Tailings Dams Monitoring in Swedish Mines using Self-Potential and Electrical Resistivity Methods

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ABSTRACT

Tailings dam failures have been occurring in recent years. Many of these failures have caused human casualties, destruction of property, and damage to environment and huge economic loss to the mining industry. The monitoring of the dam is essential to know the existing state of the dams and to ensure the safety of the dam over its life time. The present study has been conducted to test the applicability of electrical resistivity and self-potential (SP), for detecting anomalous seepage through mine tailings dams in Sweden and monitoring the physical condition of the dam. This study has demonstrated the potential of using geoelectrical methods for monitoring the conditions of the tailing dams related to seepage.

KEYWORDS: Tailings dam, Seepage, Self -potential, Resistivity, Monitoring

INTRODUCTION

Mining has been practiced in Sweden for hundreds of years, and is still a viable industry. However, due to typically low concentrations of useful mineral in the extracted ores and large volumes of ore is mined; large amounts of tailings are produced, requiring extensive tailings ponds. A tailings dam or a confining embankment is constructed to enable the deposited tailings to settle and to retain process water. The tailings dam will be exposed to different kinds of loads such as water pressure combined with the load from the tailings itself during its life cycle. The design of the Swedish tailings dams differs somewhat from conventional tailings dams internationally, as most Swedish tailings dams were originally constructed with a core of moraine similar to water retention dams. Most of them are constructed in stages according to the centerline or the downstream method with a core, filter and support fill. Moraine has often been used as construction material as it is easy to access at most of the tailings dam sites. Currently about 11 tailings dams are in operation in Sweden, (Bjelkevik, 2005). Since 2000, 25 major tailings dam failures have been reported in the world (WISE, 2014) including the one at Aitik in Sweden.

Several tailings dam failures have occurred in recent years and have resulted in extensive consequences in the form of human casualties, destruction of property, pollution of the environment and economic loss to the mining industry. Dam safety has attracted increasing attention worldwide due to the recent dam failures and thus increased the awareness among the people and the society.

Saturation of embankment soils, abutments, and differential settlements in foundations, local stress relaxation in the soil and locally increased hydraulic gradient generally reduced soil strengths. These may lead to sloughing, sliding, and instability of the dam. When water flows through poorly compacted soil, *e.g.,* in an embankment dam, internal soil erosion may 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 increases. High velocity flows through the dam embankment can cause progressive erosion and piping. Statistics from the International Commission on Large Dams (ICOLD, 1995) show that the most common cause for embankment dam failures are overtopping and internal erosion.

The usual way to monitor internal erosion is by visual inspections, pore-pressure measurements and measurement of seepage water in dikes below the dam. The detection of early stage seepage is essential for the safety of the dam. Obviously, to evaluate the condition of a dam in terms of safety, the dam needs to be inspected and monitored regularly using suitable techniques. Many different monitoring techniques *e.g.*, pore-pressure measurements, discharge measurements, temperature-resistivity measurements, radar measurements (Johansson, 1997), cross-hole seismic measurements and self-potential and resistivity (Thunehed and Triumf, 1999) monitoring have been used. 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. Due to internal erosion and seepage of the water in the dam, the physical properties of the materials may be expected to change. Geophysical methods have the potential of detecting internal erosion and anomalous seepage due to the change in physical properties of the soil. The use of geophysical techniques is generally preferred over other methods due to their non-destructive nature and cost-effectiveness. Geophysical methods have been used to study dam conditions, (*e.g.* Butler et al; 1990; Al-Saigh et al; 1994; Carlsten et al; 1995; Panthulu et al; 2001; Titov et al; 2000 and Sjödahl et al; 2005). 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 an easy and powerful method to detect leakage and time series resistivity measurements provide valuable information about change in the condition of the dam over time.

Geophysical methods thus play an important role in monitoring the integrity of the dam and in detecting anomalous seepage conditions in the dams at the early stage of their development. Most studies have been carried out on hydropower dams. The conditions of tailings dams have been considered more complicated due to the electrically conductive water filling of the pore volumes and the possible presence of ore minerals in the dam body. The principle objective of the present study was to evaluate the electrical resistivity and the self-potential methods used to detect anomalous seepage through mine tailings dams and monitor the physical condition of the dam. In order to achieve this, field measurements of resistivity and self-potential have been carried out on tailings dams to identify SP-responses related to seepage, inhomogeneities and seasonal variations of physical properties in the dam

MONITORING SITES

The study has been carried out on three tailings dams, located in the northern part of Sweden, i.e. in Kiruna (LKAB) and in Aitik and Kristineberg (Boliden AB), mines, as shown in Figure 1.

Figure 1: Location of the study area shown with small black square.

The Kiruna tailings dam is located close to the Kiirunavaara iron ore mine. The dam is about 4 kilometers in length and consists of a central core of compacted, low permeability moraine surrounded by sandy filters and supporting rock fill (Figure 2).

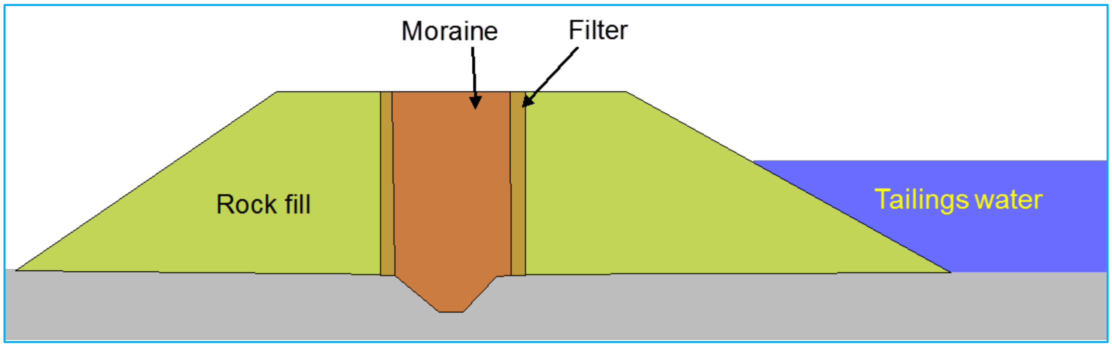

Figure 2: Schematic representation of principal design of tailings dam at Kiruna.

The Aitik mine is considered to be one of the largest open pit copper mines in Europe. A substantial amount of the tailings generated during the mining operation is deposited in a tailings pond. The Aitik dam was not built in the same manner as the Kiruna tailings dam. Instead of using an impervious core with layers of supporting fill material, the Aitik tailing dam was built as composite masses of local moraine, waste rock and slurry sand. The Kristineberg mine tailings reservoir is located in a small valley and it is controlled by the dam at one end. The dam has been raised a number of times using a range of different construction materials and techniques. That has resulted in complex internal geometry and properties of the dam.

METHODOLOGY

Self-potential (SP) is a method where naturally occurring electrical potentials are measured. There are a number of different electro-chemical processes that can create such potentials. The type that is of interest for dam investigations is the so called streaming potential. The surface of mineral grains usually has a negative electric charge. This attracts positively charged ions in the surrounding pore water and an electrical double layer is formed. Under static no-flow conditions, the saturated system is in equilibrium with a balance of electrical charge across the solid-water interface. When pore water flow with respect to a solid surface, the positive charges from 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. When the pore water moves due to a pressure gradient, the excess positive charge within the diffuse layer will be dragged along with the water flow creating an electric convection current. This convection current will cause the mobile positive charges to deplete upstream and accumulate downstream; creating an electric potential difference which is displayed schematically in Figure 3. The streaming potential is the voltage difference parallel to the direction of flow that defines the convection current. The streaming potential is manifested by a shearing of the diffuse layer caused by the hydraulic gradient.

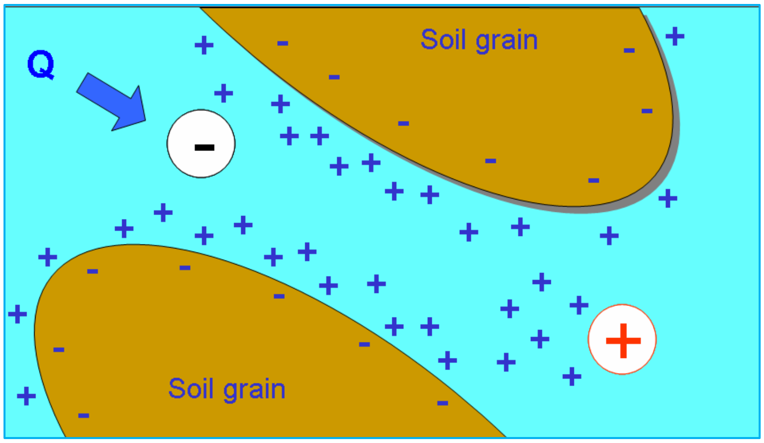

Figure 3: Schematic representations of the pore wall double layer geometry. As a liquid flows the double layer will be sheared leading to a charge separation.

Field equipment for SP measurements is simple and inexpensive. It requires a pair of non-polarized electrodes, a high impedance voltmeter and the cables to connect them. The non-polarizing electrodes used in the survey are of Cu-$CuSO_4$ type. They consist of a plastic tube as the main body filled with a saturated solution of $CuSO_4$ 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. The voltmeter used in the study was a high impedance analogue type with a precision of 0.1millivolt (mV). All the surveys were carried out using the absolute measurement method. The mobile electrode was placed in as uniform soil as possible in order to minimize electrochemical potentials caused by slight differences in soil chemistry. A fixed electrode which was already installed on the dam crest was used as a reference electrode for the measurements at the Kiruna tailings dam while a temporary electrode placed in fine soil at the time of the measurement was used as a reference at the Aitik dam. A fixed electrode about 300 m to the east of the dam was used as a reference for both measurements at the Kristineberg dam. The potential difference with the reference electrode station was measured before and after each survey. The initial and final electrode potentials determine the amount of drifts between electrodes over the particular time in the survey area. Electrode drift is caused primarily by variations in temperature or soil moisture or by 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 currents have a very wide range of periods. This effect was accounted for by making regular measurements of the SP difference between the reference point and the base point within the survey area. Great care was taken in acquiring and interpreting SP data, so that the characteristic fields associated with artificial noise sources were recognized.

The Resistivity method involves the measurement of the apparent resistivity of soil and rocks as a function of depth or position. 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 into an apparent resistivity of the sub-surface. From these measurements, the true resistivity of the subsurface can be estimated. The investigated volume can be changed by moving the electrodes. A large separation of the electrodes gives larger investigation depth. 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. Most commonly local variability is minimized, resulting in smooth models that are compatible with measured data. This means that sharp resistivity borders such as the ground water surface is visualized as a smooth transition in such an inverted section.

Electrical resistivity measurements were carried out along 6 different profiles on the Kristineberg tailings dam. The resistivity data were collected with the ABEM Lund imaging system. The system is a multi-electrode system for high-resolution 2D and 3D resistivity surveys. The measurements were carried out using a Wenner array with 2 m electrode separation. For this survey, electrodes and cables were laid out along a straight line and attached to a multi-core cable and the cable was connected to the system. After checking the connection of all electrodes properly and setting off the program, data were collected.

The SP data were processed using Surfer 8 (Golden Software, Inc). The final result of an SP survey is a contour map showing equipotential contours. Anomalies, usually greater than tens of millivolts, are correlated with known features. The nature and geometry of the sources that cause the anomalies are derived from information of material properties and the driving forces. In the case of seepage, the flow of water is the driving force and hydraulic and electric conductivities are two important material properties.

From the measured resistivity data two-dimensional (2-D) resistivity models were developed by using the program RES2DINV Ver. 3.54 (Loke, 1999). In this inversion program, the subsurface is divided into small rectangular blocks. The arrangement of the blocks is loosely tied to the distribution of the data points in the section. 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. A finite-element forward modeling subroutine was used to calculate the apparent resistivity values and a non-linear least square optimization technique was used for the inversion routine. Since there was a significant topographical relief along the survey lines, a correction for topographical effect was made. The end products of the processing are refined images of resistivity distribution in the subsurface. These images are used as a modeling 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 3, 4 and 5 and 6 meters in profile 1.

RESULTS AND DISCUSSION

Aitik Tailings Dam

SP measurements were carried out at the lower tailings dam at the Aitik mine during late summer 2003. The measurements were repeated in the autumn of 2004. The 2004 SP measurement covered a larger area of the dam than that in 2003.

The results of the measurements are shown in Figure 4. Some positive anomalies can be seen on the downstream slope, which is well-matched with the conceptual behavior of streaming potentials. Of special interest is the positive anomaly at the coordinate 7451330N that continues to the toe of the downstream slope of the dam in both SP maps (2003 and 2004). The anomaly is more distinct in the 2004 measurements. This is a streaming potential generated from the movements of the water. There was a known seepage at this part of the dam. Similar, although weaker, anomalies can be seen at coordinates 7451480N in the 2004 SP map. This is probably due to the fact that the measurements were made in the autumn after precipitation and melting of snow. The moisture 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.

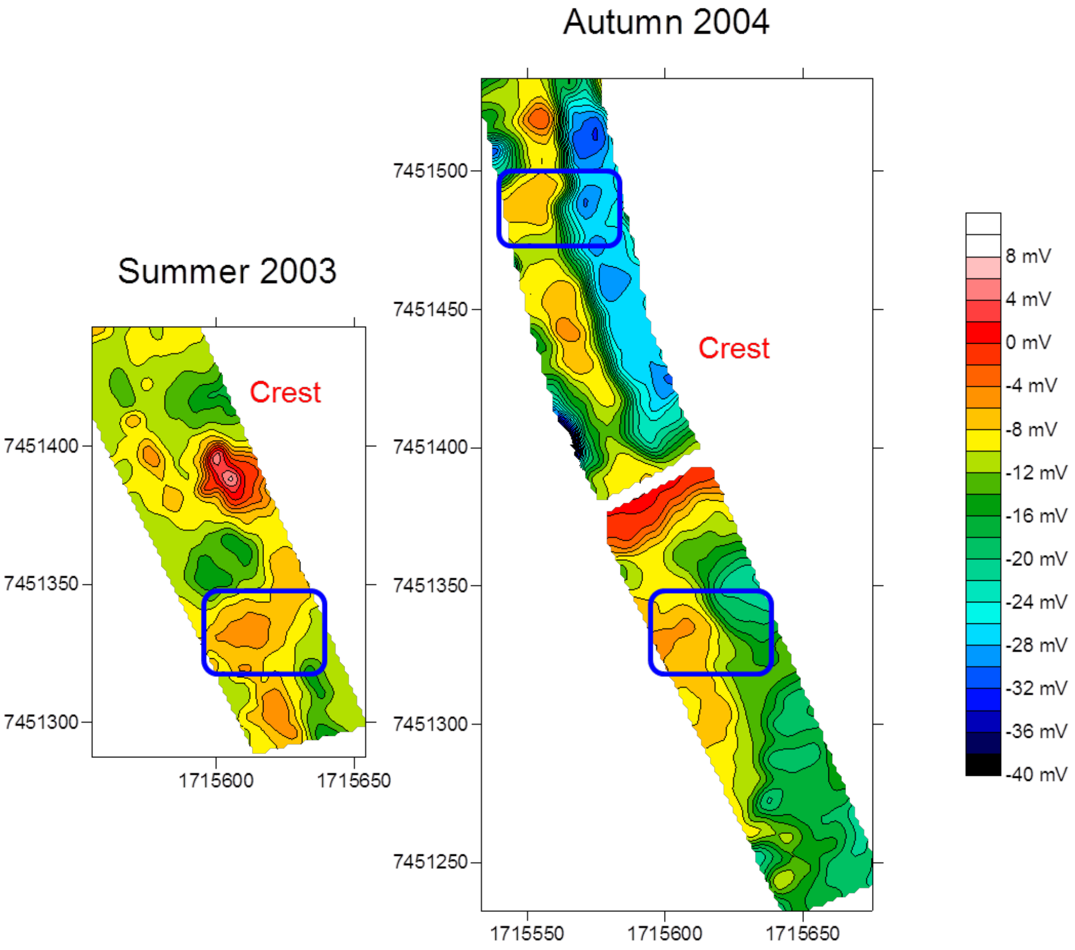

Figure 4: SP map of Aitik tailings dam from 2003(left) and 2004(right) measurements.

Kiruna Tailings Dam

The entire Kiruna tailings dam was investigated by SP measurements during 2002 (Figure 5). Three smaller areas A, B and C, which showed some SP anomalies, were selected for the further monitoring. The detailed SP measurements were carried out 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 the 2003 SP measurements were made.

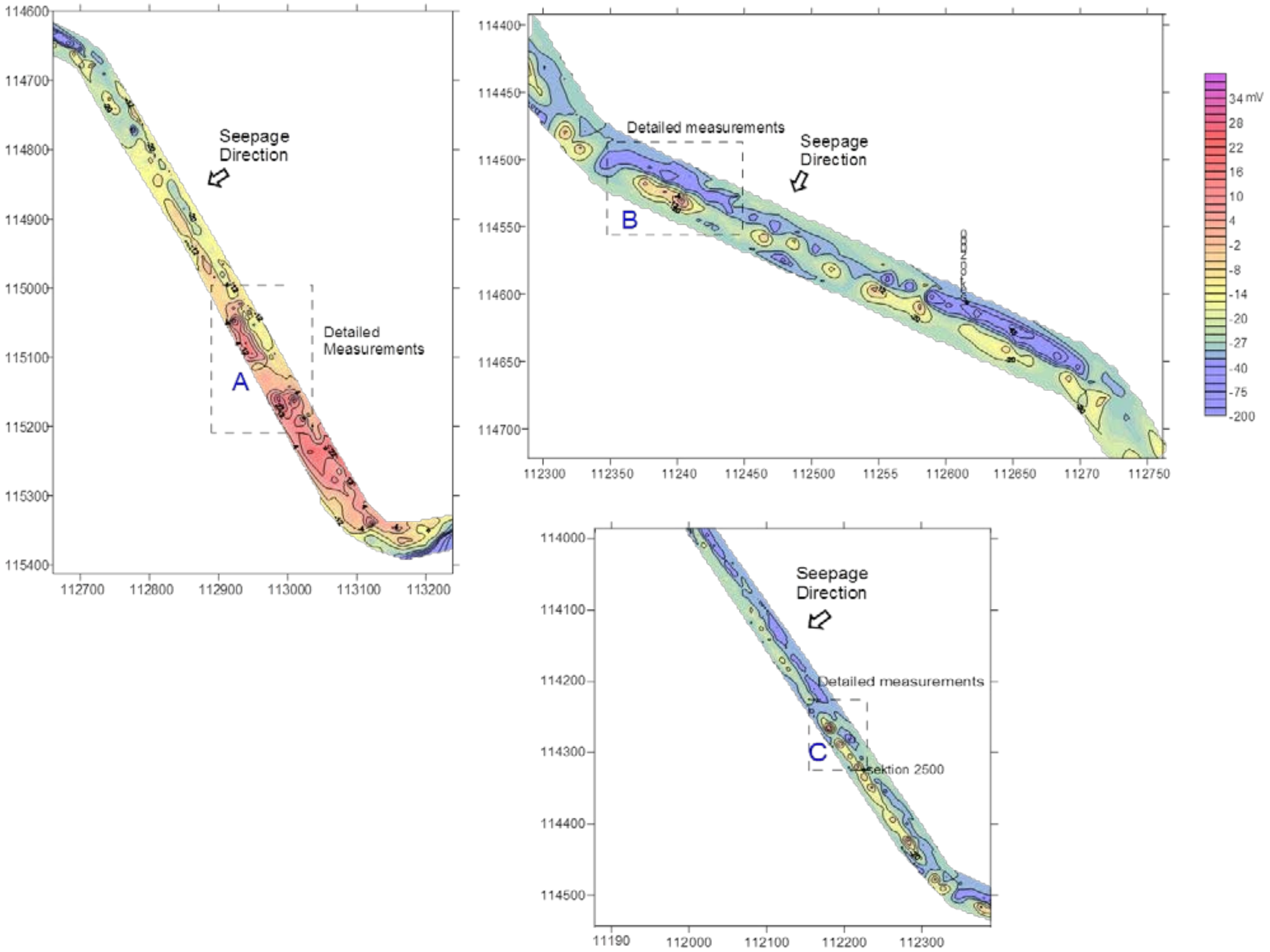

Figure 5: Results of SP measurements carried out in June 2002 at Kiruna tailings dam; the crest of the dam is to the right and the toe to the left in the map (Thunehed *et.al.*). The coordinates are in the local grid system.

The results of the detailed SP measurements from the selected area “A” of the dam is presented in Figure 6. The 2002 results reveal more positive SP values in some parts of the downstream slope of the dam which can be correlated with features of streaming potential anomalies in those areas The results from the 2003 measurements deviate from those in 2002, i.e., more negative potentials along the downstream slope. The results show reverse patterns of the streaming potential, within areas of generally negative potential along the downstream slope. The dam was raised during this period and this would have affected the potential field before it had reached equilibrium. The acquired potentials do not therefore reflect the seepage pattern within the dam. It can be noticed that if the physical condition of the dam changes, a significant change in the SP distribution would be observed.

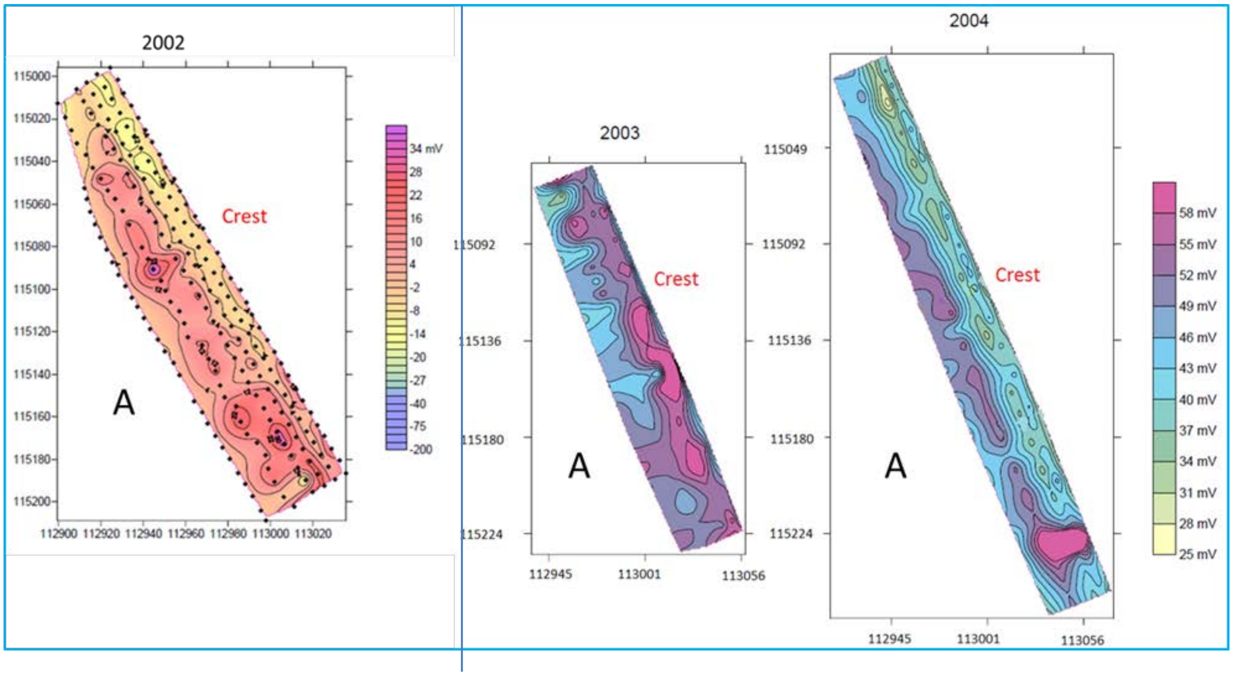

Figure 6: SP map of Kiruna tailings dam on the selected area “A” from 2002 (left) (Thunehed *et.al.*), 2003 (middle) and 2004 (right) measurements. The coordinates are in the local grid system

The 2004 measurements covered a larger area than that of previous years. The result from this measurement reveals higher SP values in some parts of the downstream slope of the dam than at the crest of the dam. This pattern can be related with features of streaming potential anomalies in those areas. The potential distribution obtained from the 2004 measurements is compatible with the results obtained from the 2002 measurements, i.e., before the raising of the dam. This confirms that the result from 2003 measurements was affected by the raising of the dam. No major anomalies were observed that can be related to anomalous seepage of water through the dam. The large positive anomaly (> 55mV) around the x- and y-coordinates 113056 and 115224, respectively, is due to potentials caused by metallic observation pipes present in the dam.

The result of the detailed SP measurements from the selected area “B” of the dam is shown in Figure 7. A local high SP anomaly with two maxima in the x- and y-coordinates 112375 – 112390 and 114515 –114525, respectively, was observed in the 2002 measurements. A high positive anomaly with a maximum 58 mV was also observed in the 2004 measurement approximately in the x- and y-coordinate112365 and 114508 respectively. The anomalies in these two measurements are located close to each other and this could be due to some local noise from water table measurement pipes installed in this area. Similarly some small patches of larger positive anomalies at the crest were observed, that could be caused by metallic observation pipes. At the top corner of the dam at the coordinates (112304, 114442), positive anomalies were observed on the downstream slope in the 2004 measurements which fits with the behavior of streaming potentials. The type of SP distribution patterns creating such an anomaly can be related to an anomalous seepage. Except this anomaly, no major anomalies that could be related to anomalous seepage of the water can be identified.

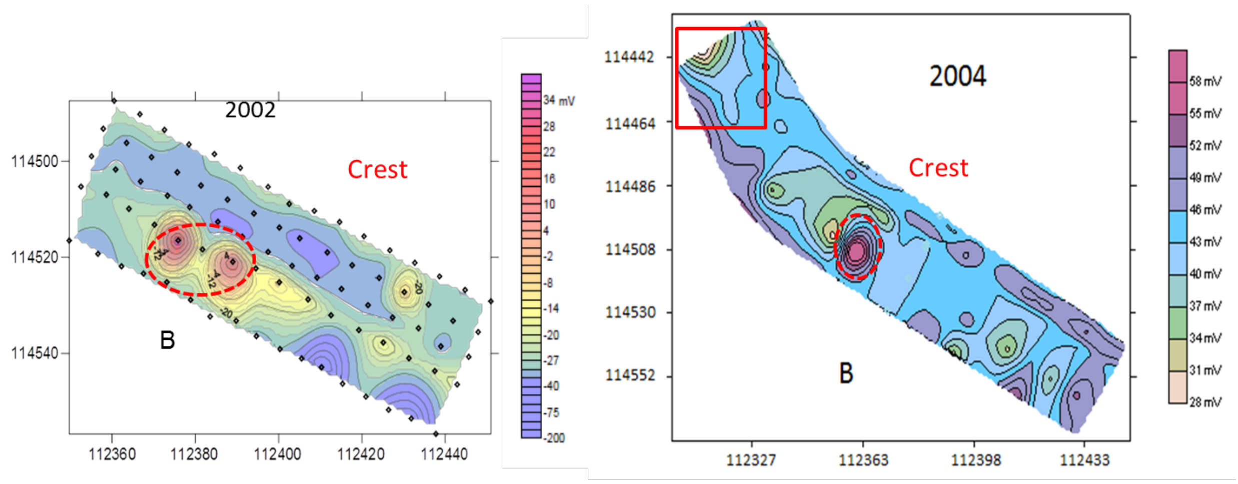

Figure 7: SP map of Kiruna tailings dam on the selected area "B" from 2002 (Thunehed *et.al.*) (left) and 2004 (right) measurements. The coordinates are in the local grid system.

The result of the detailed SP measurements from the selected area "C" of the dam is shown in Figure 8. In general, the results show lower values of SP on the upstream side and higher on the downstream side of the dam. That reflects the streaming potentials within the dam.

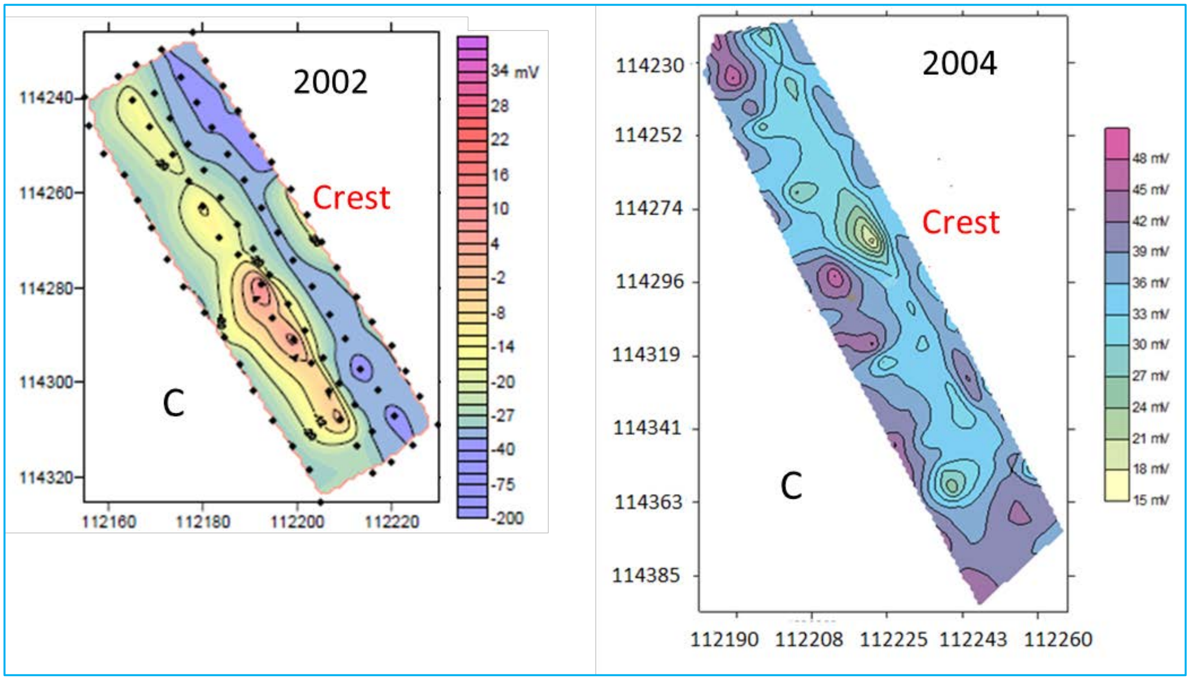

Figure 8: SP map of Kiruna tailings dam on the selected area "C" from 2002 (Thunehed *et.al.*) (left) and 2004 (right) measurements. The coordinates are in the local grid system.

Kristineberg Tailings Dam

SP measurements were carried out on two different occasions, *viz.*, in the late summers of 2003 and in 2004 and the results are shown in Figure 9.

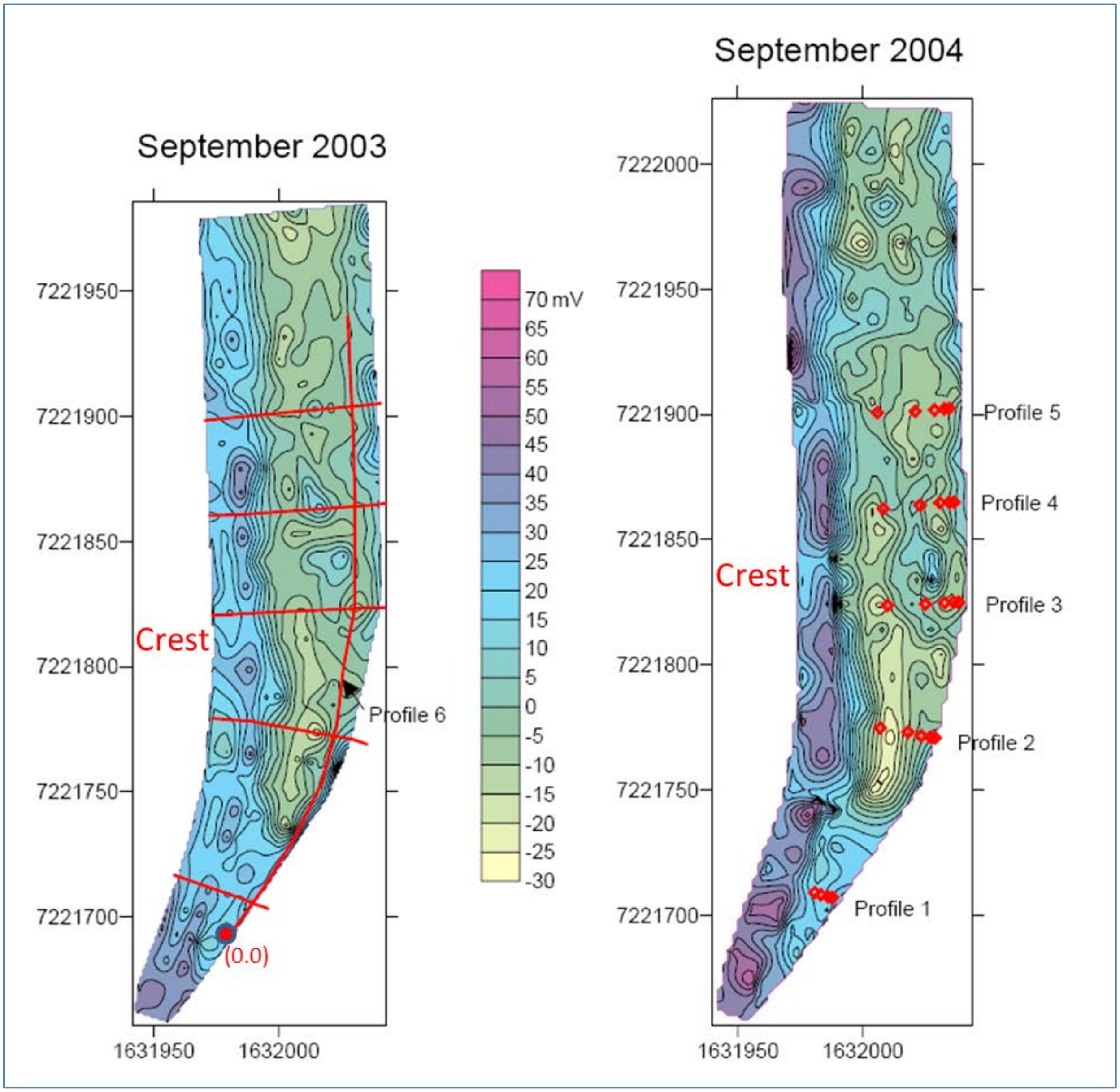

Figure 9: SP map of Kristineberg tailings dam from 2003 (left) and 2004 (right) measurements. The red diamonds in the right map show the positions of fixed electrodes and the red lines in the left map show the location of resistivity profiles.

The results from the 2003 and 2004 measurements are quite similar, with one exception that the potential on the crest of the dam is higher for the 2004 data. The crest is used as a road and consists of compacted material. The reason for higher SP values on the crest in the 2004 measurements is not known, but it might be due to the weather conditions at the time of measurement. A strong change in the background level may also affect the SP distribution at the crest of the dam. Consistent SP results are obtained on the downstream slope of the dam in both monitoring campaigns (2003 and 2004). Generally, low potential on the downstream side might be due to weathering of sulphide minerals in the dam body. This might be possible since waste rock and tailings were used as construction material when the dam was raised. No significant anomalies that could be related to seepage were observed. The SP distribution patterns in the Kristineberg tailings dam do not show streaming potential phenomena. The condition of the dam is stable during the years of measurements. If the condition of the dam were to change, changes in the patterns of the SP distribution would be expected.

The Electrical resistivity measurements were carried out along 6 different profiles on the Kristineberg tailings dam during 2004. The location of the profiles is shown in Figure 9 .The profiles 1 - 5 are perpendicular to the length of the embankment of the dam whereas profile 6 starts from the coordinate 7221690N and extends along the embankment of the dam near the base of the downstream slope (Figure9). In all profile plots the distance along the ground surface (in some profiles including also a part of the surface of the pond) is illustrated and is in the following denoted surface distance.

The resistivity model along profile 6 is shown in Figure 10. The resistivity is relatively evenly distributed along the length of the profile with high resistivity at the surface that decreases with depth. The high resistivity near the surfaces corresponds to unsaturated fill materials and the low resistivity corresponds to water saturated materials. The sharp boundary between high and low resistivity at a depth of about 3 to 5 meters indicates the groundwater level. The higher elevation of the groundwater level in the left part of Figure 10 indicates a hydraulic gradient and hence water flow towards the right.

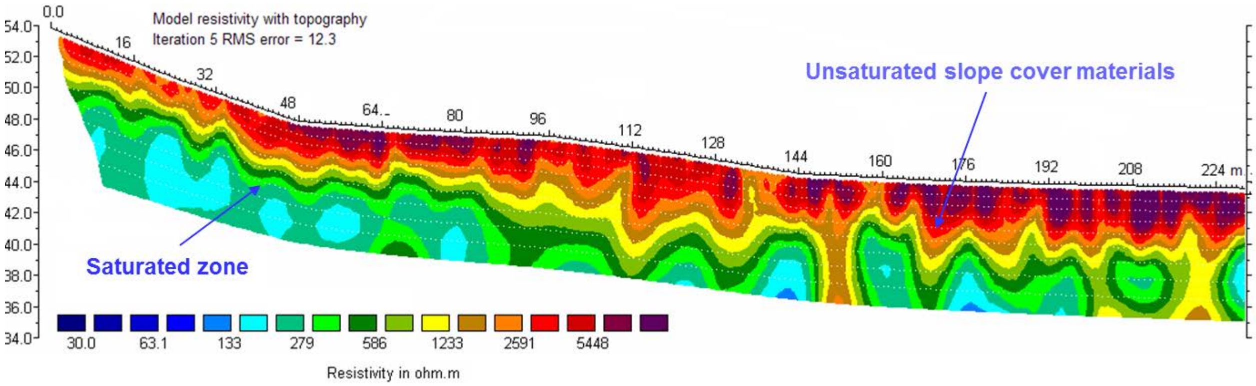

Figure 10: Resistivity section along profile 6 of the Kristineberg tailings dam.

The resistivity section along profile 1 (Figure11) shows a small zone with very low resistivity at the beginning of the profile that reflects the conductive water from the lake. A high resistivity zone near the upstream part of the dam corresponds to the coarser support-fill material. The core of the dam, which mainly consists of moraine, reflected by a resistivity below 100 (Ωm), is evident at 20 m – 32 m (with respect to the scale shown above the contour plot).

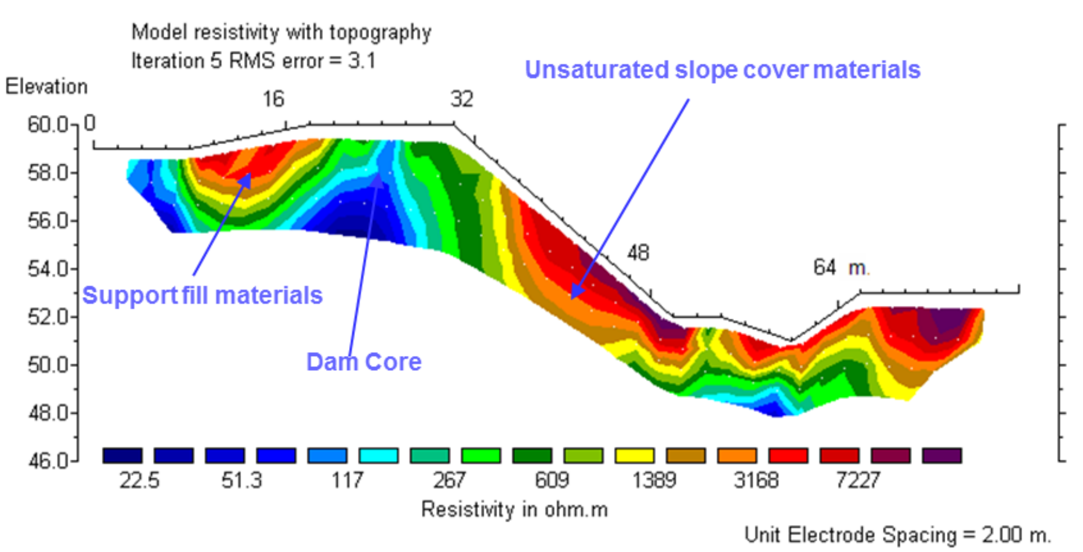

Figure 11: Resistivity section along profile 1 of the Kristineberg tailings dam.

Profile 3 is the longest of the "lateral" profiles and is almost 200 m long. 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, the pond water and the upstream support-fill materials show very low resistivity (Figure 12). The conductivity measured from the pond water confirms the results. The central part of the dam, which mainly consists of moraine, shows resistivity values just below 100 Ωm at a surface distance of about 65 m. This is a value that is compatible with the expected resistivity of a compacted moraine saturated with water from the tailings pond. The moraine contains fractions of fine-grained material and it therefore contains capillary water which increases the conductivity. A gradient in resistivity across the downstream slope of the dam has been observed and this is probably due to the sharp hydraulic gradient across the core. A low to fairly low resistivity zone can be noticed at around 15 m depth in the interval 70 m - 130 m from the starting point of the profile. The variation of the resistivity is in the range 70 - 370 Ωm which may reflect that some parts are water saturated and some are not. The downstream slope of the dam does not show any distinct seepage pattern. The support fill material on the downstream side shows high resistivity (above 1000 Ωm) 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 natural ground surface. This area starts just after the toe of the dam and covers a surface distance of about 90 m. This area was marshy at the time of the survey but might be affected by conductive water that has seeped through the dam.

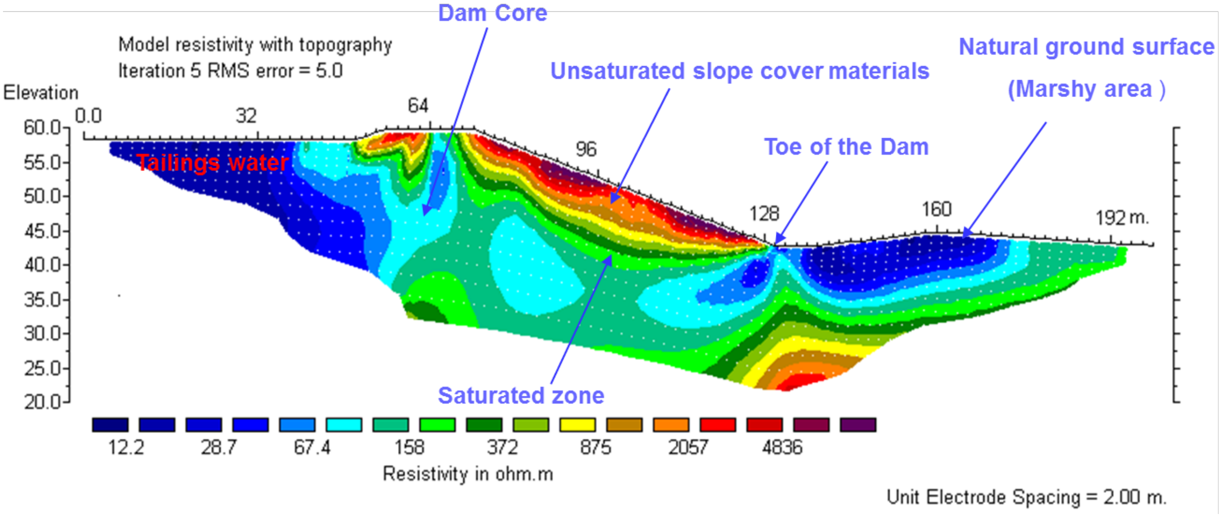

Figure 12: Resistivity section along profile 3 of the Kristineberg tailings dam.

The resistivity along profile 4 (Figure 13) shows high resistivity (> 1500 Ωm) values at the surface of the dam which corresponds to the unsaturated slope cover material. Farther along the dam (increasing surface coordinates) there is a reverse pattern in the resistivity variation i.e. a very low resistivity at the surface and increasing resistivity with the depth. This is similar to what is observed in profile 3. The low resistivity value (below 100 Ωm) at a distance of about 30 m of the profile of the dam reveals the core of the dam.

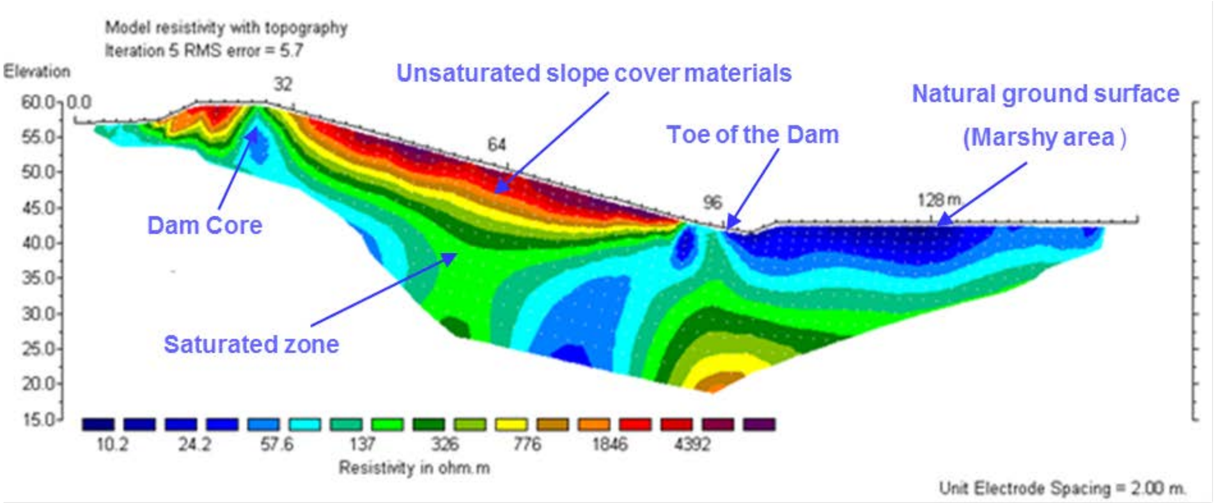

Figure 13: Resistivity section along profile 4 of Kristineberg tailings dam.

The resistivity along profile 5 (Figure 14) shows varying resistivity along the downstream slope of the dam which is different from that observed in the other profiles. This may be due to different materials used for filling and the irregular construction of the dam. The dam has been raised many times and it is probably inhomogeneous in terms of materials used for the construction. The same fairly low resistivity (< 100 Ωm) as in other profiles is however seen close to the crest of the dam which represents the core of the dam.

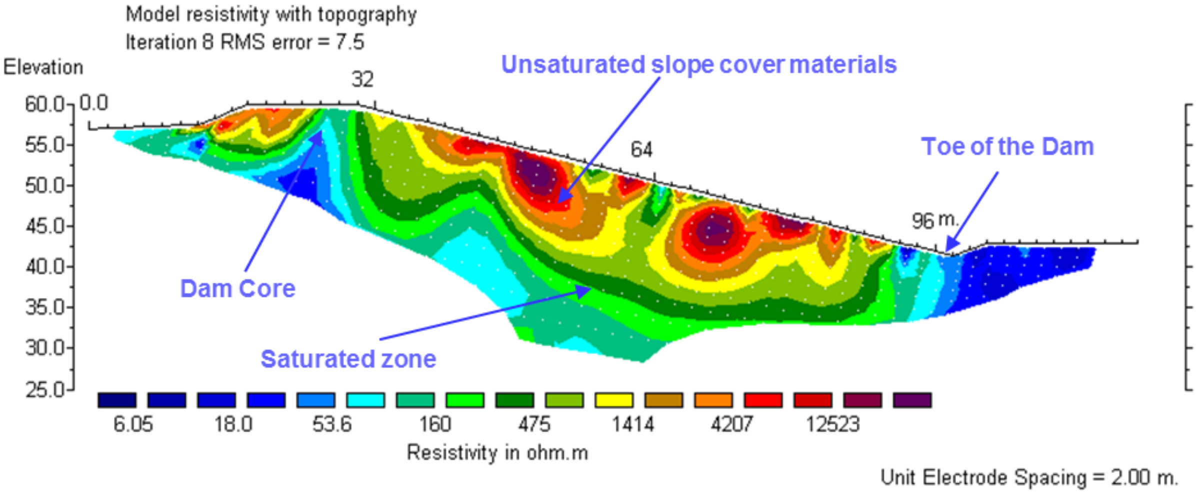

Figure 14: Resistivity section along profile 5 of the Kristineberg tailings dam.

CONCLUSIONS

This study has demonstrated the potential of using geoelectrical method for monitoring the conditions of the tailing dams related to seepage. It has shown that geoelectrical method can provide valuable information about the status of tailings dams. These methods can be used as the monitoring tools of mine tailings dams along with other methods depending upon the geometry and the electrical properties of the filling materials of the dam. The SP survey has shown its capability to detect seepage by determining the streaming potential. The electric resistivity survey defined the water table and showed clearly the dam core. It also gave information about material type, inhomogeneities and saturation in the downstream slope. This information is very important for monitoring the stability of the dam. Possible leakage zones are related to high saturation zones and low electrical resistivities.

The SP measurements in the Kristineberg dam do not reveal any significant changes in the SP pattern over the two years of measurements and no strong evidence of streaming potential related to seepage has been observed. The resistivity profiles also show consistent distribution of resistivity and no seepage zones in downstream slope. This suggests that the Kristineberg dam is fairly stable.

The SP distribution in the dam at the Kiirunavaara mine generally shows higher magnitudes of SP in the downstream part than at the crest of the dam, except for the 2003 measurements. 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 raising of the tailings dam. It takes a long time to recover the physical properties of the dam to equilibrium conditions. Therefore it is suggested to avoid measurement immediately after renovation of the dam.

In the Aitik dam, a distinct positive anomaly at the coordinates 7451330N has been detected. This anomaly which continues to the toe of the downstream slope of the dam is generated from seepage of the water.

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