various ions in the solutions of

different concentration. The migration of the ions in the direction of the concentration gradient would constitute an electric convection current, which would in turn drive an electric conduction current in the reverse direction. This conduction current creates an electric potential drop that is the measured diffusion potential anomaly. The convection current can be calculated for a known concentration gradient; however things become much more complicated in nature where several different types of ion typically contribute to creating the diffusion current.

A diffusion current density J_D will be created from the net flow of ions until it is balanced by the conduction current in the reverse direction to the steady state conditions. NaCl is one solute that usually exists in natural electrolytes, and the net diffusion current density J_D can then be expressed by:

$$J_D = e^o \nabla C (D_{Na} - D_{Cl}) \quad (2.6)$$

Where e^o is the elementary electric charge, and C is the electrolyte concentration. D_{Na} and D_{Cl} are the diffusivities of cations and anions of Na and Cl, respectively. A diffusion current density J_D will be created from the net flow of ions until it is balanced by the conduction current in the reverse direction to the steady state conditions. NaCl is one solute that usually exists in natural electrolytes, and the net diffusion of cations and anions of Na and Cl, respectively.

It is believed that concentration differences in the groundwater may contribute to background potentials encountered in most SP investigations; however their influence can be very difficult to determine. If the concentration of electrolytes in the ground varies locally, the background SP anomalies will be in the order of fractions of a millivolt to some tens of millivolts (Parasnis, 1997). Such background anomalies should disappear in the absence of concentration differences in the ground, since the flow of ions creates an equilibrium state, but in reality it seems that the concentration difference occurs all time. No suitable explanation exists for why diffusion potentials persist over time. The phenomenon is not fully understood but it is suggested that the concentration differences are regenerated by redox reactions involving oxygen from the atmosphere.

2.2.4 Sedimentation potentials

Sedimentation potentials are the result of the exact same mechanism that creates streaming potentials; however in this case solid particles move with respect to a liquid that is stationary as a whole. In principle, sedimentation potentials could occur where there are standing water bodies with high concentrations of suspended sediments; however the physical conditions required for generating significant SP anomalies would very rarely exist in nature.

2.2.5 Adsorption potentials

SP anomalies due to ion adsorption are known to occur above quartz and pegmatite granite bodies and are generally in the order of +20 to +40mV. Such self-potentials have been attributed to the adsorption of positive and negative ions on the surface of these veins (Parasnis, 1997), but the electrochemical mechanism is not clear. The measured SP anomaly

is the potential drop due to a current flow, thus the adsorption of a layer of static positive ions would not sustain the anomaly. Similar SP anomalies observed over clay deposits probably also belong in this category.

2.2.6 Thermoelectric potentials

If a temperature gradient is maintained across a rock sample, a corresponding potential gradient will appear across the sample. Several workers have reported SP-anomalies resulted from thermal sources in conjunction with survey in geothermal areas. Relatively large anomalies, both positive and negative can be observed in those areas (Corwin and Hoover, 1979). These anomalies are generally generated by a combination of both electrokinetic and thermoelectric coupling. On the electrokinetic side, streaming potentials are created when thermal sources induce convection of the groundwater. The thermoelectric effect is not fully understood, but is believed to involve the differential diffusion rates of both ions in the groundwater and electrons and ions in the soil and rock. The magnitude of this thermoelectric coupling effect is generally expressed as a ratio of resulting electric potential gradient to the temperature difference. This ratio is called the thermoelectric coupling coefficient, has been shown to lie between -0.09 and 1.36 mV/°C for a variety of rock types (Nourbehecht, 1963).

2.2.7 Other sources of SP potentials

There are other sources for potentials which may influence the normal distribution self-potential. The occurrence of ground vegetation can lead to spurious potential anomalies, most likely due to its effect on soil moisture content and contributing streaming potentials. It is even possible that diffusion potentials occur around the roots of plants. It has also been observed that areas of dense vegetation tend to give positive SP values compared to areas of bare soil. Geo-hydraulic changes e.g. precipitation and thawing melting snow will typically influence the magnitude of SP anomalies due to streaming potentials. However, self potentials may vary significantly over a year but returns to the same pattern as the geohydraulic conditions are re-established (Bergström, 1998). Artificial noise sources such as grounded electrical machinery and power lines, buried metal casing, pipelines, which all case misrepresent the normal potentials. The temporal drifts that occur from temperature changes in the electrode, moisture and chemical fluctuation in the soil can also affect the SP.

2.3 Influence of the resistivity distribution on SP

The resistivity distribution in the ground will play an important role in the shape of any measured SP anomalies. Such anomalies are caused by one or more of the electro-chemical mechanisms described above. Each of these mechanisms can be thought of as an electric current source with a set geometry and strength, emphasizing the fact that a measured SP anomaly is a potential drop due to current flow in the ground. These sources result in SP anomalies with wavelengths in the range of a few meters to tens of meters and amplitudes from a few millivolts to tens of millivolts (Ernstson et al., 1986). For a homogeneous and isotropic ground, the geometry of the sources determines the shape of the SP anomaly; however the existences of any resistivity variations distort the shape of the anomaly.

2.4 Field procedure

Field equipments for SP measurements are simple and inexpensive. It requires a pair of non-polarized electrodes, a high impedance voltmeter and the cables to connect them. Special non-polarized electrodes should be used for SP measurements, although there are cases of simple metal stakes performing adequately (Butler et al.,1990). Usually the electrochemical reactions occur where the metal meets ground moisture create potentials, called redox potentials, which may overshadow the self-potentials. The non- polarizing electrodes used in the survey are of Cu-CuSO₄ type. It consists of plastic tube as main body filled with saturated solution of CuSO₄ and connected with a bare copper wire immersed in the electrolyte. Contact with soil is made through a wooden plug which acts as a porous membrane. Any voltmeter used in SP investigation should have relatively high input impedance, at least 10⁸ ohms, in order to prevent drawing appreciable current from the ground, which would disturb the potential distribution and cause polarization of the electrodes. Most modern voltmeters have suitably high input impedance. The voltmeter used in the study was high impedance analog type with a measuring precision of 0.1mV.

There are two different field procedures for SP investigations: gradient and absolute potential. For the gradient method a dipole with a constant electrode separation (l) is moved along the survey area. If l is not too great then the ratio of the potential difference to length, $\Delta V/l$ measures the potential gradient. The absolute potential can be obtained by summing the potential differences along the profile; however the value obtained would contain the accumulated noise from each individual measurement. This can be reduced somewhat by 'leapfrogging', where the forward electrode becomes the rear electrode for the next measurement and only the rear electrode moves forward. Care must be taken in recording the polarity of each measurement when using this technique.

The absolute measurement method involves a stationary electrode and a traveling electrode, connected by long cable reels. The stationary, or reference, electrode is usually placed outside of the study area in a spot where the SP values are expected to remain steady. The stationary electrode is connected to the negative terminal of the voltmeter and the mobile electrode is connected to the positive terminal. This method provides the absolute potential difference between the measurement points in the survey area and the stationary reference electrode. All the surveys were performed using the absolute measurements methods. The traveling electrode was placed in as uniform soil as possible in order to minimize electrochemical potentials caused by slight differences in soil chemistry. Before doing the measurements along the survey line, the potential difference with the base electrode station was measured. The measurements were also made at the end of each survey. The initial and final electrode potentials determine the amount of drift between electrodes over the particular time in the survey area. Electrode drift is caused primarily by variations temperature or soil moisture and contamination of the electrolyte by ions introduced from the soil. Changes in the telluric currents induce true changes in the potential distribution in the subsurface. These current have a very wide range of periods. This effect was accounted for by making regular measurements of the SP difference between two reference points and the base points within the survey area. Usually drift was insignificant, of the order a few millivolt only, except for a survey in Aitik in 2004.

The magnitudes of SP anomalies associated with subsurface water movement are generally

smaller than those associated with mineral and geothermal exploration, and the presence of man-made structures in the study area can create significant noise anomalies. It is therefore imperative that great care must be taken in acquiring and interpreting SP data, and that the characteristic fields associated with artificial noise sources are recognized.

2.5 Interpreting SP data

The final result of an SP survey is a profile or map contour showing equipotentials. Most SP interpretation is qualitative. Anomalies, usually greater than tens of millivolts, are correlated with known features. The interpretation procedures selected will depend on the desired goals of investigation, quality of field data and the availability of additional geophysical and hydrogeological data. There have been many attempts of quantitative interpretation based on theoretical anomalies calculated for simple geometric bodies located in a homogeneous half-space. Despite providing valuable insight into the streaming potential phenomenon, by disregarding the electric resistivity distribution this approach really only provides a qualitative understanding. Quantitative interpretation of SP anomalies can be achieved through numerical modeling techniques. The strength and geometry of the current sources that cause the anomalies are derived from knowledge of material properties and the driving forces, and the electric potential distribution is then calculated from this data.

The qualitative interpretation involves visual inspection of SP data to look for patterns known to be the characteristic of preferred source. For the case of streaming potentials the driving force is the flow of liquid caused by, for example, a hydraulic potential difference and the hydraulic and electric conductivities are two important material properties. SP anomaly associated with seepage through or under an earth dam is well approximated by the electric potential distribution caused by a positive and a negative current source at the outflow and inflow areas, respectively. The streaming potential gradient is in the same direction as the pressure gradient.

2. 6 Results and discussion

2.6.1 Aitik tailings dam

SP measurements were performed at the lower reservoir (IJ-dam) in Aitik at late summer 2003. The measurements were repeated in the autumn of 2004. The 2004 SP measurement covers a larger area of the dam than the 2003 survey. The IJ-dam is covered by coarse surface material and the conditions for SP measurements are not favorable since it is difficult to get good contact of electrode with the ground. The data are therefore a bit noisy, thus it has been filtered.

The results of the measurements are shown in Figure 2.2. Positive anomalies can be seen on the downstream slope, which is compatible with the conceptual behavior of streaming potentials. Of special interest is the positive anomaly at the coordinate 7451330 north that continues to the toe of the downstream slope of the dam in both maps. This is a streaming potential generated from the movements of the water. There is a known seepage anomaly at this part of the dam. Similar, although weaker, anomalies can be seen at coordinates 7451450

and 7451480, north in the 2004 SP map. The anomaly is more distinct in the 2004 measurements. This is probably due to the measurements were made in the autumn after precipitation and melting of snow. The Moist and water saturation was probably higher in the autumn 2004 than in the summer 2003.

The largest differences in the results between the surveys are seen at the crest of the dam. The 2004 measurements were conducted during two days with different weather situations. The southern part of the dam was measured on a cold day when the surface material on the crest was partly frozen. The weather changed and was warmer when the northern part was measured. A large positive anomaly at crest of the dam at 7451380N is seen in both years' results. This high positive anomaly is probably due to observation pipes.

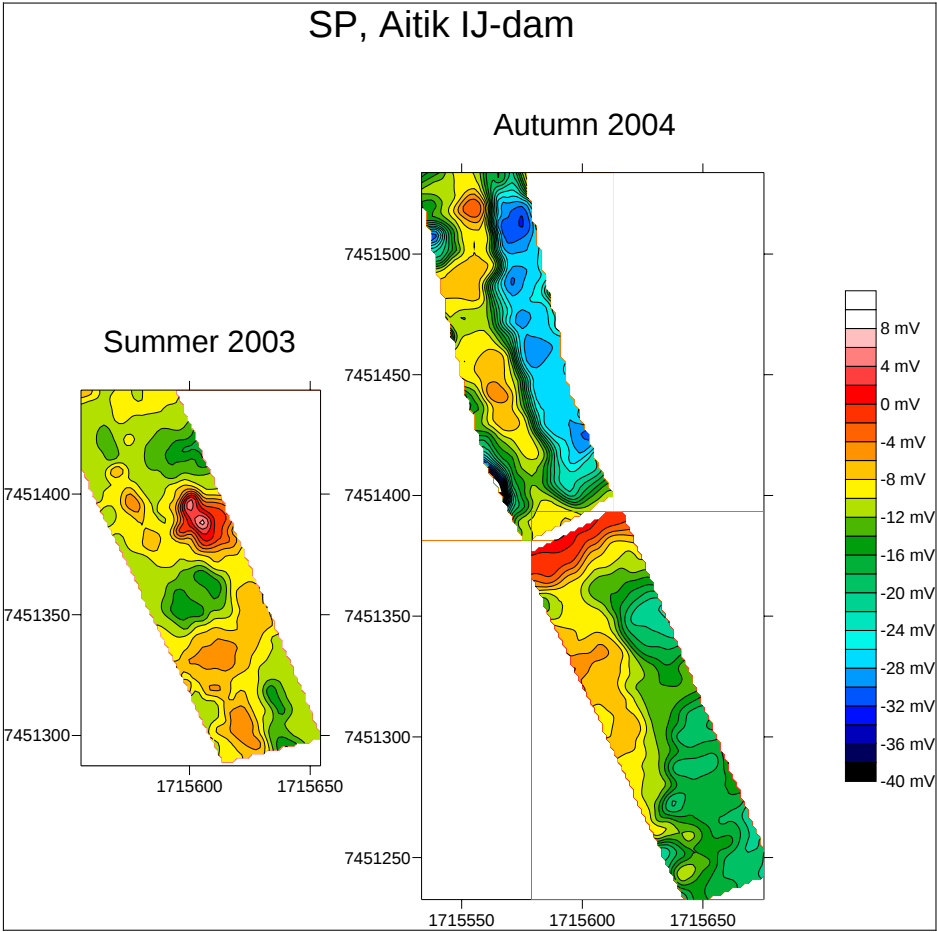


Figure 2.2. SP map showing results from the Aitik lower reservoir (IJ) dam measurements. Crest of the dam is to the right and the toe to the left in the maps.

2.6.2 Kristineberg tailings dam

SP measurements with mobile equipment were carried out at two different occasions, in the late summers of 2003 and 2004. The crest and the downstream slope of the dam were measured at both occasions and the results can be seen in Figure 2.3. A fixed electrode to the east of the dam was used as a reference at both occasions.

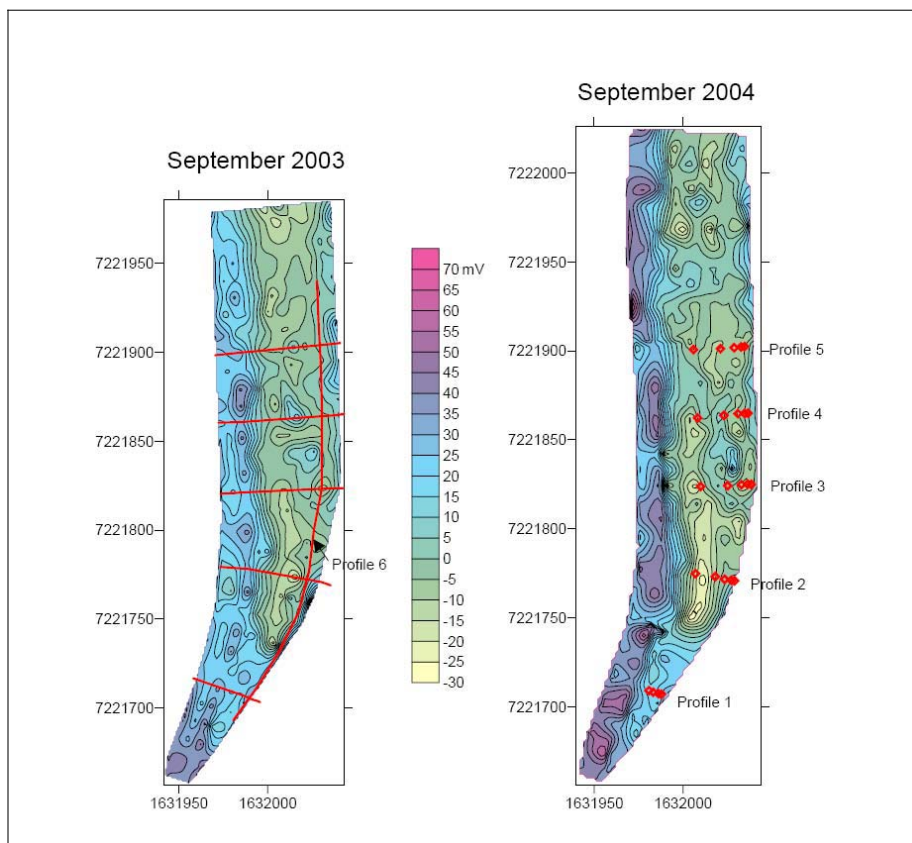


Figure 2.3. SP maps of measurements performed on the tailings dam at Kristineberg. The crest of the dam is to the left and the toe to the right in the maps. The red symbols in the right map show the positions of fixed electrodes and the red lines in the left map show the location of resistivity profiles.

The results are quite similar, however with one exception. The potential on the crest of the dam is higher for the 2004 data. The reason for this is not known, but might be due to weather conditions at the time of measurement. The crest is used as a road and consists of compacted material. The SP pattern on the downstream slope is quite similar in the result from the both measurements. No significant anomalies that might be related to seepage can be seen. There is a negative anomaly around the area of the coordinate 1632010E/7221760N and a higher

background level in the southernmost part of the dam. Both these features do not resemble streaming potential anomalies and might be due to variations in construction material in the dam, keeping the somewhat complicated internal geometry of the dam in mind. The generally low potentials on the downstream side might be result from the weathering of sulphide minerals in the dam body or in the tailings. Waste rock and tailings are also used for the construction material for the dam when the dam is raised. The repeatability of the results is quite good except for the result at the crest.

Strong change in background level may also affect SP distributions at the crest of the dam. The downstream part of the dam is stable and saturated with water and gives consistent SP results from both years of measurements. The self-potential distribution patterns in the Kristineberg tailings dam do not show streaming potential phenomena. This is probably because of the construction of the road using compacted materials. The road totally dammed the water of the impoundments and does not give rise water movements in the dam. The effect of the road overshadowed streaming potential patterns in the dam. But the physical condition of the dam has not changed during the years of measurements. If the condition of the dam changes, the sign of the changing patterns of the SP distribution might be expected.

2.6.3 Kiruna tailings dam

The entire Kiruna dam was mapped by SP measurements during 2002. Four smaller areas, which have some SP anomalies, were selected for detailed SP measurements. The measurements were performed in those areas during summer 2002 and repeated thereafter during the autumns of 2003 and 2004. The dam was raised by around 1.5 meters in the summer 2003 just before 2003 SP measurements were made.

Summer 2002

The results of SP measurements on the entire southern tailings dam at Kiruna can be seen in Figures 2.4 and 2.5. There is a general pattern of positive SP values at the downstream slope, which reflects the streaming potentials developed over the dam core. A few anomalies are seen, but they are quite small. Three smaller parts of the dam (Figures 2.4 and 2.5), which SP anomalies have been found were selected for detailed SP measurements. The result from the detail measurements are presented in the Figure 2.6. The data reveals features of streaming potentials anomalies in those areas. The dense measurements confirmed the anomalies but the magnitudes of the potentials are not exactly the same as in Figures 2.4 and 2.6. This is partly due to the difference in measurement density and the noise overprint on the data caused by e.g. near-surface moisture variations. The time difference between the large area survey and the detailed surveys were between one and five days.

Autumn 2003

The tailings dam at Kiruna was raised by approximately 1.5 meters during the summer 2003. Detailed SP measurements were thereafter conducted in the selected area “A” of the dam (Figure 2.4).

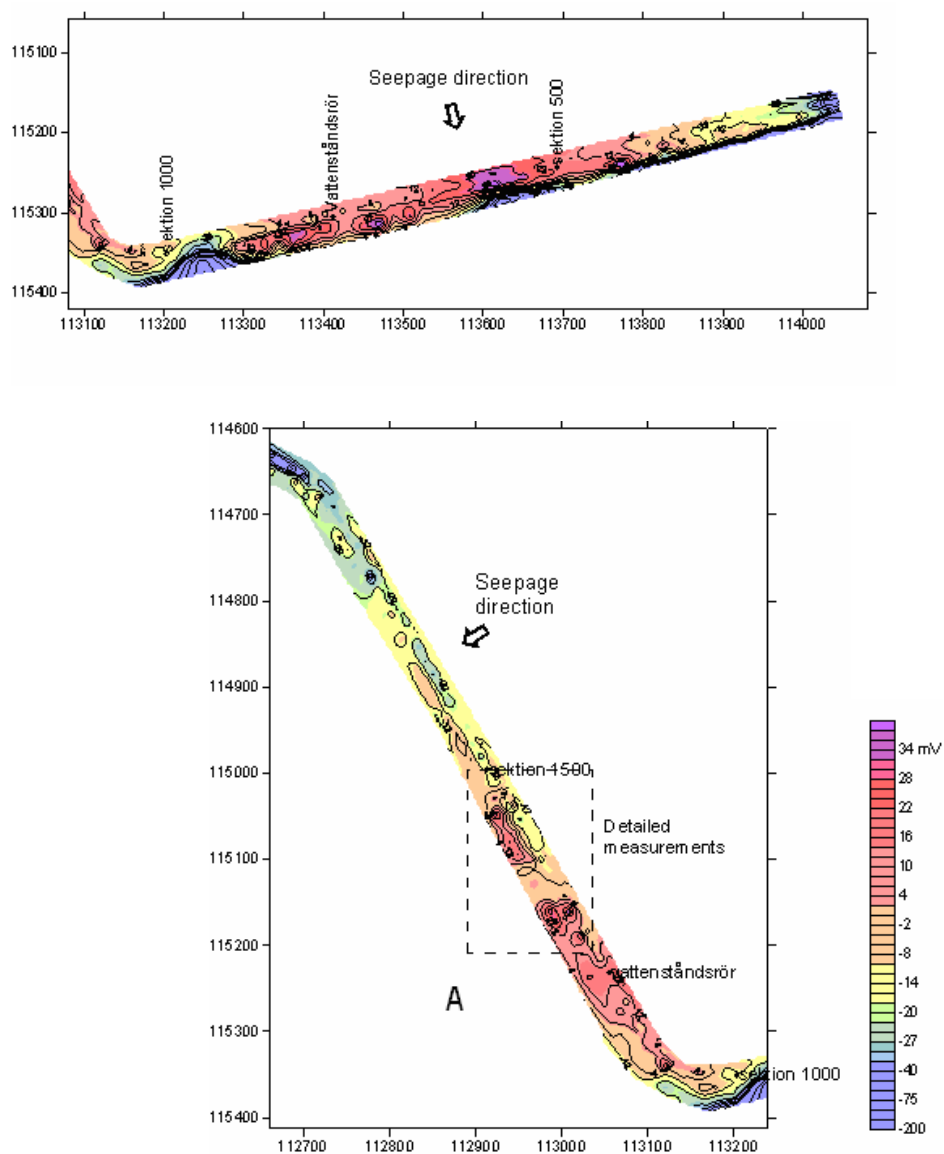


Figure 2.4. SP maps from the measurements performed in June 2002, Kiruna tailings dam. Marked area (coded by "A") is selected for the other detailed measurements. ((Coordinates are in local grid system))

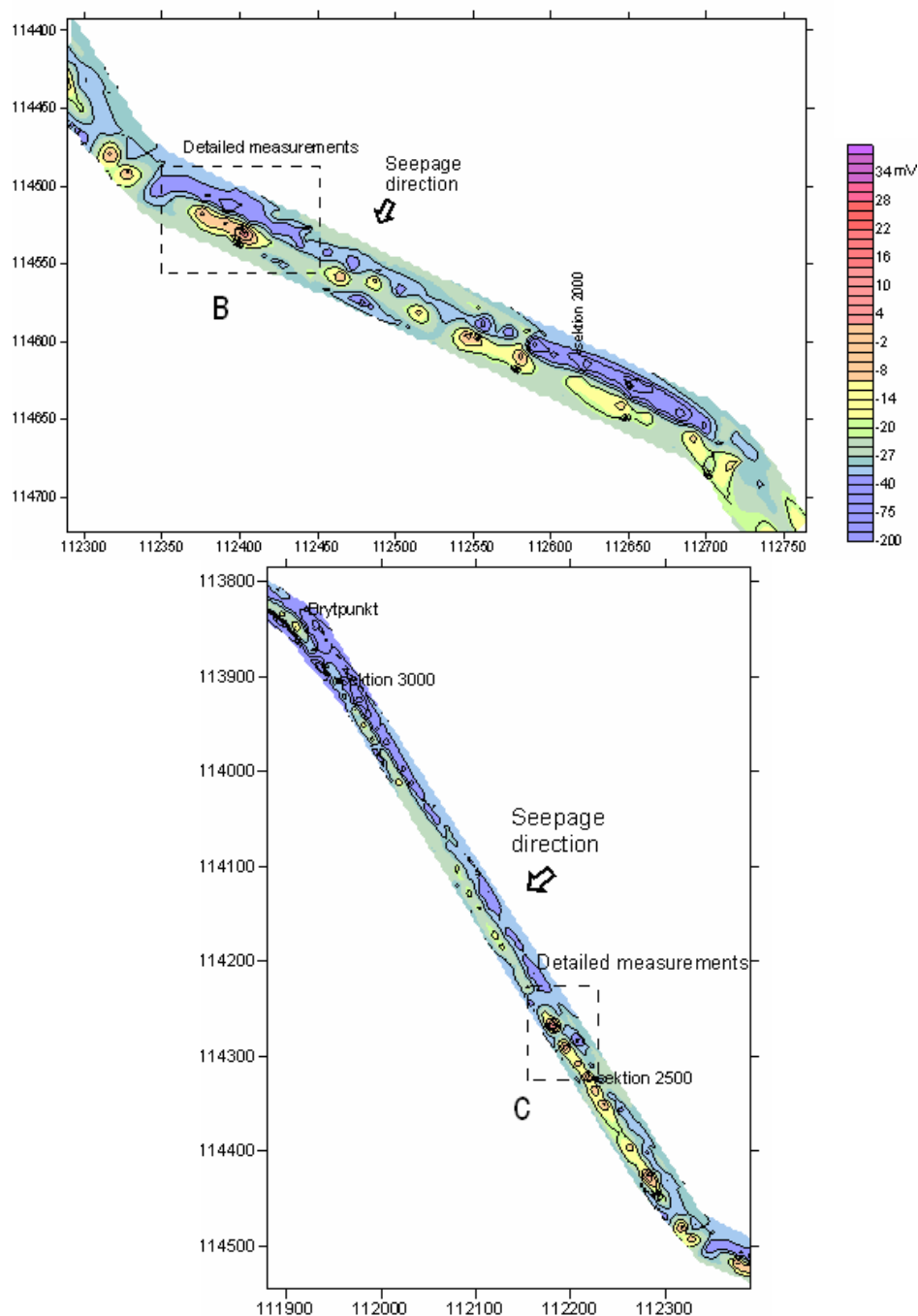


Figure 2.5. SP maps of measurements performed in June 2002, Kiruna tailings dam. Marked areas (coded by "B" and "C") are selected for the other detailed measurements. (Coordinates are in local grid system)

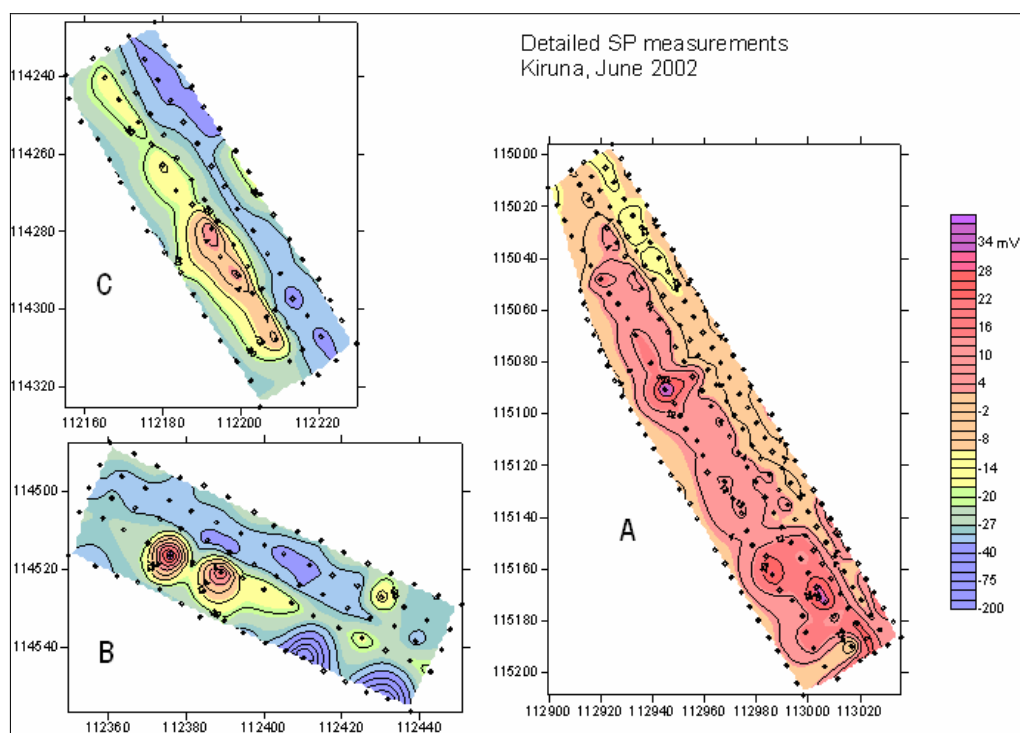


Figure 2.6. SP maps of measurements performed in June 2002, Kirunavaara tailings dam; detailed measurements of selected areas A, B and C. (see Figures 2.4 and 2.5 for locations). (Coordinates are in local grid system)

The results (Figure 2.7) from 2003 measurements deviate from 2002 measurements; with in general, more negative potentials along the downstream slope. The result show reverse patterns of the streaming potentials, with in general negative potentials along the downstream slope. It is likely that a redistribution of soil moisture was taking place when the 2003 measurements were performed and that this has affected the measured data. It is also possible that the pressure distribution in the dam core has not reached equilibrium. The acquired potentials are therefore probably not reflecting the seepage pattern within the dam. But it is noticed that if the physical condition of the dam changes, a significant change in the SP distribution is observed.

Autumn 2004

SP measurements were once again repeated during the autumn of 2004. The measurements cover the same parts of the dam as in details survey in 2002 but include a lager area. The results of the measurements form selected area “A” is shown in figure 2.7. The potential

distribution obtained from 2004 measurements is compatible with the results obtained from 2002 measurements (Figure 2.6) i.e. before the raising of the dam. This confirms the result from 2003 measurements is affected by the raising of the dam. No major anomalies have been seen that can be related to anomalous seepage of water through the dam. The large positive anomaly ($>55\text{mV}$) around the area coordinate E1681650/ N7531500 (Figure 2.7) is due to potentials caused by metallic observation pipes present in the dam.

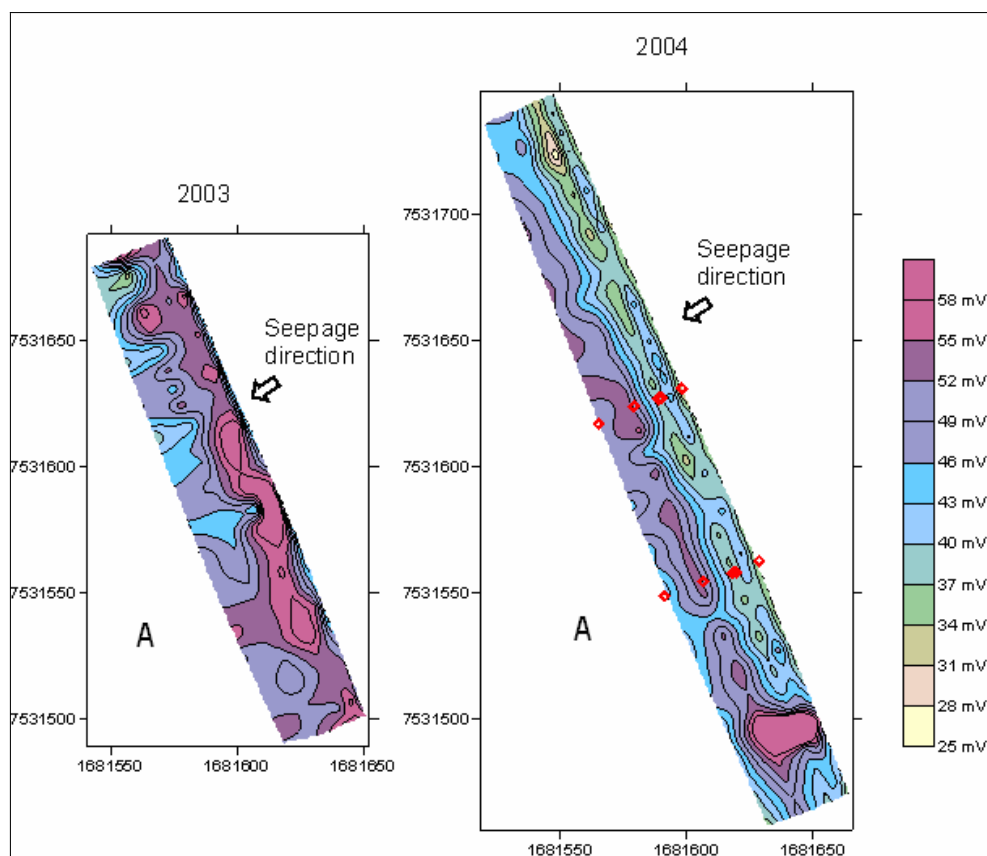


Figure 2.7. SP maps of measurements performed in October 2003 (left) and September 2004 (right), Kiruna Tailings dam, detailed measurements of selected area "A" (see Figure 2.4 for location). The 2003 measurements were performed shortly after the dam had been raised. Red symbols show the location of fixed electrodes (profile 1 bottom, profile 2 top). Coordinates are given in Swedish national grid coordinate system.

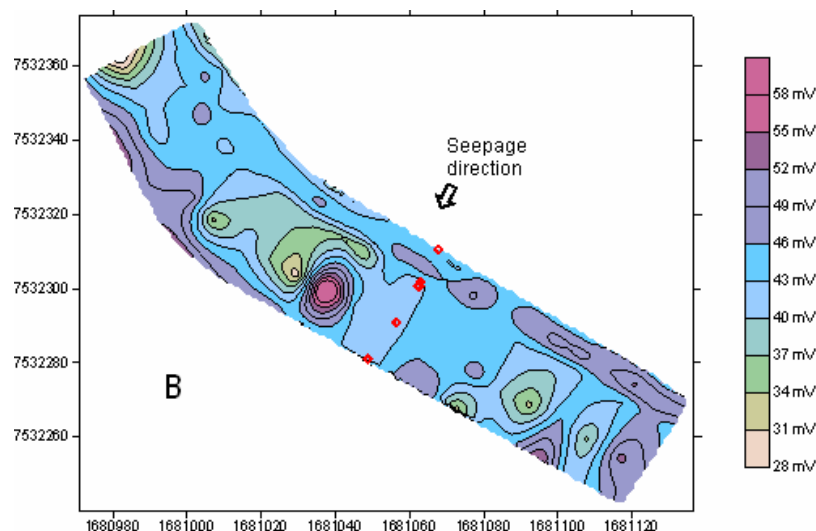


Figure 2.8. SP map of measurements performed in September 2004 Kiruna tailings dam, detailed measurements of selected area "B" (see Figure 2.5 for location). Red symbols show the location of fixed electrodes in profile 3. Coordinates are given in Swedish national grid coordinate system.

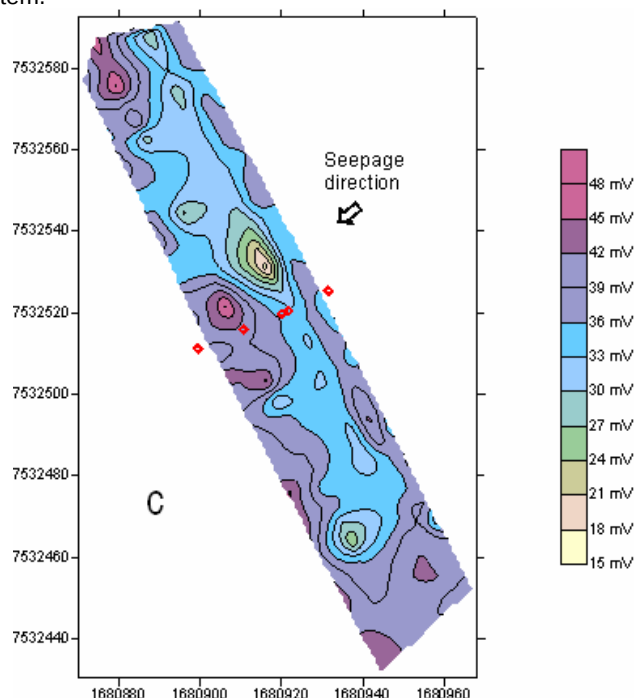


Figure 2.9. SP maps of measurements performed in September 2004, Kiruna tailings dam; detailed measurements of selected areas "C" (see Figure 2.5 for location). Red symbols show the location of fixed electrodes for profile 4. Coordinates are given in Swedish national grid coordinate system.

The result of the SP measurements in 2004 from the selected area “B” of the dam is shown in Figure 2.8. The overall patterns of SP show similarity with the 2002 measurement (Figure 2.6) of the area. A very local high SP anomaly (Figure 2.8) has also been noticed in the area of coordinate E161040/N7532290, this could be a result from some local noise. Similarly some small patches of larger positive anomaly (Figure 2.8) at the crest has been observed, that could be caused by metallic observation pipes. At the North -West corner (Figure 2.8) of the dam area, at the coordinate of E1680990/N7532350, more positive anomalies can be observed on the downstream slope which is well-matched with the behavior of streaming potentials. The type of SP distribution patterns creating such anomaly can be related to anomalous seepage; however the measurement does not cover further area of that section of the dam. It is not necessary that the path of water flow is always straight towards the downstream. It can follow other direction depending upon the materials and the slope of the dam. Except this anomaly, no major anomalies that can be related to anomalous seepage of the water can be identified.

The result of the SP measurements in 2004 from the selected area “C” of the dam is shown in Figure 2.8. In general results show lower values of SP on the upstream side of the dam and higher to on the toe of the dam. That reflects the streaming potentials within the dam. A clear streaming potential features can be noticed in the areas, at the coordinates 7532500 N to 7532540N of the dam. A small but larger positive anomaly ($>35\text{mV}$) at the crest of the dam (Figure 2.9) around 1680940E/7532490N are due to potentials generated by metallic observation pipes installed for water monitoring in the dam.

Generally, in all sections, higher magnitude of SP values is obtained on the toe and lower values on the crest of the dam. This suggests a streaming potential phenomenon within the dam.

3. Resistivity surveys

3.1 Introduction

Electrical resistivity method is a geophysical method which utilizes direct currents or low frequency alternating currents to investigate the electrical properties (resistivity) of the subsurface. The electrical resistivity method is one of the most widely used, a quick and cheap way of getting subsurface information. The method is also known as geoelectricity and direct current resistivity (DC resistivity). The purpose of resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. The method has been used in the search for water bearing formations, in stratigraphic correlations in oil fields and prospecting for conductive ore bodies, but also for detection of fractures and cavities in the subsurface, for delineating archaeological features and in monitoring pollution in the ground (Parasnis, 1997). The electrical resistivity varies between different geological materials, depending mainly on variations in water contents and dissolved ions in water. Resistivity investigations can thus be used to identify zones with different physical properties that can be related to variations in geological conditions.

3.2 Resistivity of rocks and minerals

The electric resistivity of natural rocks and sediments can vary greatly and depends on a number of factors. The amount and interconnectivity of various minerals will play a role. The resistivity of silicate minerals is typically very high ($10^6 \Omega\text{m}$ and up) whereas sulphides and most oxide minerals can be considered semiconductors with resistivities in the range of 10^{-6} to $10^{-2} \Omega\text{m}$. Graphite also exhibit semiconductor properties with resistivities of the same order as for sulphides. The typical range of electrical resistivities of earth materials is depicted in table 4.1.

The resistivity of water depends strongly on the concentration of salts, which provide dissolved ions that act as charge carriers. Fresh groundwater will usually have a resistivity in the range of 10 to 100 Ωm , while saltwater is more conductive by a factor from 100 to 1000 less resistive (0.1 Ωm) (Thunehed, 2000). Contrasts in electrical conductivities are expected like e.g. between soil and rocks, or soil above and beneath the groundwater surface. The ability of a medium to conduct an electric current is termed electrical conductivity σ (S/m) and the inverse of it is electrical resistivity ρ (Ωm). When a static electric field E (V/m) is applied, a current density J (A/m²) is established. Ohm's law in the case of a linear isotropic medium state that

$$E = \rho J = \frac{J}{\sigma} \quad (3.1)$$

Earth bulk materials are comprised of a solid phase (rocks and soils) and a space phase (pores, cracks, micro fissures, fractures, etc.) that occupy the space between the solid materials. Thus the bulk resistivity of earth materials is associated with the resistivity of the solid phase, (rock matrix) and the resistivity of materials that fill the open space, which may be air, oil or any liquid. The resistivity of an electrolyte in pore spaces dominates the formation resistivity in most cases. The degree of pore interconnectivity will greatly influence a rock's bulk

resistivity and the shape of the pores will also have some effect. The most widely used relationship between the porosity (ϕ), water saturation (S_w), resistivity of the electrolyte (ρ_w) and bulk resistivity (ρ) can be expressed by Archie's law.

$$\rho = \rho_w S_w^{-n} \phi^{-m} \quad (3.2)$$

where m and n are certain parameter.

The value of n is the saturation exponent, usually close to 2, if more than 30% pore space is water-filled but can be much greater for lesser water content. The exponent m is the cementation factor that varies with degree of compaction, cementation and consolidation .It varies from about 1.3 for loose, Tertiary sediments to about 1.95 for well cemented Palaeozoic ones (Parasnis, 1997).

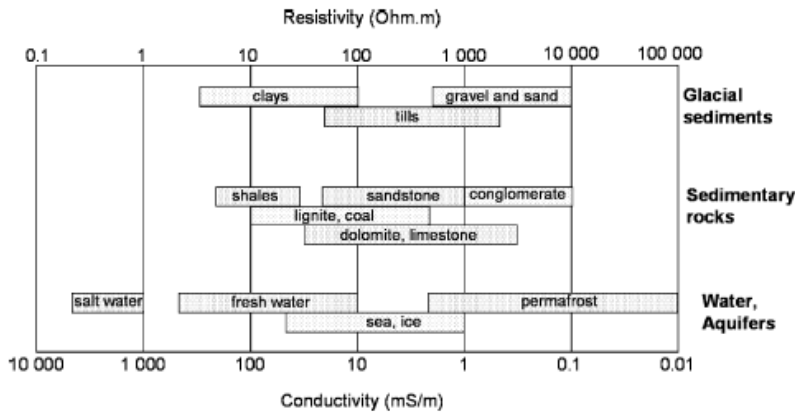


Table 4.1. Typical ranges of electrical resistivities of earth materials (modified from Palacky, 1987).

The rock matrix cannot be assumed to be an insulator when clay minerals are present. In fact clay minerals are very good conductors due to the presence of mobile ions adsorbed to the grains. At the interface between the grains of clay minerals and the electrolyte, the ions in the electrolyte will be attracted or repelled from the clay surface and produce an electric double layer. The resistivity of an electrical double layer is the surface resistivity ρ_s ($= 1/\sigma_s$), expressed in ohm-meter. The bulk resistivity when the surface resistivity is present is expressed by a modification of Archie's law:

$$\rho = \rho_w S_w^{-n} \phi^{-m} + \sigma_s \quad (3.3)$$

This property is present for all silicate minerals to a greater or lesser extent. For very well cemented or crystalline rocks with lower porosity, it might be dominating conductivity mechanism even when no clay present.

3.3 Resistivity measurements

The resistivity of the ground is measured by injecting current with two electrodes and measuring the resulting potential difference with two other electrodes. The readings are usually converted to an apparent resistivity, corresponding to the resistivity of a homogeneous half-space that would give the same result. The investigated volume can be changed by moving the electrodes. Large separations give larger investigation depths. Modern data acquisition systems have made it feasible to measure resistivity along profiles with several electrode separations. The data are usually inverted to a vertical resistivity section, assuming 2D geometry perpendicular to the profile. The inversion process is generally under-determined, which means constraints have to be applied to the model. Most commonly local variability is minimized, resulting in smooth models that are compatible with measured data. This means that sharp resistivity borders like e.g. the ground water surface is visualized as a smooth transition in such an inverted section.

If an electric current I (A) is flowing through a linear conductor of uniform cross-section A (m^2) and a length L (m). Ohm's law states that

$$\Delta V = IR \quad (3.4)$$

where ΔV is the potential difference (volt, V) between the ends of the conductor and R (ohm, Ω) is the resistance of the conductor. The resistivity (ρ) that is the physical property of the conductor that can be defined by

$$\rho = \frac{RA}{L} \quad (3.5)$$

The basis of the electrical resistivity method is to introduce a known current into the ground and measure potential differences on the surface to estimate the resistivity of the subsurface. In a homogeneous and isotropic half-space, electrical equipotentials are hemispherical, when the current electrodes are located at the soil surface as shown in figure 1. The current density J (A/m^2) has then to be calculated for all the radial directions with:

$$J = \frac{I}{2\pi r^2} \quad (3.6)$$

where $2\pi r^2$ is the area of a hemispherical sphere of radius r . The potential V can then be expressed as follows:

$$V = \frac{\rho I}{2\pi r} \quad (3.7)$$

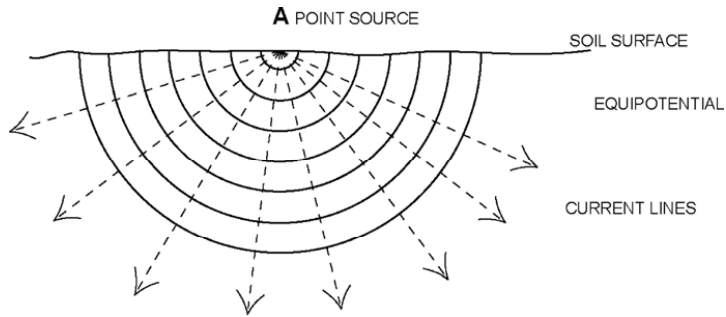


Figure 3.1. Distribution of the current flow in a homogeneous ground.

The resistivity measurements are made by introducing a DC or low-frequency alternating current into the ground by means of two electrodes (A, B in Figure 3.2) connected to a portable power source. The resulting potential difference is measured on the ground with two potential electrodes (M, N). The potential field produced in the underground is dependent on the dispersion of the specific electrical resistance.

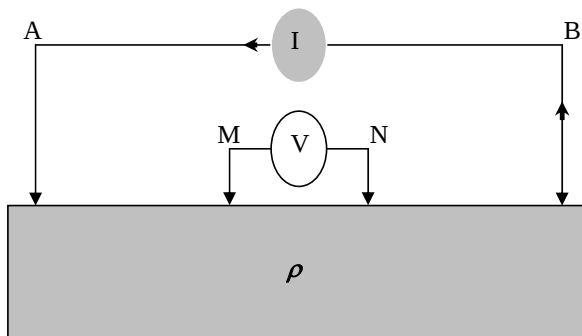


Figure 3.2. Outline of four electrodes array for resistivity measurement on the surface.

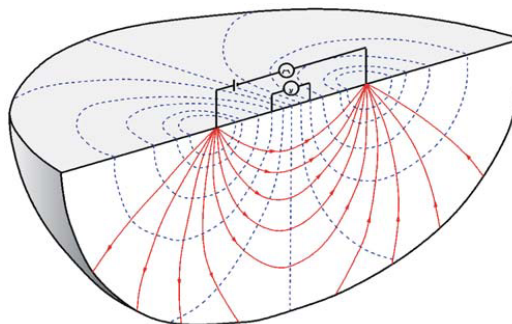


Figure 3.3. Current dipole (solid lines) and potential field (dashed lines) showed in the situation of homogenous dispersion resistance.

If the resistance is a homogenous, the electric current- and potential-field lines are produced as illustrated in Figure 3.3.

The Potential difference (ΔV) measured between the electrodes M and N is given by equations

$$\Delta V = V_M - V_N \quad (3.8)$$

Where

$$V_M = \frac{\rho I}{2\pi} \left(\frac{1}{AM} - \frac{1}{BM} \right) \quad (3.9)$$

$$V_N = \frac{\rho I}{2\pi} \left(\frac{1}{AN} - \frac{1}{BN} \right) \quad (3.10)$$

Thus

$$\Delta V = \frac{\rho I}{2\pi} \left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right) \quad (3.11)$$

Where AM, BM, AN and BN represent the geometrical distance between the electrodes A and M, B and M, A and N, and B and N, respectively. The electrical resistivity is then calculated using:

$$\begin{aligned} \rho &= \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{BN} - \frac{1}{AM} + \frac{1}{BN} \right)} \left(\frac{\Delta V}{I} \right) \\ &= K \frac{\Delta V}{I} \end{aligned} \quad (3.12)$$

$$\text{Where } K = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{AN} - \frac{1}{AM} + \frac{1}{BN} \right)} \quad (3.13)$$

K is the geometric coefficient that depends on the arrangement of the four electrodes A, B, M and N.

3.4 Apparent resistivity

Equation (3.12) can be used to calculate the true resistivity of the underground if the medium is homogenous. The resistivity so obtained will be constant and independent of both electrode configuration on and surface location. If the ground is inhomogeneous, the resistivity (ρ), as

calculated from Equation (3.12), will vary on altering the geometrical arrangement of the electrodes. The resistivity that is then calculated is termed the apparent resistivity, ρ_a and it should be considered as some sort of average resistivities encountered in the heterogeneous underground. In general, all field data are apparent resistivity. They are interpreted to obtain the true resistivities of the layers in the ground. The apparent resistivity will be close to the true resistivity in the vicinity of electrodes when the relative electrode spacing is very small.

There are different methods involved to get the apparent resistivity of the subsurface. Resistivity profiling is on, in which the spacing of electrodes is kept constant along the survey line. This provides a lateral resistivity distribution at a constant depth. Vertical electrical sounding (VES) method gives the apparent resistivity variation with depth for a horizontal layered earth. This is achieved by taking number of measurements at a common midpoint with successive larger electrode separation. The calculated resistivity is plotted as a function of electrode separation to produce a sounding curve. Two dimensional electrical profiling; also known as electrical imaging, shows both vertical and lateral variations in electrical resistivity. This method provides pseudosection of electrical resistivity distribution (both later and vertical) of subsurface. The current and potential electrodes are expanded to obtain the information from greater depth and shifted along a profile line to determine lateral changes in electrical resistivity. In the present study, electrical imaging technique was used to obtain the subsurface distribution of electrical resistivity.

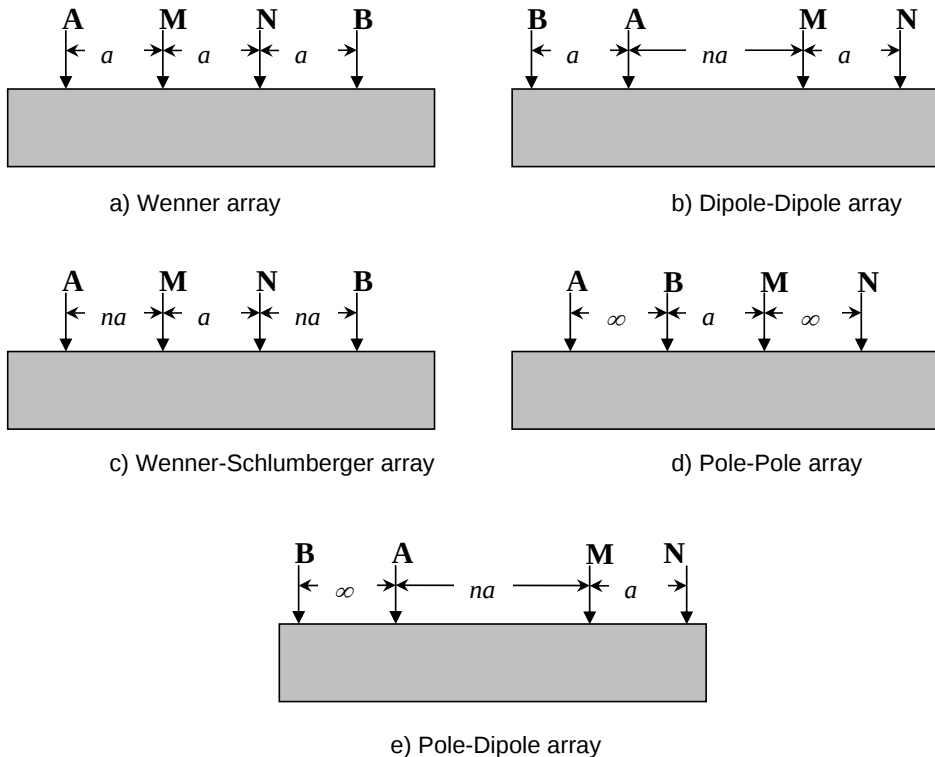


Figure 3.4. Common electrode arrays that are used in resistivity surveys.

3.5 Electrode Configurations

There are a number of different electrode configurations available for resistivity surveys. The arrays that are most commonly used for two dimensions (2-D) resistivity imaging surveys are Wenner, Dipole-Dipole, Wenner-Schlumberger, Pole-Pole and Pole-Dipole (Fig. 3.4). Choice of array generally depends on the nature of the investigation, field condition, and the sensitivity of the resistivity meter, the background noise level and manpower. The sensitivity of the array is estimated from the potential difference that can be measured from a specific change in resistivity. Normally, the highest sensitivity can be obtained closest to the electrode.

3.6 Data acquisition

During the course of the project a number of resistivity investigations were performed at different times on the Kristineberg tailings dam. Resistivity pseudosections have been measured along six profiles on the dam (see Figure 2.3). Data were first collected in the late summer 2003 using a pole-dipole array (Figure 3.4e) and a multi-channel system. This system consists of a multi-channel board for connecting two current and eight potential electrodes to an ABEM SAS 4000 Terrameter with multi-channel software. A common electrode spacing of minimum two meters was used for all pseudosections. These resulted in an investigation depth of around 7.5 meters.

During late autumn 2004 the resistivity data was again collected along profiles PS1, PS3, PS4 and PS5 with the ABEM Lund imaging system. The system is a multi-electrode system for high-resolution 2D and 3D resistivity surveys. The measurements were performed using a Wenner array (Fig 3.4a) with 2 meters electrode separation. In general, the Wenner is good in resolving vertical changes (i.e. horizontal structures), but relatively poor in detecting horizontal changes (i.e. narrow vertical structures). The median depth of investigation of the array is approximately 0.5 times the “a” spacing used. Compared to other arrays, the Wenner array has a moderate depth of investigation. The signal strength is inversely proportional to the geometric factor used to calculate the apparent resistivity value for the array. For the Wenner array, the geometric factor is $2\pi a$, which is smaller than the geometric factor for other arrays. Among the common arrays, the Wenner array has the highest signal strength. This can be an important factor if the survey is carried in areas with high background noise. One disadvantage of this array for 2-D surveys is the relatively poor horizontal coverage as the electrode spacing is increased (Loke, 2000).

For this survey electrodes and cables were laid out with a straight line attached to a multi-core cable. This system automatically collects data after connecting all the electrodes properly and setting the programme. For example, if we use a sequence of measurements for the Wenner electrode array for a system with 40 electrodes, all the measurements will be performed with electrode spacing of “1×2 meters”. For this case in the first measurement, electrodes number 1, 2, 3 and 4 are used. Electrode 1 was used as the first current electrode C1, electrode 2 as the first potential electrode P1, electrode 3 as the second potential electrode P2 and electrode 4 as the second current electrode C2. For the second measurement, electrodes number 2, 3, 4 and 5 are used for C1, P1, P2 and C2 respectively. This is repeated down the line of electrodes until electrodes 37, 38, 39 and 40 are used for the last measurement.

After completing the sequence of measurements with “2 meters” spacing, the next sequence of measurements with “2× 2 meters” electrode spacing is made. First electrodes 1, 3, 5 and 7

are used for the first measurement. The electrodes are chosen so that the spacing between adjacent electrodes is “4 meters”. For the second measurement, electrodes 2, 4, 6 and 8 are used. This process is repeated down the line until electrodes 32, 36, 38 and 40 are used for the last measurement with spacing “4 meters”. The same process is repeated for measurements with “3× 2”, “4× 2”, “5× 2”, “6× 2” and other spacings.

The data were transferred from instrument to PC by protocol generation software and file conversion software of the Lund imaging system.

3.7 Data processing

From the measured data two-dimensional (2-D) resistivity models were calculated by using the program RES2DINV Ver. 3.54 (Loke, 2004). In this inversion program, the subsurface is divided into small rectangular blocks (Figure 3.5). The arrangement of the blocks is loosely tied to the distribution of the data points in the pseudosection. Each block represents a data point of apparent resistivity. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation. The number of blocks normally does not exceed the number of data points. A finite-element forward modeling subroutine has been used to calculate the apparent resistivity values and a non-linear least squares optimization technique is used for the inversion routine. The optimization method basically tries to reduce the difference between calculated and measured apparent resistivity values by adjusting the resistivity values of model blocks. Since there is a significant topographical relief along the survey lines, a correction for topographical effect is made. When the program reads a data file with topographic data, it will automatically select a finite-element method which incorporates topography into the modeling mesh used. Then the topographic modeling is performed by inverting the data set. The end products of processing by the program are refined images of resistivity distribution in the subsurface. These images are used as a modelling guide in the stage of data processing. These results from the modeling gave an investigation depth of around 25 meters in the central parts of the profiles PS3-04, PS4-04 and PS5-04 and 6 meters in profile PS1-04.

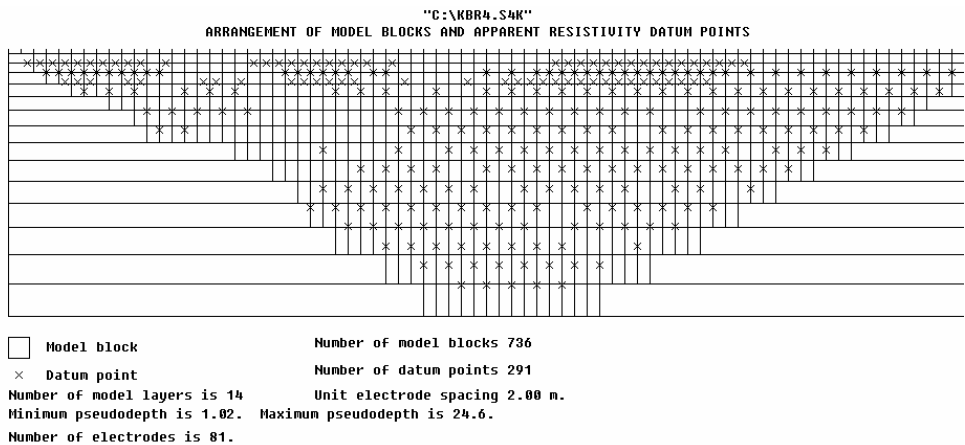


Figure 3.5. Arrangement of model blocks and apparent resistivity datum points in pseudosection PS4-04.

3.8 Result and Discussion

The six resistivity pseudosections obtained from the Kristineberg tailings dam during the 2003 measurements are presented in Figures 3.6 and 3.7. The locations of the profile are shown in Figure 2.3. The data from the Profile PS1 to PS5 generally display similar resistivity distributions, however, along profile PS2 there is an anomalously high resistivity structure in the deeper parts. This may be explained by an unusually high error obtained for that inversion model. Pseudosections of the profiles PS1 to PS5 all show a low resistivity zone near the crest of the dam which extends down to the maximum depth of the investigation and it can be related with core of the dam.

Profile PS6 (Figure 3.7) was measured along the dam near the base of the downstream side. The resulting pseudosection displays a relatively even distribution of resistivity along its length with high resistivities at the surface that decrease with depth. The high resistivities near the surfaces corresponds to unsaturated fill materials and the low resistivities correspond to water saturated material. The sharp boundary between high and low resistivity at the depth of about 3 to 5 meters shows the groundwater level.

The resistivity pseudosections acquired from the measurements in 2004 are shown in Figures 3.8 to 3.11. All the profiles are perpendicular to the extension of the dams and lies along corresponding resistivity profiles of the previous year. The length of the profiles in the 2004 measurements has been extended in both ends. The profiles PS1 and PS3 of the 2003 survey coincide with the PS1-04 and PS3-04 at distance along the profile at 15m-55m and 55m-130m respectively, whereas profiles PS4 and PS5 survey match PS4-04 and PS5-04 (2004 profiles) between 20m-90m. The Pseudosections of all the profiles (PS1-04, PS3-04, PS4-04 and PS5-04) are fairly similar to those of 2003.

The pseudosection of profile PS1-04 (figure 3.8) shows a small very low resistivity zones at the beginning of the profile that reflects the conductive water from the lake. A high resistivity zone near the upstream of the dam corresponds to the more coarse support fill. The core of the dam, which mainly consists of moraine is reflected by a resistivity below 100 (Ωm) between 20m-32m of the horizontal distance of the profile. The supports fill on the downstream side shows high resistivities above 1000 (Ωm) in all profiles, resistivities that correspond to quite dry material. The continuation of the high resistivity zones towards the end of the profile PS1-04, which is different from other profiles is probably due to the presence of dry coarse materials in shallow depth.

The profile PS3-04 (Figure 3.9) is the longest profiles and extends up to nearly 200m. The presence of a thin ice sheet on the pond during the time of the survey made it possible to extend the profile on the upstream side. As expected pond water and the upstream support fill show very low resistivities. The conductivity measured from the pond water confirms the results. The central part of the dam, which mainly consists of moraine, shows resistivities just below 100 (Ωm) at 65m of the profile, this is a value that is compatible with the expected resistivity of a compacted moraine saturated with water from the tailings pond. The same fairly low resistivity can be seen close to the crest of the dam, where the core of compacted moraine prevents seepage. The moraine contains fractions of fine-grained material and it therefore contains capillary water which increases the conductivity. A gradient in resistivity across the dam core has been seen, this is probably due to the sharp hydraulic gradient across the core.

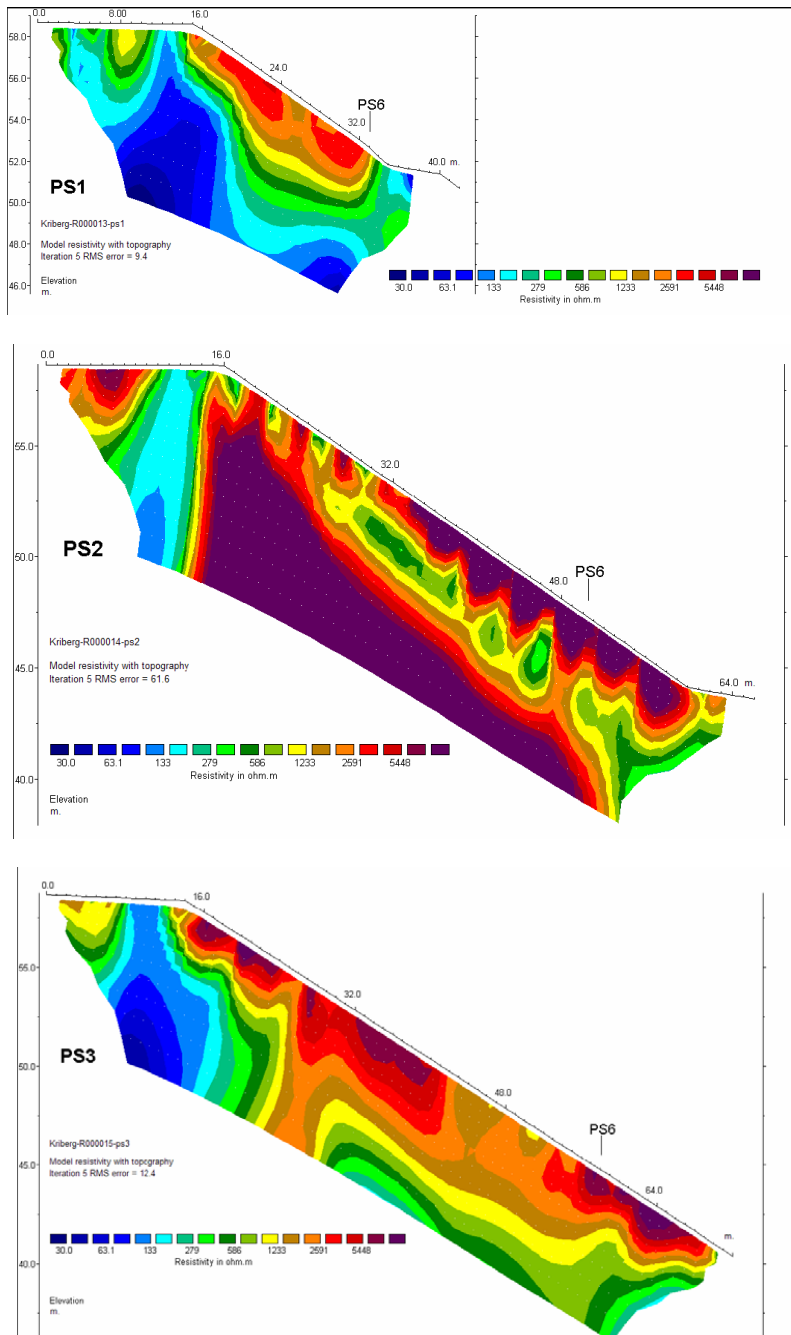


Figure 3.6. Resistivity pseudosections PS1, PS2 and PS3 of the Kristineberg tailings dam from 2003 measurements. (After Bérubé 2004).

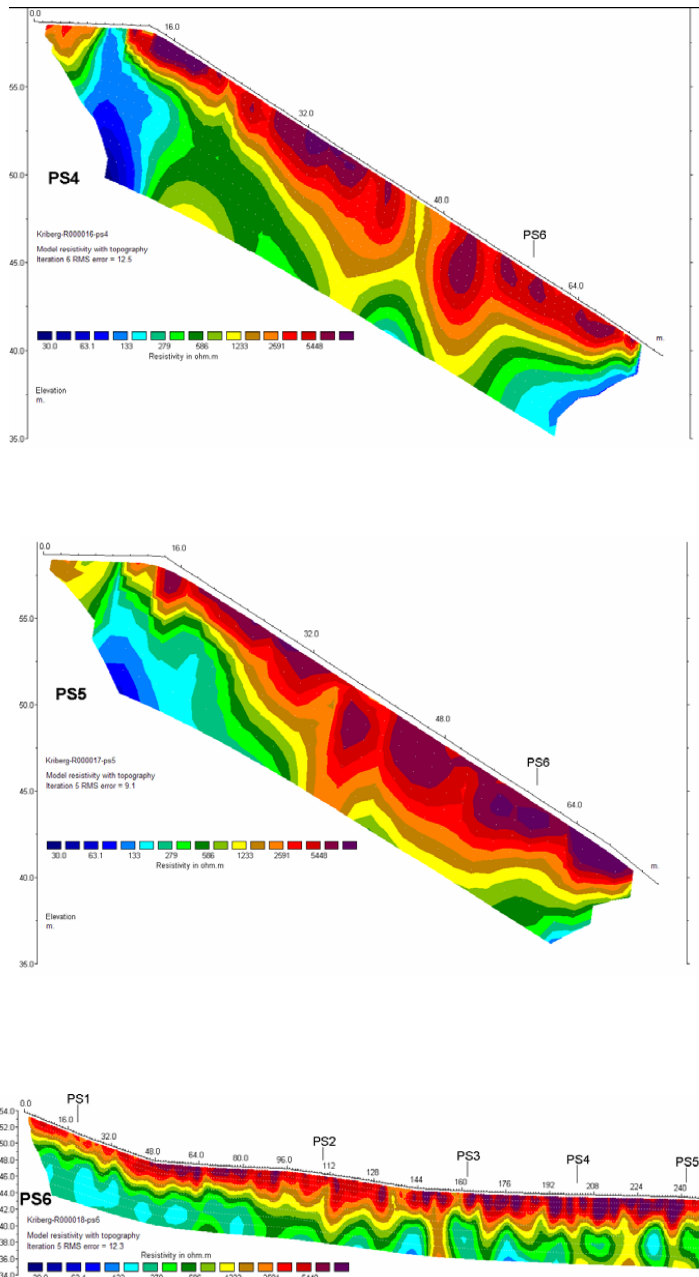


Figure 3.7. Resistivity pseudosections PS4, PS5 and PS6 of the Kristineberg tailings dam from 2003 measurements (After Bérubé 2004).

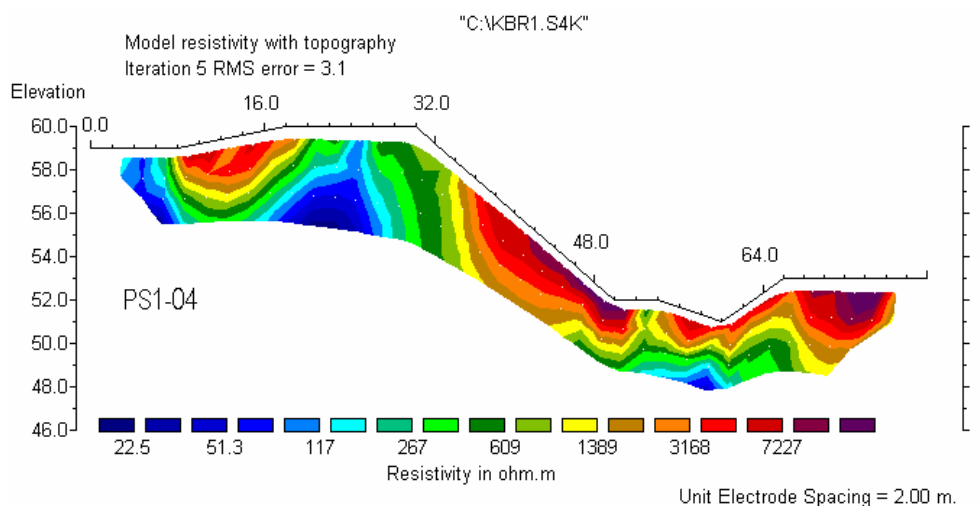


Figure 3.8. Resistivity pseudosection PS1-04 of the Kristineberg tailings dam obtained from 2004 measurements.

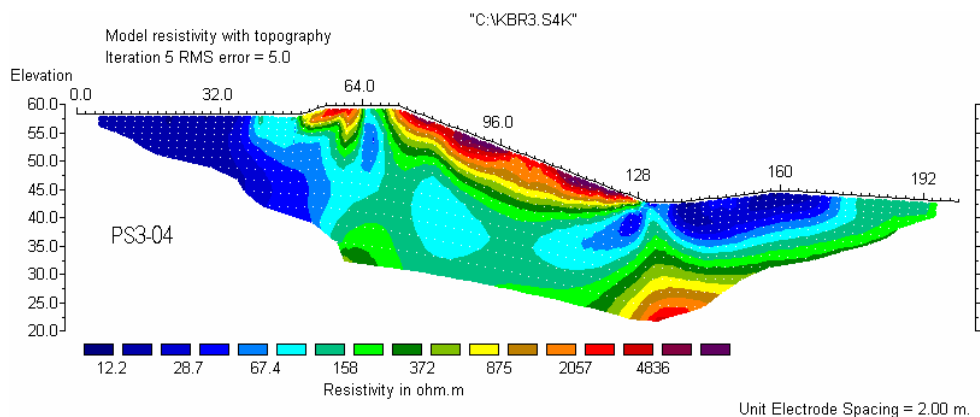


Figure 3.9. Resistivity pseudosection PS3-04 of the Kristineberg tailings dam obtained from 2004 measurements.

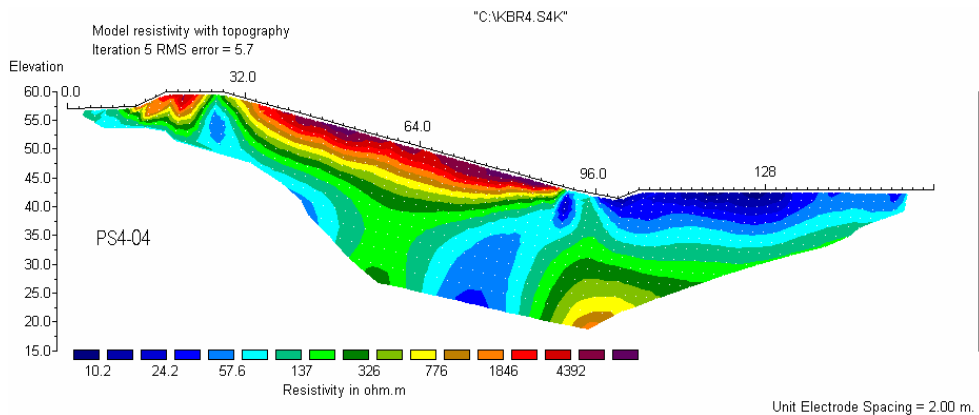


Figure 3.10. Resistivity pseudosection PS4-04 of Kristineberg tailings dam obtained from 2004 measurements.

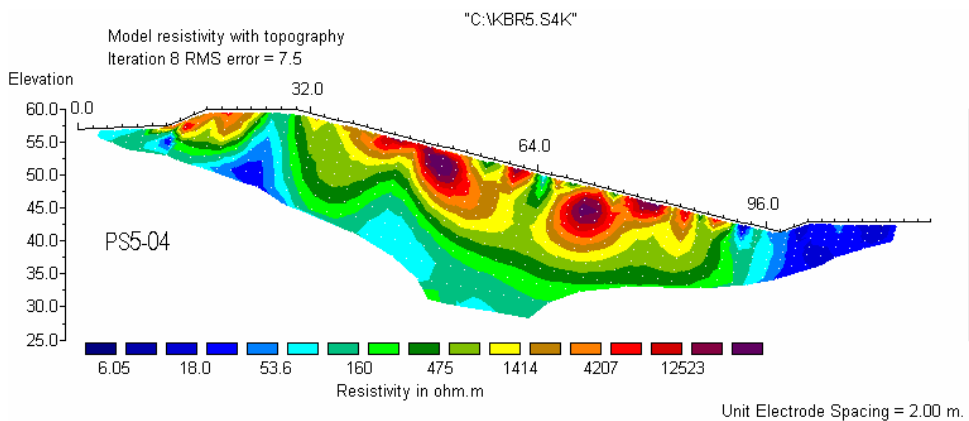


Figure 3.11. Resistivity pseudosection PS5-04 of the Kristineberg tailings dam obtained from 2004 measurements.

A low to fairly low resistivity zones can be noticed around 15m depth of the pseudo-section from 70m. to about 130m .The variation of the resistivities is from 70 Ω m to 370 Ω m which may reflect that some parts are water saturated and some are not .This probably do not show any distinct seepage pattern. The supports fill on the downstream side shows high resistivities well above 1000(Ω m), which is correlated with quite dry material. A very conductive zone with a resistivity similar to that of the pond water can be seen on the downstream side of the dam for a distance of some 90 meters. That area was swampy at the time of the survey .This

low resistivity suggests that the pore water in the soil must be even more conductive than the pond water.

The pseudosection of the profile PS4-04 (Figure 3.10) shows high resistivity ($>1500 \Omega\text{m}$) values at the surface and it decrease ($<100\Omega\text{m}$) with depth. This is seen from ca 23 m to about 90 m along the profile. After that, there is a reverse pattern in the resistivity distribution, i.e. a very low resistivity at the surface and increasing resistivities with depth. This is similar with what is observed for profile PS3-04 (Fig 3.9). The low resistivity value (below $100 \Omega\text{m}$) at the crest of the dam reveals the core of the dam.

Along the profile PS5-04 (figure 3.11) the resistivities deviate somewhat from the results from 2003 measurements showing small patches of low resistivities zone. This can be explained by the resolution of 2004 survey is higher than the resolution of the 2003 survey. The pseudosection obtained from the profile PS5-04 (Figure 3.11) shows varying resistivities along the slope, different from what is seen along the other profiles. This can be due to different materials used for filling and the irregular construction of dam. The dam has been raised many times and it is probably inhomogeneous in terms of materials used for construction. The same fairly low resistivity as in other profiles is however seen close to the crest of the dam which represents core of compacted moraine. At the end of the profile, a high conductive zone, also seen in the profiles PS3-04 and PS-04, is observed.

4. Electrical resistivity measurements on soil samples

Soil samples have been collected from the all three tailings dams for lab measurements. The purpose of the lab measurements is to obtain more information about the electrical properties of the tailing cover materials in different condition, as well as to look into how the electrical properties of the soils will be affected by internal erosion inside a dam. Samples have also collected of impoundment water so that laboratory measurements on the soil samples can be done with the samples soaked in that kind of water.

4.1 Resistivity of soils

Most common minerals like silicates can be regarded as electrical insulators. The electric current is conducted through a soil by the water present in pore spaces. High resistivity is thus expected for soils with low porosity, low water saturation and/or low pore water salinity. However, the electric resistivity is also influenced by phenomena at the mineral grain – pore water interface. Clay minerals have an ability to adsorb ions in an exchangeable state and clayey soils are therefore usually of low resistivity. A similar property can also be found for other minerals although to a lesser extent. The effective resistivity in a single pore space is lower at the mineral grain interface resulting in an effect called surface conductivity. Unsaturated soils, containing just some capillary water, can therefore have lower resistivity than what otherwise might be expected.

4.2 Factors affecting resistivity

The electrical resistivity is a function of a number of soil properties, including the nature of the solid constituents (particle size distribution, mineralogy), arrangement of voids (porosity, pore size distribution, connectivity), degree of water saturation (water content), electrical resistivity of the fluid (solute concentration) and temperature. These parameters affect the electrical resistivity in different ways and to different extents.

4.2.1 Archie's Formula

Formulas that relate the resistivity of the different components to the bulk resistivity of the conducting medium are referred to as mixing law, and the simplest of these is Archie's formula (Abu-Hassanein et al. 1996). Archie's formula relates the electrical resistivity of saturated soil ρ to the electrical resistivity of its pore fluid ρ_w and the geometry of the pore spaces in the soil by the relationship:

$$\rho = a\rho_w\phi^{-m} \quad (4.1)$$

Where ϕ = porosity of the soil, and a and m are constants that depend on the type of soil or rock. For unconsolidated clay free soil $a = 1$, and the constant m usually refer to cementation factor, and it varies between 1.4 and 2.2 for clean sands and gravels encountered the ground-water aquifers (Abu-Hassanein et al. 1996). The equation 4.1 shows that the electrical resistivity of saturated soil is sensitive to the porosity, the electrical resistivity of the pore fluid, and the soil fabric and type. For a given soil with a constant a and m , as the porosity

decreases, the electrical resistivity of the soil increases, and as the electrical resistivity of the pore fluid increases, the electrical resistivity of the soil increases. Archie's formula has been recognized as an oversimplification, but is still valid as long as the pore fluid resistivity is low and there are relatively small quantities of conducting clay minerals present in the soil.

4.2.2 Soil type

The resistivity of the solid matrix is the result of electron conductance through the grain-to-grain contacts of adjoining sand grains of the aquifer. Electrical conduction in clean sands and gravels occurs almost exclusively in liquid contained in the pores, because quartz sand is virtually a non-conducting material and matrix solids resistivity is considered infinitely high. In clayey soils and clay-bearing rocks, however, electrical conduction occurs in the pores and on the surfaces of electrically charged clay minerals. For clays, surface conductance can be a significant factor affecting the bulk electrical resistivity of the soil.

4.2.3 Ionic content of pore fluid

Ionic content of the pore fluid determines its electrical resistivity. An increase in ionic content or the amount of dissolved solids in the pore fluid will produce a large decrease in electrical resistivity. If insulating contaminants are present in the pore water, resistivity will increase. The influence of the conductive contaminants is greater than that of non-conducting contaminants (Campanella and Weemee 1990).

4.1.4 Hydraulic conductivity

Hydraulic conductivity is dependent on several factors, many of which are the same that influence resistivity. Because ions flow through some of the same paths as water, the electrical resistivity and hydraulic conductivity of soils are expected to be affected by similar variables. Among these variables are fluid viscosity, pore-size distribution, grain-size distribution, void ratio, roughness of mineral particles, and degree of soil saturation. In clayey soils, structure, ionic content, and thickness of the water layers held to the clay play an important role in determining hydraulic conductivity. Also influencing the hydraulic conductivity in compacted clays are factors such as changes in density, void ratio, molding-water content, compactive effort, and compaction method, all of which are variables affecting the size, shape, and connectivity of the pores (Abu-Hassanein et al. 1996). It is important to note that the relationship between electrical resistivity and hydraulic conductivity varies with different soils.

4.1.5 Compaction Variables

The degree of compaction is measured by its dry unit weight. Water is added to soften the dry soil, and particles are able to slide past one another and create a denser soil until the soil reaches the optimum moisture content. This value is reached when the most possible void space is taken up by solid particles. After this point, too much water separates particles that were previously more densely packed. As the compaction effort is increased, the maximum dry unit weight of compaction is also increased, while the optimum moisture content is

decreased to some extent. However, hydraulic conductivity decreases with the increase in moisture content. It reaches a minimum value at approximately the optimum moisture content. Beyond that point, the hydraulic conductivity increases slightly. High resistivity can be expected for soils compacted with low water content and/or high air-filled porosity. Thus, data from field measurement of resistivity can be used as an indicator of hydraulic conductivity.

4.1.6 Saturation

For constant water resistivity, resistivity differences between unsaturated sediments, such as a fine gravel and silt, are generally much larger than for the same sediments in a saturated condition, with finer sediments being less resistive than coarser sediments.

4.1.7 Particle-Size Distribution

With an increase in percentage of fines in sandy soils, electrical resistivity is affected in three ways. First, porosity will be decreased, since the fines will occupy void space between sand grains, and decreasing porosity has the effect of increasing the resistivity. Secondly, the presence of fines in the soil generally indicates the presence of conducting clay minerals, which would result in a decrease in the resistivity. Thirdly, soils with higher fines content also generally have higher specific surface, which improves surface conductance (Abu-Hassanein et al. 1996). In general, surface resistance increases as soils become increasingly coarse-grained

4.1.8 Temperature

The viscosity of the pore fluid affects the conductivity of a particular ion in an electrolyte. The most important factor affecting viscosity, and hence conductivity, is the pore fluid temperature. Ion agitation increases with temperature when the viscosity of a fluid decreases. Thus, the electrical resistivity decreases when the temperature increases.

4.3 Collection of samples

Seventeen samples were collected manually from different part of the tailings dams including three water samples from the tailings pond. The soil samples consist of tailings sand, moraine and dam surface cover materials. The soil samples were kept in plastic bags to prevent drying.

4.4 Measuring procedure

For direct measurements of soil samples, it is necessary to compact the sample into a regular form such as a cylinder or a box so that it's cross sectional area and length can be calculated.

A simplified sketch of the equipment for laboratory resistivity measurement is shown in Fig. 4.1. The current (I) is introduced through metallic plates at the ends of the tubes and the resulting potential difference (ΔV) is measured between two rings separated by the distance L .

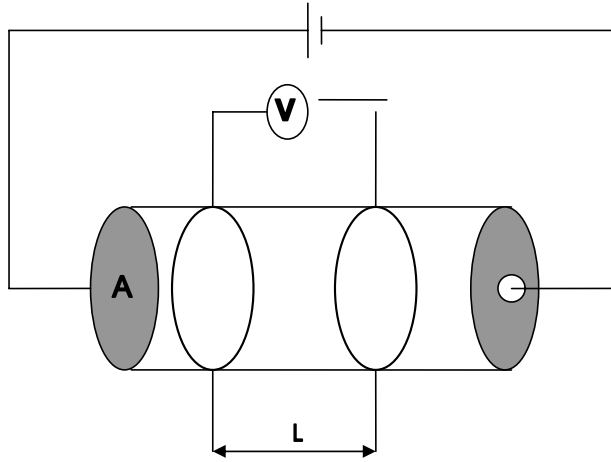


Figure 4.1. A simplified sketch of the equipment for laboratory resistivity measurement on soil samples

Under the assumption that the current density is constant over cross sectional area A between the ring electrodes, the resistivity of the soil sample can be calculated as:

$$\rho = \frac{\Delta V}{I} \frac{A}{L}$$

The samples were measured in the laboratory shortly after collection. This gave a general idea about the resistivity of the soils at unsaturated situations with just capillary water although moisture content and compaction are not same as in the field. The samples were then soaked with impoundment water from the respective dams and the resistivity was measured again. It should be noted that the samples were not dried before soaking with water from the tailing ponds and that the conductive impoundment water therefore was diluted by the fresh capillary water that remains in the samples.

The samples were sieved and separated into grain size fractions in order to investigate how the electrical properties of the soils would be affected by internal erosion inside a dam. The finest mesh size was 0.07 mm. The resistivity of the coarse grained fractions (>0.25mm) soaked in water from the impoundments was first measured. Then finer fractions were added and mixed with the previous sample. Compaction was performed after each fraction was added and the resistivity was then measured again. This process would then correspond to reversed internal erosion.

4.5 Results and Discussion

The resistivity values determined in the lab is only an approximation of the true in-situ values. The lab samples may be disturbed, they can not be compacted to exactly the same extent as in the field, and they do not have exactly the same moisture content and they are not at the same temperature.

Particle size distribution used in the laboratory measurements are presented as relative weight fraction distribution. The relative weight fraction is acquired by the appropriate weight of the fraction used for the measurements by dividing the total weight of all fractions. This gives the relative quantity of the different particles sizes used for the measurements of the soil samples.

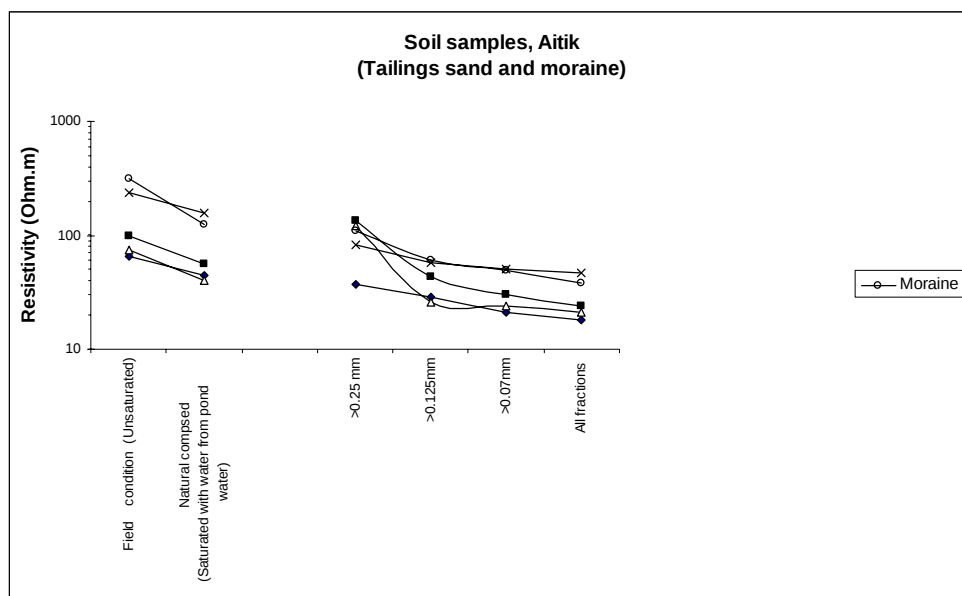


Figure 4.2a. Resistivity measurements on five soil samples from Aitik. The resistivity of the moraine sample is shown by the symbol ○. The other symbols refer to tailings sand.

The results of the soil resistivity measurements and relative weights of grain size fractions used for different measurements are presented in Figure 4.2. to Figure 4.4. In natural composed samples, the resistivity decreases significantly from an unsaturated to saturated condition as expected. The resistivity in saturated conditions is the combined resistivity of the solids materials and the water. The resistivity decreases by 40% to 90% from field condition to the saturated condition. The decreasing factor is not the same for the samples due to differences in moisture content in the field condition.

The resistivity measurements of the samples from the Aitik (Figure 4.2a) show a decrease in resistivity as finer particles are added to the coarser samples containing particles size >0.25mm. A moraine sample follows the same trend. In two samples, the resistivity decreases

in greater factor from coarser fraction ($>0.25\text{mm}$) to the fraction containing $>0.125\text{mm}$ particles size with compare to other soil samples and moraine. This may be due to the presence of conductive minerals grain in that fraction of the soil. The decrease in resistivity in the moraine is due to surface conductivity.

The laboratory measurements of the samples from the Kiruna (Figure 4.3a) and Kristineberg (Figure. 4.4a) reflects the same pattern of electrical resistivity variation as finer fraction material is added to the samples. The decrease in resistivity shows lower extent (about $10\ \Omega\text{m}$ - $15\ \Omega\text{m}$) from the samples from Kiruna.

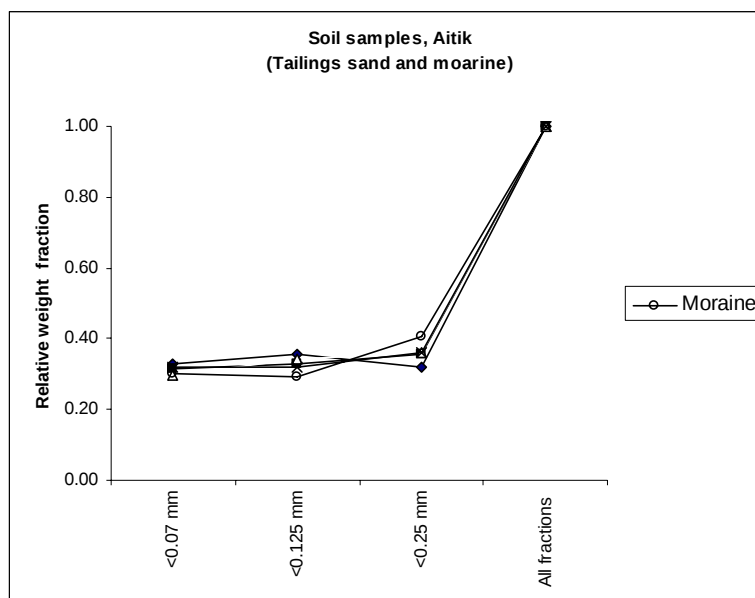


Figure 4.2b. Relative weights of grain size fractions of the soils from Aitik used for resistivity measurement.

Seepage of water in the dam might create internal erosion. During this process, fine grained materials are transported away and the remaining grain materials will give rise to increased porosity and a decrease in resistivity is expected. Thus, increased content of fines will decrease the porosity, which has the effect of increasing resistivity, if the effect from mineral grain-electrolyte interface is negligible. However, the laboratory measurements reveal that the addition of finer fraction in all soil samples decreases the resistivity. This may be explained by the presence some conducting minerals in the fines and surface conduction on the other minerals than clay is a significant factor affecting the bulk electrical resistivity of soil.

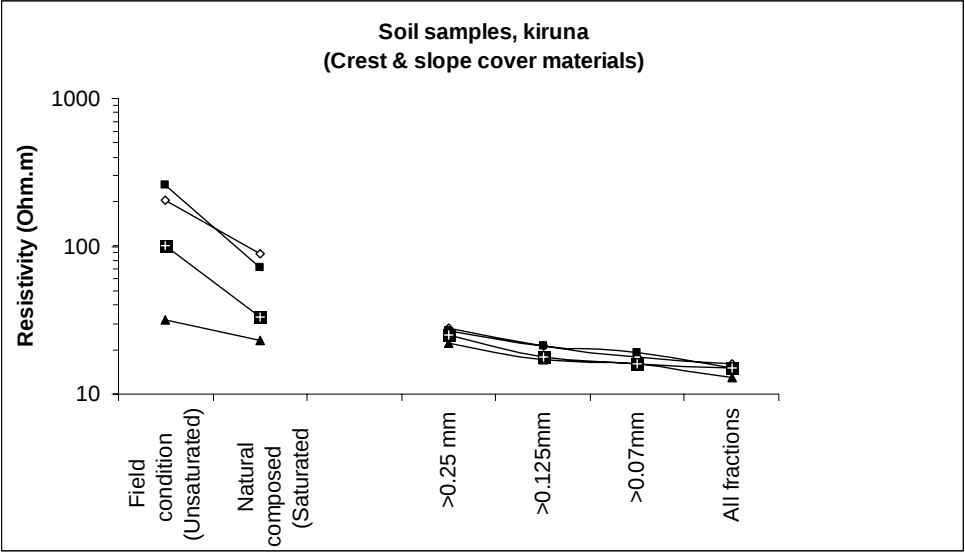


Figure 4.3a. Laboratory resistivity measurements on four soil samples from Kiruna.

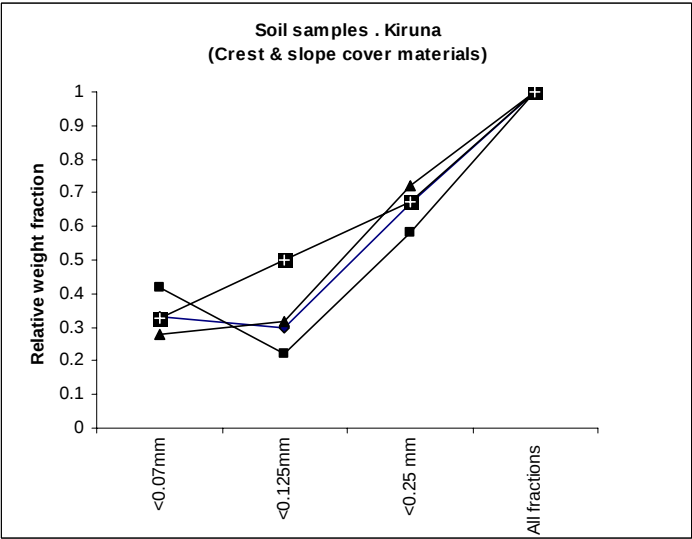


Figure 4.3b. Relative weights of grain size fractions of the soils from Kiruna used for resistivity measurement.

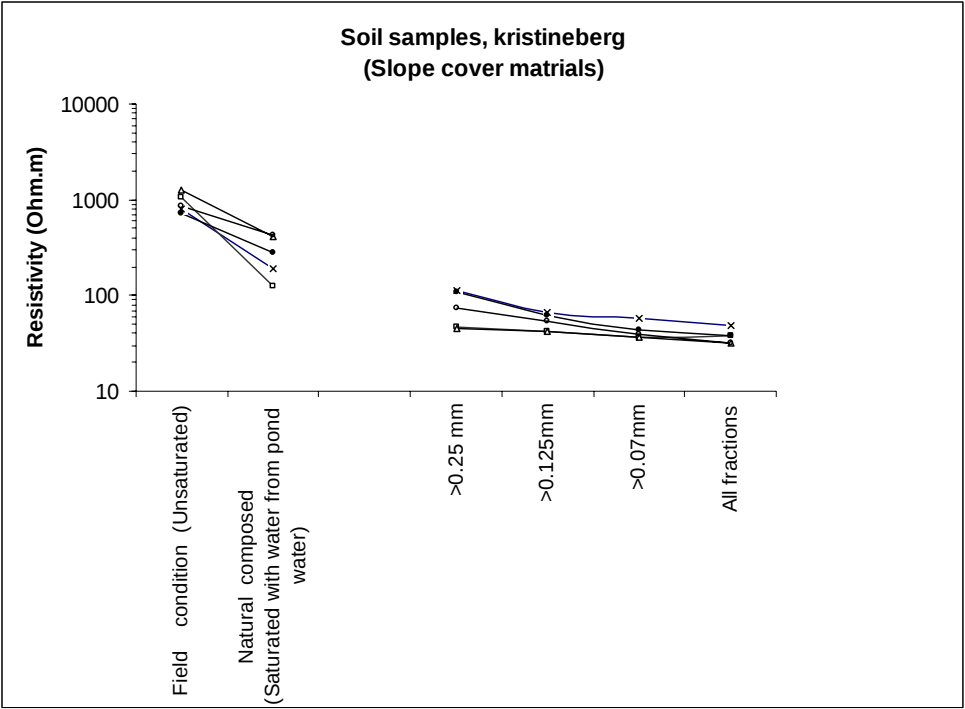


Figure 4.4a. Laboratory resistivity measurements on four soil samples from Kristineberg.

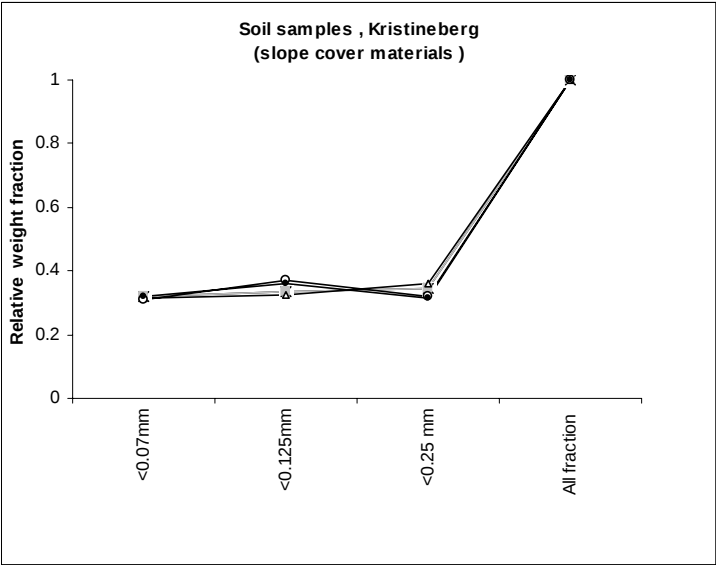


Figure 4.4b. Relative weights of grain size fractions of the soils from Kristineberg used for resistivity measurement.

In general, the measurements reveal that there is a decrease in the resistivity as finer particles are added to the coarser samples, saturated with the water from tailing pond. Small decrease in resistivity value when the fine grained added to the coarser grained fraction is important during internal erosion process and play significant role to determine streaming potential effect. The increase in resistivity due to internal erosion results an increase in streaming potential. Internal erosion may thus be reflected by an increase in resistivity.

5. Resistivity and self-potential measurements on fixed electrodes

5.1 Introduction

Seeping of water within embankment dams can lead to internal erosion. The detection of seepage at the early stage of their development is therefore essential for the safety of a water retaining structure e.g. dam. To evaluate the condition of dams in terms of safety reasons, dams need to be inspected and monitored regularly. Many different techniques e.g., pore-pressure measurements, discharge measurements, temperature-resistivity measurements, radar measurements (Johansson,1997) and self-potential and resistivity (Thunehed and Triumf, 1999) have been used for monitoring. Resistivity and self-potential (SP) monitoring has been widely applied for solving environmental and engineering problems of embankment dams by studying the changes in the subsurface properties with time. SP changes are caused by water movements through the dam and resistivity changes reflect the changes in the electrical properties of the dam materials. Measuring SP over time is a powerful and easy way to detect leakage and time series resistivity measurements provide valuable information about change in condition of the dam over a time.

Brief overviews of self-potential and resistivity methods have already been given in earlier chapters and will not be repeated here. Although fixed electrodes were only installed on portions of the dam surfaces, this provides useful information of variation in materials properties and seepage condition of the dam due to seasonal variations. Long term measurements require a steady monitoring system, which can provide consistent data. For regular dam monitoring a built-in electrode system should be used. The electrodes might all be connected to a simple workstation that would connect and disconnect various electrode combinations, providing continuous monitoring of the SP and resistivity distributions in the dam. Such a system has already been installed on the Suorva dam in northern Sweden and has been running for several years (Triumf et al, 1995).

5.2 Fixed electrodes installation

In addition to the mobile electrode SP and resistivity surveys, fixed electrodes were installed on the Kristeneberg and the Kiruna tailings dams to monitor SP and resistivity variations over time. The fixed electrodes used for SP measurements here were of non-polarising type consisting of small cotton bags filled with a mixture of moraine, bentonite clay and copper-sulphate powder. The current electrodes for resistivity measurement has a similar construction, but without the copper-sulphate. The ends of the connecting copper wires were spread out in the bags in order to provide good contact with the mixtures. The electrodes were then buried at a depth of roughly one meter in pits dug along profiles running up the face of the dam. The holes were refilled with moraine to keep the electrode moist and stable condition. Cables were run from each electrode up to the crest of the dam to assist connections to the power source for measurements.

Fixed electrodes were placed along the five pseudosection profiles on the slope of the Kristineberg dam (Figure 2.3) in order to monitoring of SP and resistivity variations over time. The electrodes consist of two current electrodes and three potential electrodes. A simplified sketch of the position and the numbering of the electrodes for all profile is shown in figure 5.1. Electrode 1(C1) and 4(C4) were used as current electrodes and electrode 2(P2), electrode3 (P3), and electrode 5(P5) are potential electrodes for all profiles. The spacing

between the current electrodes and potentials electrodes is not same for all profile and also the spacing between among the electrodes are not constant.

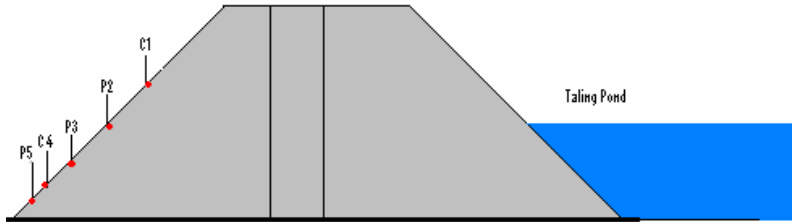


Figure 5.1. A simplified sketch of position and numbering of fixed electrodes placed on the Kristineberg dam.

The profile one on the Kristineberg is the shortest profile and separations among the electrodes are shorter than other profiles. The distance between current electrode C1 and potential electrodes P2, P3, and P5 are about 2.5m, 5 and 8m, respectively and with reference to current electrodes C4 the distance to the respective potential electrodes are 4.5m, 2m, 1.5 m. In profile 2, the spacing between current electrode C1 and potential electrodes P2, P3, and P5 are 11m, 16m and 21.5m respectively, whereas the spacing between current the electrode C4 and the potential electrodes are 8.5, 3.5 and 2m respectively. In the rest of the profiles the distance between the current and the potential electrodes are more or less the same. The spacing between current electrode C1 and potential electrodes P2, P3, and P5 are approximately 15m, 23m and 28.5m, respectively and with corresponding distances between current electrode C4 and the potential electrodes are 11.5, 3.5m and 2m respectively.

Installation of electrodes in the Kiruna dam was made when the height of the dam was raised in summer 2003. The electrodes were installed in those sections of the dam where SP anomalies were observed in previous (2002) measurements (Figures 2.4-2.6). Four profiles of fixed electrodes were installed across the dam (Figures 2.7- 2.9), each system consisting of one current electrode and four potential electrodes. The four potential electrodes were installed on the upstream crest (electrode 0), on the downstream crest (Electrode 1), midway on the downstream slope (Electrode 2) and at the toe of the downstream slope (Electrode 3). The current electrode was placed on the downstream crest, about a meter from potential electrode 1. A simplified sketch of the electrodes position on the dam for all profile is shown in Figure 5.2. The distance between the current electrode with potential electrodes 0, 1, 2 and 3 are roughly 9m, 1 m., 11 m and 26 m respectively in the Kiruna dam.

The surface of the dam is covered by a large rock fragments and an excavation tractor was used to dig holes on the crest and toe of the dam. The excavation for the hole on the slope of the dam was done manually. The filed condition is not suitable like in the Kristineberg tailings dam to install more other current electrode on the slope of the dam.

The spacing between the current electrode and potential electrode determines the depth of depth of investigation, the larger the separation the greater the depth. In the Kristineberg dam, a reference electrode was installed at some distance from dam to east of the dam to measure the SP while in the Kiruna dam the reference electrode was placed at the upstream crest.

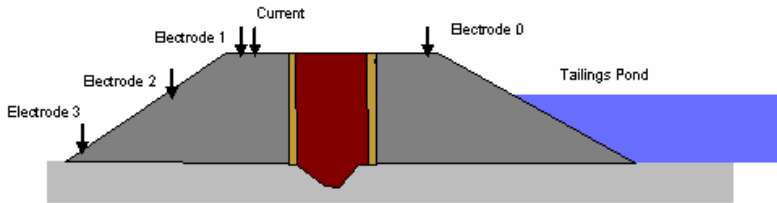


Figure 5.2. A simplified sketch of position and numbering of fixed electrodes placed on the Kiruna dam.

5.3 Data collection

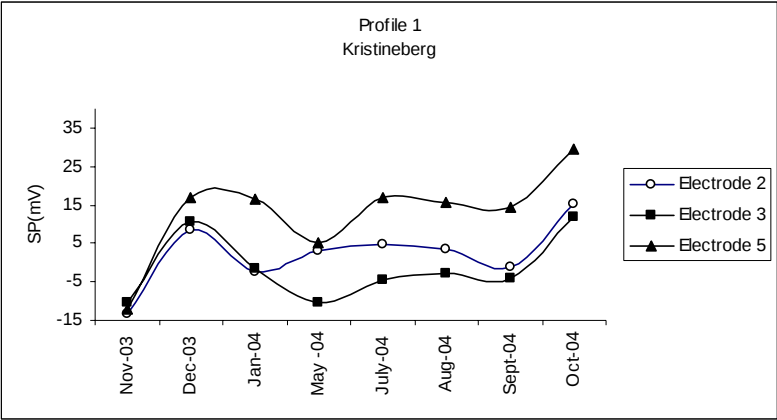
Measurements were carried out at a roughly monthly interval for one year starting in November 2003 and ending in October 2004. SP measurements were taken with a high impedance analog voltmeter. Resistivity measurements were done with Terrameter ABEM SAS 300B using a Pole-pole array. In the Kristineberg dam, two resistivity measurements were conducted with reference to current electrode1 (C1) and current electrode 4(C2) for the same potential electrode.

5.4 Results and discussion

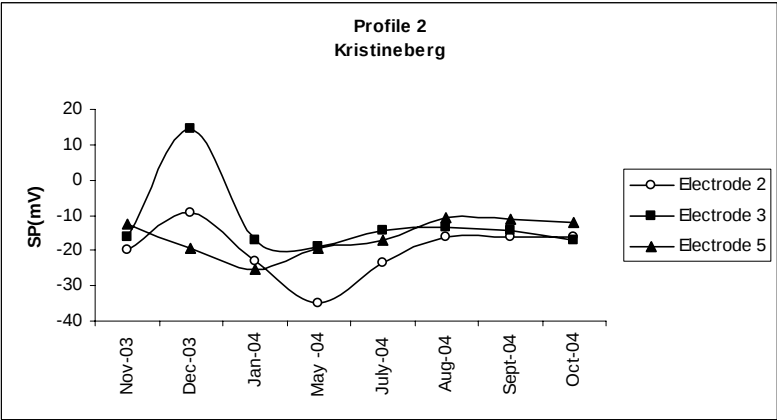
The data obtained from the fixed electrodes measurements reflects the condition of the dam during the year. The results show that even small relative variation of SP and resistivity values can easily be detected from the repeated measurements of the fixed electrode installed in the dams. If there are major changes in the dam condition due to seeping and internal erosion, the physical properties of the materials within the dam also varies, which means the condition of the dam can be monitored via regular measurements of the SP and resistivity.

5.4.1 SP measurements at the Kristineberg dam

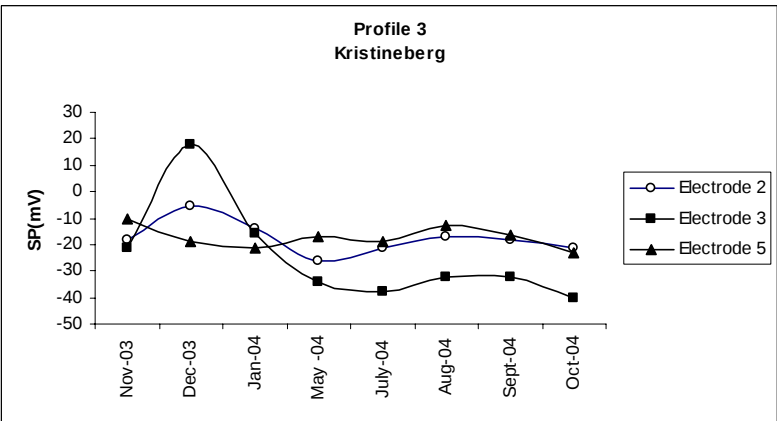
The results from repeated SP measurements in Kristineberg are presented in the Figures 5.3 and 5.4. The SP obtained from most of the electrodes in all profiles shows fluctuation of SP values during winter period. SP values measured from electrode 3 in the profile 3 (Figure 5.3a) shows the maximum variation (from +17 mV to -16mV) between December 2003 and January 2004.



(a)

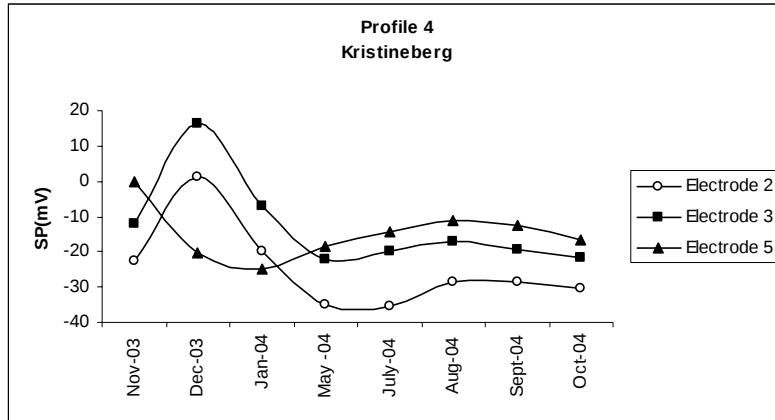


(b)

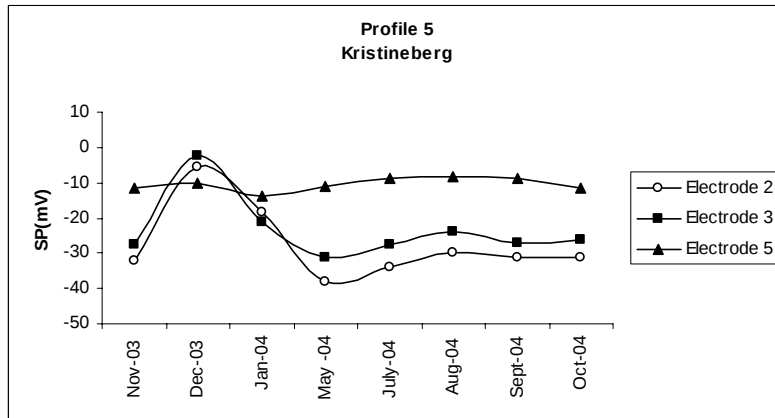


(c)

Figure 5.3. SP measurements with fixed electrodes, Kristineberg profiles 1 to 3



(a)



(b)

Figure 5.4. SP measurements with fixed electrodes, Kristineberg profiles 4 and 5.

Similarly large fluctuation (around 25mV) of a SP values can be seen in the electrodes 3 in all profiles (Figure 5.3 and 5.4). This large fluctuation in the SP during winter period is due to physical changes with in the dam when the temperature goes down. These unstable values during the winters are probably due to changes in contact resistance at the electrodes due to freezing. This effect seems to be biggest in the central part (electrodes 2 and 3) of the dam slope.

Thus in the winter periods when the ground is freezing, the moisture condition and contact resistance of the electrode is most affected showing unsteady SP values. When summer comes the condition is stabilized and gives more stable values of SP. This trend continues up to the autumn when the condition change again. The SP values in the summer period do not show such a large variation like in the winter period. A trend of increasing SP can be seen for the

electrodes at profile 1 (Figure 5.3a) from May to October. Similar trends can also be seen for most of the electrodes at the other profiles, but to a much lesser extent and with a slight decrease for the last October measurement. This is probably due to high contact resistance at the electrodes when the temperature goes down in the end of the autumn and during the winter and water flow become much steady during the summer. The SP measurement from the fixed electrode at the Kristineberg dam varies particularly during winter is somehow affected by the freezing of the ground. The SP values in the profile 4 and 5 shows an higher values downstream of the slope from May to October i.e. the higher SP values are obtained in the toe of the dam. The trend of the SP values obtained does however not resemble the any pattern of seepage through the dam core.

5.4.2 Resistivity measurements at the Kristineberg dam

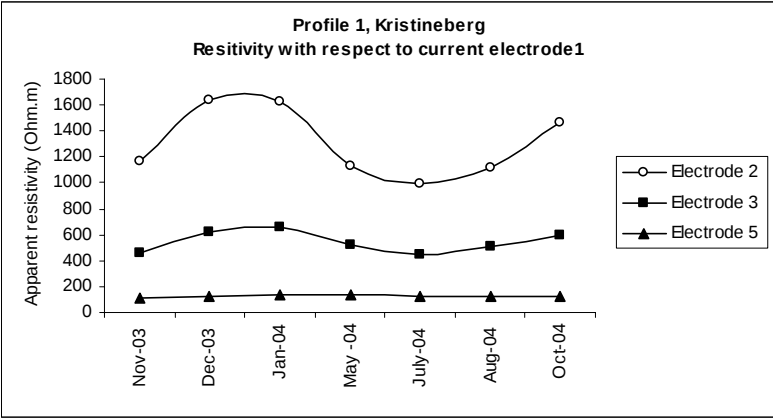
Two current electrodes current electrode1 (C1) and current electrode 4(C2) were placed along the slope of the Kristineberg dam, which means that two types of arrangement for resistivity measurement is possible for the same potential electrode. The results obtained from the measurements are discussed below.

5.4.2.1 Resistivity measurements with current electrode 1

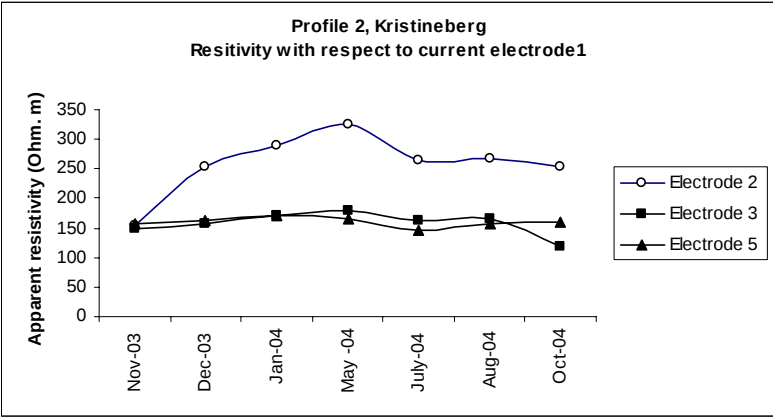
The results of resistivity measurements with the current electrodes number 1 are displayed in Figures 5.5 and 5.6. The general trend of the apparent resistivity values obtained from electrode 2 (close to the current electrode) shows the resistivity increases from the first measurements in November 2003 to May 2004. The apparent resistivity obtained from electrode 2 in the all profiles gives information from shallow depths (the local variations) of the dam and the resistivities much affected by seasonal changes with in the dam. The decrease in the apparent resistivity is due to melting of the ice and precipitation. The decrease in resistivity start after may and goes on to the end of the autumn. This represents the freezing and thawing effect within in the dam. The highest value of apparent resistivity is obtained from the measurements in May, except for in profile 1 (Figure 5.5a).The apparent resistivity from electrode 2 in profile 1 (Figure 5.5a) show minimum resistivity values in May/July while in other profiles a maximum is obtained in the same the period. This is probably due to melting of the snow may have started earlier in this area compare with other areas.

The profile 1 in Kristineberg is the shortest profile and the electrodes are closer than in other profiles. Thus the electrode 3 in the profile 1 (Figure 5.5a) still reflects resistivities at the shallow depths and the resistivity increases from November 2003 to January 2004 and then decrease when summer comes. The apparent resistivity then rise when the autumn comes. The apparent resistivity obtained from this electrode is still thus influences by the seasonal variations of the climate.

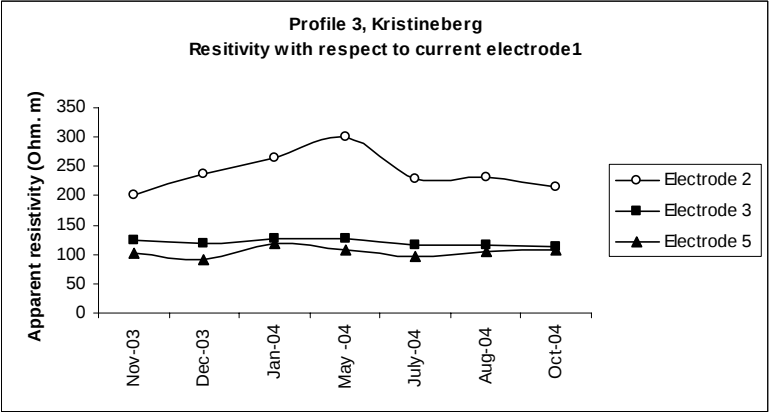
The apparent resistivities recorded with potential electrodes 3 and 5, besides electrode 3 of the profile1, are fairly low (up to 150 Ωm) (Figure 5.5 and 5.6). This indicates that these data corresponds to an investigated volume of the dam that is partly water saturated. The data shows high consistency in the apparent resistivity values and is not affected by the seasonal variations of the climate. The data from electrode 5 in the profile 5 (Figure 5.6b) shows a constant resistivity values (<90 Ωm) corresponding to the resistivity of totally saturated zones.



(a)

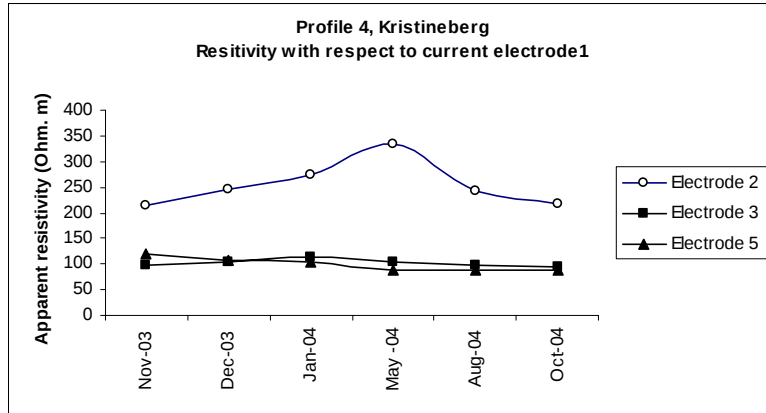


(b)

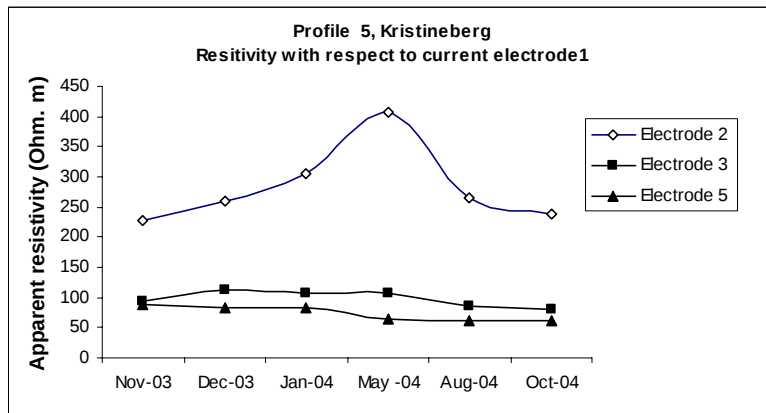


(c)

Figure 5.5. Resistivity measurements with reference to current electrode 1 (C1), Kristineberg profiles 1 to 3



(a)

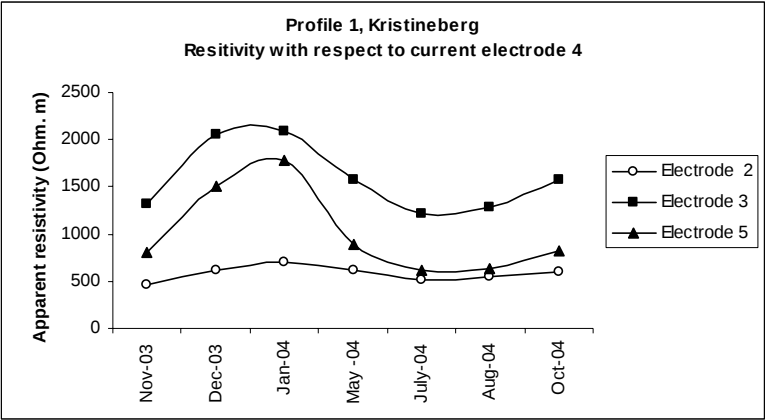


(b)

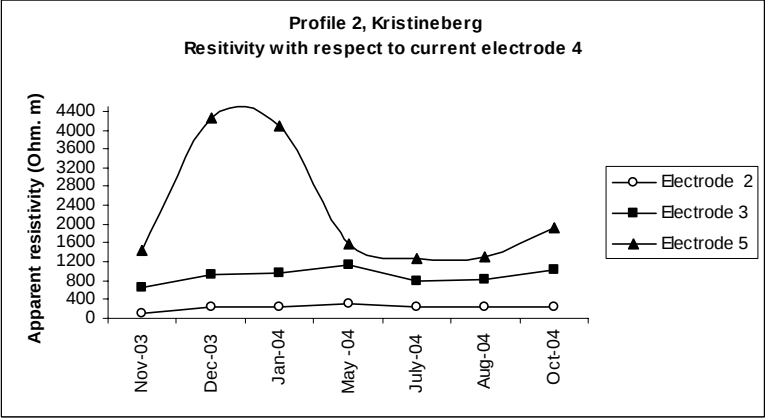
Figure 5.6. Resistivity measurements with reference to current electrode 1 (C1), Kristineberg profiles 4 and 5

5.4.2.2 Resistivity measurements with current electrode 4

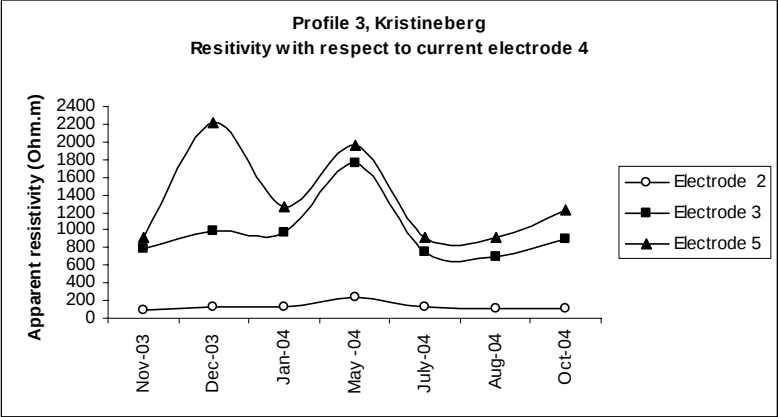
Corresponding resistivity data recorded with the current electrodes number 4 are presented in Figures 5.7 and 5.8 .The distances between this current electrode and the potential electrodes 3 and 5 are quiet short (see section 5.2). Those electrodes sample a smaller volume of the subsurface and thus give information of more or less local variation of the properties within the dam.



(a)

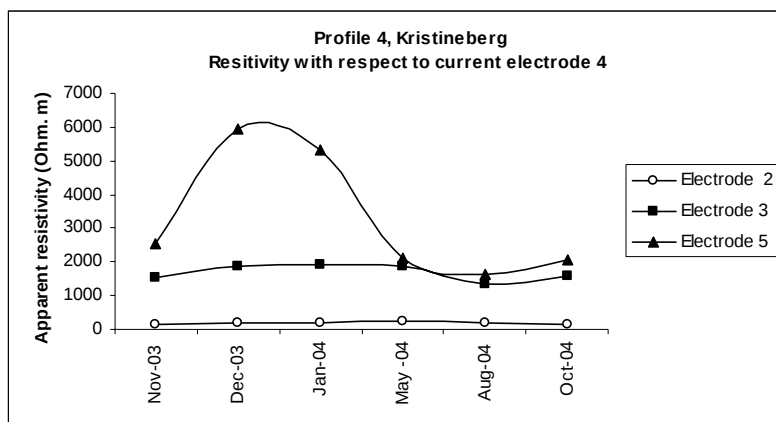


(b)

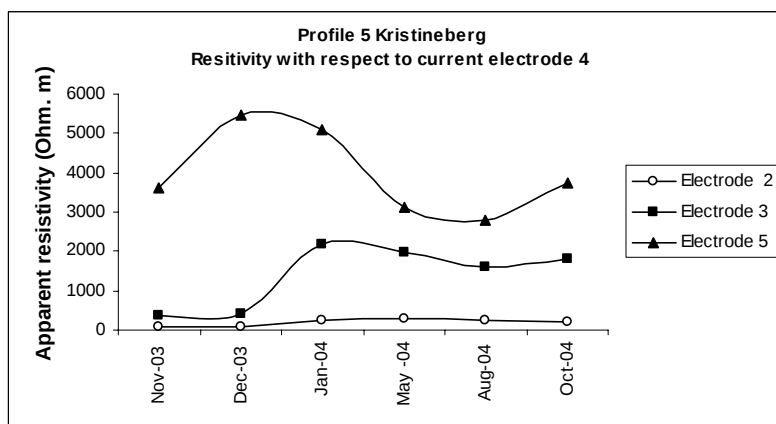


(c)

Figure 5.7. Resistivity measurements with reference to current electrode 4 (C4), Kristineberg profiles 1 to 3



(a)



(b)

Figure 5.8. Resistivity measurements with reference to current electrode 4 (C4), Kristineberg profiles 4 and 5.

The obtained data from the measurements of those electrodes show an increase in apparent resistivity during and the winter 2003 and the autumn 2004 and a decrease during the summer 2004 in all profile except for the profile 3 (Figure 5.7c). This is probably due to partial freezing of the top soil in winter and rises of groundwater table after melting ice and infiltrations water when summer comes. Thus there would be high influx during this time and consequently ground water table rises. This indicates that these data corresponds to an investigated volume that is partly water saturated and partly dry. It is surprising that apparent resistivity data shows an increase in resistivity in May in electrode 3 and 5 of profile 3. It is difficult to sort out the governing factor for this, and probably due to error of measurement. Generally; the highest sensitivity can be obtained closest to the current electrode. Electrode 2 (the electrode far from the current) in all profiles (Figures 5.7 and 5.8) except profile 1, show high stability in the resistivity during the years.

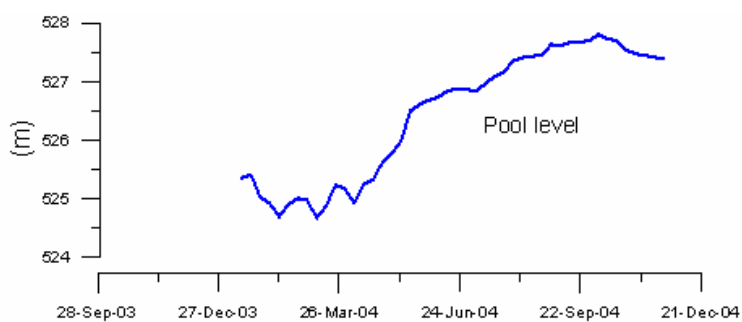
The apparent resistivity values (about 50 Ωm) obtained from electrode 2 in all profiles (except profile 1) reflects the resistivity water saturated zones from all the time and are not affected by the climate condition. The separation between the electrode 2 and current electrode in profile 1 (Figure 5. 4) is smallest (4.5m) compare with other profiles and the apparent resistivity start increasing from the autumn and then decreases when the summer comes. This electrode does not sample the same volume as with electrode 2 in other profiles and it is somewhat affected by seasonal change.

The resistivity data indicate that a seasonal variation in groundwater level exists in the downstream slope of the dam. However there is no sudden fall in resistivity values that can be correlated with an anomalous seepage through in the dam.

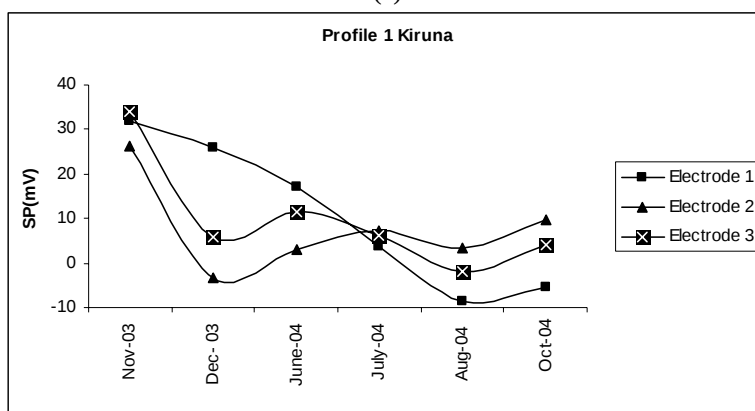
5.4.3 SP measurements at the Kiruna dam

The results of repeated SP measurements from fixed electrodes in the Kiruna dam are shown in Figures 5.9 and 5.10. Electrode 0, installed at the upstream crest has been used as a reference electrode for each respective profile to measure the SP. The SP measurements from almost all electrodes in the profile 1, 3 and 4 (Figure 5.9 and 5.10) show a decreasing trend of SP values during June to August and. The pool level (Figure 5.9 a) of the impoundment has increased during the same period. The general trend of SP can thus be correlated inversely with the pool level. The electrode 2 of profile 2 (Figure 5.9c), which is installed on the slope of the dam, reflects a different behaviour than other profiles with increasing SP related to increased pool level. Similarly electrode 3 of the same profile shows an increasing trend of SP (but lesser extent) with the increase in pool level of the impoundment. This might be interpreted as an anomalous behaviour; however, one full season is probably a very short time period for conclusive interpretations. The decreased SP due to increased pool level for the other profiles are opposite to what might be expected. It is however possible that the soils in the dam has a reversed cross-coupling conductivity due to e.g. presence of grains of ore minerals or the unusual chemistry of the water in the tailings pond. These measurements were done after renovation of the dam. The physical conditions of the dam have not been stabilized during the time of measurements and at the same time, change in temperature causes unsteady physical conditions within the dam. So the data do not show consistency due to variations of moisture condition in the dam. The SP data from the autumn and the winter periods fluctuate largely, after that it tends to be stable. The high fluctuation (about 40 mV) of the SP values from November to December is probably due to high movements of the water inside the dam showing temporally unsteady condition. Also the reference electrode, placed at the upstream crest might be unstable due to change in pool level. It is noted that long time is required to return in equilibrium position of the dam after raising the height of dam. An extended series of measurements would however be required to fully sort this out.

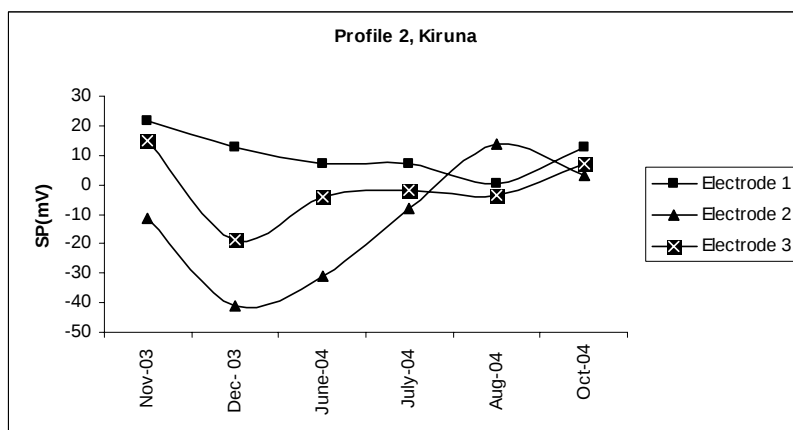
The SP measurements were repeated late in the summer 2004 within three days. The results are very similar and show variations of SP magnitude in order of 1 to 2 mV. This means the short time variations in SP values can be ruled out and short term noise level of the measurements is negligible.



(a)

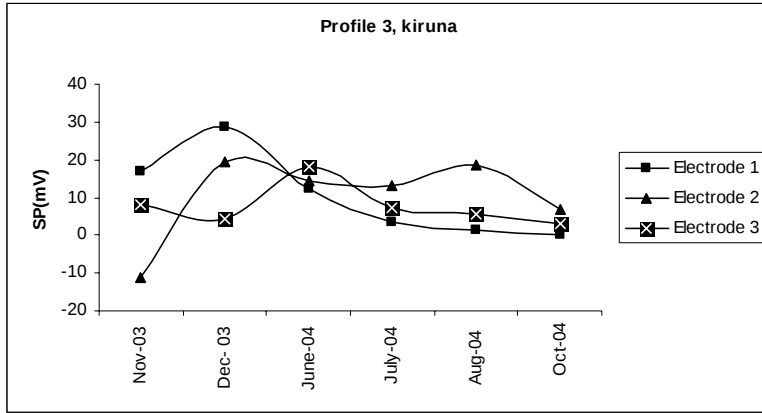


(b)

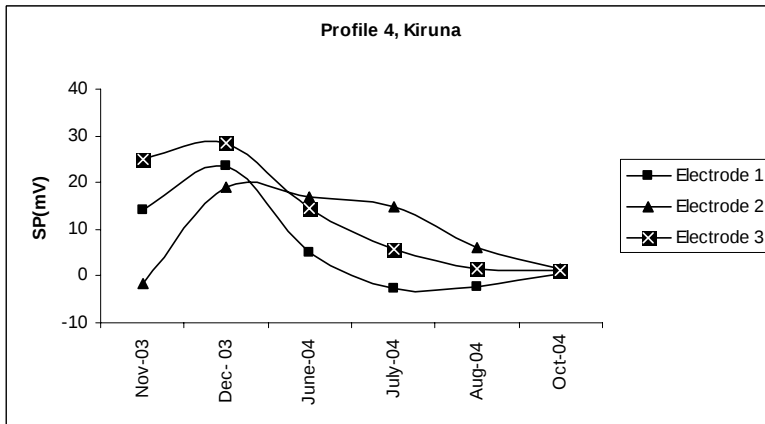


(c)

Figure 5.9. SP measurements of profiles 1 and 2 with fixed electrodes Kiruna and pool level.



(a)

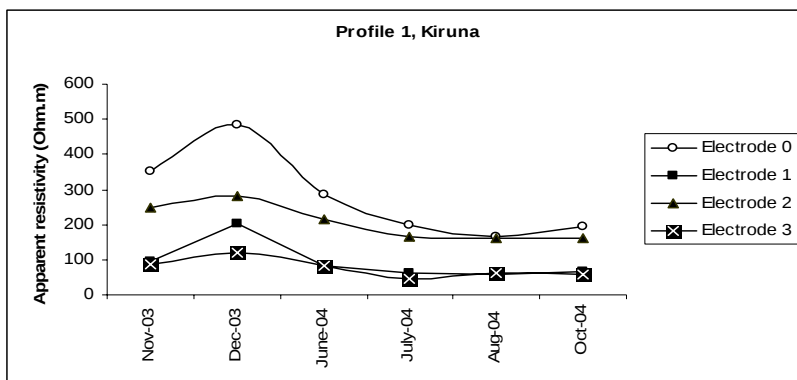


(b)

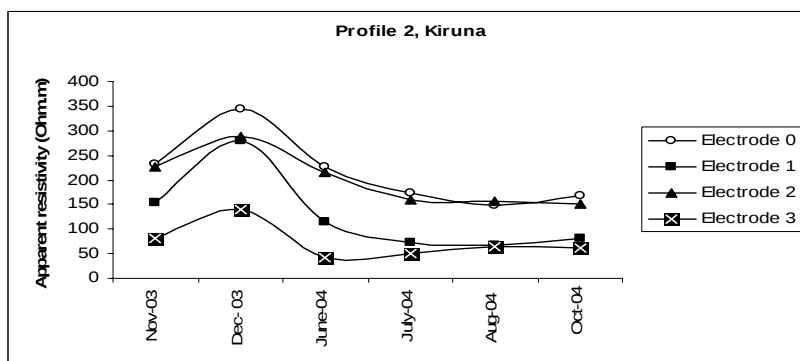
Figure 5.10. SP measurements of profiles 3 and 4 with fixed electrodes, Kiruna.

5.4.4 Resistivity measurements at the Kiruna dam

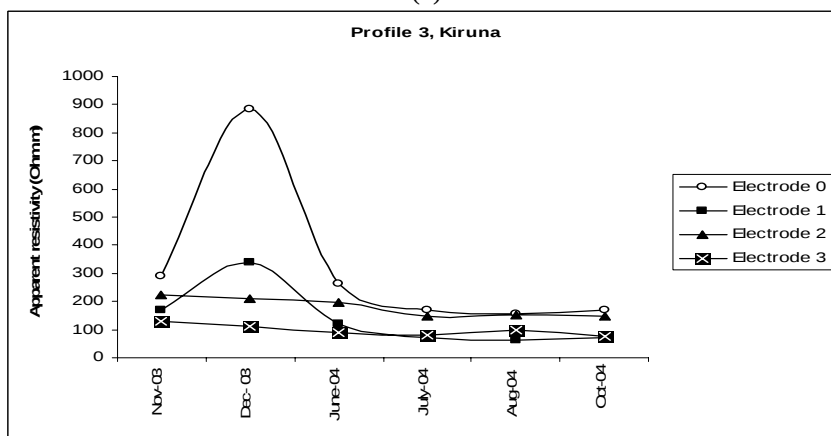
Resistivity measurements with fixed electrodes at the Kiruna dam are presented in Figures 5.11 and 5.12. The electrode 0 in almost all profile shows an increase in apparent resistivity during the winter and then a sharp decrease when the summer comes. This is due to the freezing of the top soil on the dam. The apparent resistivity obtained with the electrode 0, which is installed at the upstream crests of the dam, is also influenced by the pool level.



(a)



(b)



(c)

Figure 5.11. Resistivity measurements of profiles 1, 2 and 3 with fixed electrode, Kiruna.

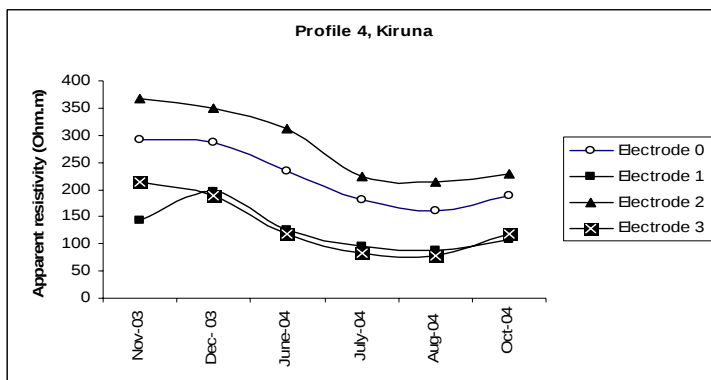


Figure 5.12. Resistivity measurements of profile 4 with fixed electrode, Kiruna.

Electrode 1, which is very close (1m) to the current electrode in all profile also shows some higher resistivity values in December 2003 than other months. However this increase is not as high as expected for the soil so close to the surface and it is lower than the resistivity obtained from other electrodes. This can be explained by the closest electrode there will be high current density. The materials used for fillings probably contain clay particles and waste rock from the mining with large amount of conductive minerals grain. Thus it can generate some induced polarization (IP) in the area where current density is high. So the apparent resistivity data obtained electrode 1 might be affected by IP.

Electrode 2 in the profile 1, 2 and 4 (Figure 5.11 a-b and 5.12) follows the seasonal cycle showing higher resistivities during winters and lower resistivity during summer. The apparent resistivity measured with those electrodes is influenced by the variations in pool level of the impoundment. The apparent resistivity value obtained from electrode 2 in profile 3 (Figure 5.11 c) is very stable and reflects a water saturated subsurface. Electrode 3 which is placed at toe of the dam gives the information mostly from the saturated parts of the dam. Small change in the resistivity related with the water table is however detected. If there is a significant change of groundwater level on the downstream side of the dam causing the seepage water through the dam, that would be reflected in the apparent resistivity time series data.

6. Conclusions

This work has demonstrated the potential of using geophysical methods for monitoring the conditions and time changes of the condition in mine tailings dams. The work has also provided new results that give more details about subsurface condition in three tailings dams located in the northern part of Sweden. The main conclusions drawn from the study are summarized here.

The physical condition of the Kristineberg dam seems not to have changed during the years of measurements 2003 and 2004. The results of the electrical resistivity survey from 2004 in the Kristineberg tailings dams are fairly similar those obtained from 2003. The SP distribution in the dam also reveals that there have been no significant changes in SP values from 2003 to 2004 and no strong evidence of the streaming potential has been obtained from the two years of measurements. It is necessary to monitor the dam in coming years to see if the patterns changes with possible changes in the condition of the dam.

In the Kiruna dam generally higher magnitudes of SP values is obtained on the toe than on the crest of the dam. This suggests that a streaming potential is developed over the dam core. The 2003 measurement shows that physical properties (electrical and SP-response) have been strongly influenced by the rising of the height of the tailings dam.

In the Aitik IJ-dam a distinct positive anomaly at the coordinate 7451330 north has been detected. The anomaly which continues to the toe of the downstream slope of the dam, is generated from a known seepage of the water. Some other SP anomalies on the downstream slope of the dam that could be related to seepage have been also identified.

Seasonal resistivity variations in the tailings dams in Kristineberg have been detected from the fixed potential electrodes placed close to the current electrodes. Fairly stable values of SP during summer have been obtained from the fixed electrode measurement in Kristineberg. The trend of the SP values obtained does however not resemble the any pattern of seepage through the dam core. Unsteady physical conditions within the dam after increasing the height of the dam has been reflected in the SP measurements in Kiruna. The apparent resistivity measured in Kiruna dam has been some how influenced by the variations in pool level of the impoundment. The fixed electrodes survey provides stable background readings and small change in the apparent resistivity and SP is detected. The anomaly due to leakage of water through the dam can be obviously detected in the time series measurements from fixed electrodes.

The laboratory measurements on soil samples from the dams reveal a decrease in resistivity as finer particles are added to the samples that contained coarser fractions. Internal erosion may thus be reflected by an increase in resistivity.

Time series measurements of the resistivity and the SP are suitable for monitoring variations of the dam conditions with reference to seasonal changes and water table fluctuations. Furthermore, repeated measurements of the resistivity and the SP should be done with perfectly constant time interval and for long time periods to determine eventual changes in the resistivity and SP related with seepage.

It is not recommended that the measurements are performed in the short time after the renovation of the dam. It takes a long time to recover the physical properties of the dam in equilibrium condition.

Electric resistivity survey has proven successful to define the water table in the dam, which give support to the interpretation of SP data for detection of seepage zones. Resistivity investigations is also an important tool for getting information of internal resistivity structure of the dam associated with material inhomogeneities and water saturation. Possible leakage zones are related with high saturation zone and low electrical resistivities and SP survey has shown its capability to detect seepage by determining the streaming potentials.

These methods may also find the use in the future monitoring tools of mine tailings dams along with other method depending upon the geometry, electrical properties of the filling materials and the environment of the dam.

References

- Abu-Hassanein, Zeyad S.; Benson, Craig H.; Blotz, Lisa R., 1996. Electrical resistivity of compacted clays. *Journal of Geotechnical Engineering* 122, p. 397-406.
- Al-Saigh, N.H., Mohammed, Z.S. and Dahman, M.S. 1994. Detection of waterleakage from dams by self-potential method. *Engineering Geology* 37, p.115–121.
- Benckert A., 2003. Tailings dam safety in Sweden. Proceedings of “International Symposium on Major Challenges in Tailings Dams” at the International Commission on Large Dams (ICOLD) Congress. Montreal, Canada, p 35-45.
- Bergström, J., 1998. Geophysical methods for investigating and monitoring the integrity of sealing layers on mining waste deposits. Licentiate Thesis, Luleå University of Technology, 1998:24.
- Bérubé, A.P. 2004. Investigating the streaming potential phenomenon using electric measurements and numerical modelling with special reference to seepage monitoring in embankment dams. Ph.D. Thesis. Luleå University of Technology, 2004:59.
- Bjelkevik A., 2005a. Water cover closure design for tailings dams -state of the art. Research report, Luleå University of Technology, 2005:19.
- Bjelkevik A., 2005 b. Stability of tailings dams: focus on water cover closure, Licentiate Thesis, Luleå University of Technology. 2005:85
- Bogoslovsky V.A., Ogilvy A.A., 1970a. Natural potential anomalies as a quantitative index of the rate of water seepage from reservoirs. *Geophysical Prospecting* 18, p 261–268.
- Bogoslovsky V.A., Ogilvy A.A., 1970b. Application of geophysical methods for studying the technical status of earth dams. *Geophysical Prospecting* 18, p758–773.
- Bogoslovsky V.A., Ogilvy A.A., 1974. Detailed electrometric and thermometric observations in offshore areas. *Geophysical Prospecting* 22, p 381–392.
- Bogoslovsky V.A., Ogilvy A.A. 1977. Geophysical methods for the investigation of landslides. *Geophysics* 42, p 562–571.
- Butler D.K., 1984. Geophysical methods for seepage detection, mapping and monitoring. 54th SEG Meeting, 1984, Atlanta, Expanded Abstracts, p157–160.
- Butler, D.K., Llopis, J.L., Dobecki, T.L., Wilt, M.J., Corwin, R.F. and Olhoeft, G. 1990. Comprehensive geophysics investigation of an existing dam foundation: Engineering geophysics research and development, Part 2. *The Leading Edge* 9, p 44–53.

- Campanella, R. G.; Weemees, I. 1990. Development and use of an electrical resistivity cone for groundwater contamination studies. *Canadian Geotechnical Journal*, 27, p 557-567.
- Carlsten, S., Johansson S. and Wörman A. Radar Techniques for indication of internal erosion in Embankment dams, 1995, *Journal of Applied Geophysics* 33, p 43-156.
- Corry C.E.1985. Spontaneous polarization associated with porphyry sulphide mineralization. *Geophysics* 50, p 1020–1034.
- Corwin R.F, Hoover D.B. 1979. The self-potential method in geothermal exploration. *Geophysics* 44, p 226–245.
- Corwin R.F. 1990. The self-potential for environmental and engineering applications. In *Geotechnical and Environmental Geophysics*, Ward SH(ed.). Society of Exploration Geophysicists, Tulsa, USA, *Investigations in Geophysics*, no. 5, p127–145.
- Ernstson, K. and Scherer, H.U., 1986. Self-potential variations time and their relation to hydrogeologic and meteorological parameters, *Geophysics*, 51, p. 1967-1977.
- ICOLD. 1996. Bulletin 106: A guide to Tailings Dams and impoundments – Design, construction, use and rehabilitation. Published by International Commission on Large Dams together with UNEP, United Nations Environmental Program.
- ICOLD. 1995. Dam failures statistical analysis. Bulletin 99 Published by The International Commission on Large Dams
- Johansson, S. 1997. Seepage monitoring in embankment dams. Doctoral thesis, Royal Institute of Technology, Stockholm, Sweden.
- Kilty, K.T. 1984. On the origin and interpretation of self-potential anomalies. *Geophysical Prospecting* 32, p 51–62.
- Lögn O, Bolviken B. 1974. Self potentials at the Joma pyrite deposit. *Geoexploration* 12, p 11–28.
- Loke, M.H., 2000. Electrical imaging surveys for environmental and engineering studies, A practical guide to 2-D and 3-D surveys, Dr. M.H.Loke, p. 59, Internet site:<http://www.geoelectrical.com>.
- Loke, M.H., 2004, RES2DINV ver. 3.54 Rapid 2-D Resistivity & IP inversion using the least-squares method, ABEM Instrument AB, user manual. Internet site :<http://www.geoelectrical.com>.
- Morgan, F.D., Williams, E.R., and Madden, T.R., 1989, Streaming potential properties of westerly granite with applications, *Journal of Geophysical Research*, 94, p. 12,449-12,461.

- Nourbehecht, B. 1963. Irreversible thermodynamic effects in inhomogeneous media and their application in certain geoelectrical problems. PhD thesis, Massachusetts Institute of Technology.
- Ogilvy, A.A., Ayed, M.A., and Bogoslovsky, V.A., 1969, Geophysical studies of water leakages from reservoirs: *Geophysical Prospecting*, 27, p. 36-72.
- Palacky, G.J., 1987. Clay mapping using electromagnetic methods. *First Break* 5, p 295–306.
- Panthulu, T.V., Krishnaiah, C. and Shirke, J.M. 2001. Detection of seepage paths in earth dams using self-potential and electrical resistivity methods. *Engineering Geology* 59, p 281–295.
- Parasnis, D.S. 1997. *Principles of Applied Geophysics*. 5th ed. London: Chapman and Hall.
- Rao MBR. 1953. Self-potential anomalies due to subsurface water flow at Gerimenapenta, Madras State, India. *Transactions of the American Institute of Mineralogy, Metallurgy, Petroleum Engineering and Mining Engineering*. p 400–403.
- Sato M, Mooney HM. 1960. The electrochemical mechanism of sulphide self-potential. *Geophysics* 25, p 226–249
- Schiavone D, Quarto R. 1984. Self-potential prospecting in the study of water movements. *Geoexploration* 22, p 47–58.
- Sjödahl P., Dahlin T. and Johansson S. 2004. Using resistivity measurements for dam safety evaluation at Enemossen tailings dam, proceeding. 9th Meeting Environmental and Engineering Geophysics, Utrecht, The Netherlands, 6-9 September 2004, A017, 4p
- Thunehed, H. 2000. Mapping and characterisation of Swedish bedrock by DC resistivity and transient-field electromagnetic measurement. PhD thesis, Luleå University of Technology, 2000:17
- Thunehed, H., and Triumf, C., A.1999. Seepage Monitoring on an Embankment Dam with Geophysical Methods. *Journal of Conference Abstracts*, Vol. 4, No.1, Symposium J05. *Environmental Geophysics*.
- Titov K., Loukhmano; Vand Potapov; A. 2000. Monitoring of water seepage from a reservoir using resistivity and self polarization methods: case history of the Petergoph fountain water supply, *First Break* 18, p.432-434
- Triumf, C-A., Thunehed, H. and Enström, A. 1995. Övervakning av tätkärnans funktion genom mätning självpotential och resistivitet. VASO dammkommittés rapport, 23. Stockholm: VASO
- Vick S.G. 1990. *Planning, Design, and Analysis of Tailings Dams*. BiTech Publishers Ltd. Vancouver, Canada. ISBN 0-921095-12-0. 369 p

Vick S.G. 1999. Tailings Dam Safety – Implications for the Dam Safety Community. Proceedings “Canadian Dam Safety Association’s 2nd Annual Conference”, Sudbury, Canada. October 1999. p.1-12.

