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ORIGINAL ARTICLE

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Using resistivity measurements for dam safety evaluation at Enemossen tailings dam in southern Sweden

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Abstract Internal erosion is a major reason for embankment dam failures. Resistivity measurements is an essentially non-destructive technique, which may have the possibility of detecting internal erosion processes and anomalous seepage at an early stage before the safety of the dam is at stake. This paper presents results from part of a dam safety investigation conducted at the Enemossen tailings dam in southern Sweden. Longitudinal resistivity sections, 2D measurements along the dam crest, provided an overview of the whole dam and served to detect anomalous zones. In selected areas, additional cross-sectional 2D surveys gave detailed information about the geo-electrical situations in the embankments. This information is valuable for similar investigations as information about resistivity in embankment construction material is scarce. Known problem areas were associated with low resistivities, even though the resistivity measurements alone did not provide enough information to confidently come to a decision about the status of the dams.

Keywords Resistivity · Embankment dam · Tailings dam · Sweden

Introduction

Embankment dams are made of earth or rock. Internal erosion is one of the major causes of embankment dam failures. Resistivity measurements may have the possibility of detecting internal erosion processes and anomalous seepage at an early stage before the safety of the dam is at stake. The technique is essentially non-destructive, which is particularly important when working with embankment dams where drilling and other penetrating investigations are preferably avoided. This paper presents results from part of a dam safety investigation conducted at the Enemossen tailings dam in southern Sweden. Tailings dams are a type of embankment dam that impounds mining waste. The mining waste, which consists of fine-grained waste materials left after mechanical or chemical separation of minerals from crushed ore, is typically pumped into a storage reservoir and the tailings dams are built to hold these volumes in place.

The aim of this study was to examine the extent of the damage around the latest reported sinkhole and to examine the integrity of the entire dams in order to detect other deficiencies. The investigation comprised temperature, resistivity, induced polarisation (IP) and self potential (SP) measurements together with standard visual inspections and piezometer readings. Part of the results from the resistivity measurements will be presented here. Measuring temperature over time is a powerful and sensitive way to detect leakage pathways and to estimate flow rates. The method is, however, limited to a specific area, and the same goes for most conventional methods. Other methods with the possibility to scan larger areas are therefore requested, and most geophysical methods are of this kind. Among the methods tested, resistivity measurements were considered the most successful. A general overview of all measurements, as well as a more detailed description of the dams, is given by Salmon and Johansson (2003).

In recent years much effort has been put into dam safety work in Sweden. During the same time a number of incidents involving tailings dam have occurred, which have increased consciousness among the public and the authorities. As a consequence, strong focus has also been put on dam safety for tailings dam. Eight large tailings dams were in operation in Sweden in 2003, and an additional one commenced in 2004. Three of them have been subjected to uncontrolled erosion through the dam body or the foundation over the last 10-year period, and one of these incidents developed to a complete failure (Benckert 2003).

When the electrical properties of the tailings distinguish from the surrounding materials, resistivity measurements can be used to assess leakage and propagation for environmental purposes. This type of investigations has been conducted many times as regard to mine drainage (e.g. Abraheem et al. 1990; Buselli and Lu 2001; Yuval and Oldenburg 1996). The technique is similar to the one used to detect leakage from landfills. Using resistivity for safety investigations of tailings dams is, however, less common, but the technique is similar to leakage detection on other types of embankments or river dykes where some recent examples from the literature include among others: Panthulu et al. 2001; Titov et al. 2000; Van Tuyen et al. 2000; Voronkov et al. 2004. Looking at the measurement programs carried out in such investigations, 2D surveying parallel to the dam along the dam crest or at a certain level on the slopes is nearly always made use of. It is often the only feasible way to conduct a survey in practice. Mapping true resistivities (inversion) from such data, however, leads to problems with severe 3D-effects. Two approaches, both disregarding these effects and thereby paying less or no attention to absolute resistivity values, then, suggest themselves. The first one is to find anomalies in space along the dam comparing healthy sections with known problem areas. This approach has been used in this study. The second way to tackle the problem is to find changes over time, but this requires repeated measurements or regular monitoring.

When it comes to detecting areas with anomalous seepage or internal erosion, two processes working against each other are complicating the issue. Firstly, these areas get increased water content, which decreases resistivity. Secondly, in the case of internal erosion, resistivity will increase due to washout of fines in the earth material. Therefore, as much as possible, it is essential to be familiar with the electrical properties of the involved materials.

The Enemossen tailings facility

The Zinkgruvan mine is situated in southern Sweden close to the northern end of lake Vättern. Mainly zinc and lead are produced. Large volumes of ore is involved in the process. Parts of the tailings are reused as fillings in the mine but the major part is stored in the Enemossen tailings facility which is located some 4 km away from the mine.

The tailings facility at Enemossen covers an area of 0.60 km^2 and contains a volume of seven million cubic meter. It is restricted by two embankment dams along the north and the east sides and elsewhere the tailings are kept in place by natural ground.

Dam X-Y, located in the east, is the highest and longest of the two dams. It starts at chainage 0/018 m (this format represents length marks along the dam in meters and is used throughout the paper) and ends at chainage 0/825 m that gives a total length of 807 m. At the highest part between chainage 0/320 m and 0/600 m the dam is 27 m high. The oldest part of the dam was built in 1976, and as the mining activity expanded, the dams were raised five times. Initially the dams were raised using the downstream method up to elevation 180 masl (meters above sea level). Later the centre-line method was used between elevation 180 masl and 185 masl and finally also the upstream method was used up to the current crest elevation at 192 masl. These methods are conventional construction methods for tailings dams, and they are thoroughly described in, for instance, Fell et al. (1992). In contrast to other embankment dams, the final height is usually not determined when a tailings dam is first built. Instead, the dam is raised along with expanded production of tailings from the mine, and this can be done either by expansion on the downstream side (downstream method), upstream side (upstream method) or both (centreline method). Nevertheless, the combination of these different methods at Enemossen results in an unusual layout of the core as shown in Fig. 1.

Dam E-F is located along the northern border of the tailings area. It is constructed in a similar manner to the X-Y dam. However, it is considerably smaller and no incidents have been reported in history. Therefore, focus in this study will be on the X-Y dam.

Both dams are constructed according to conventional methods for construction of tailings dams. The main part is founded on soil or pervious rock. In case of foundation on soil, at least 4 m have been excavated for the dam core. The core consists of a fine-grained till with a fines content of 40–45% and a low hydraulic conductivity of about 10^{-8}–10^{-10} m/s (SWECO 2003). The minimum width of the core, measured perpendicular to the core, is 3 m. Considering the slope of the latest dam raise, this corresponds to a core width of 5.5 m at the crest (Fig. 1).

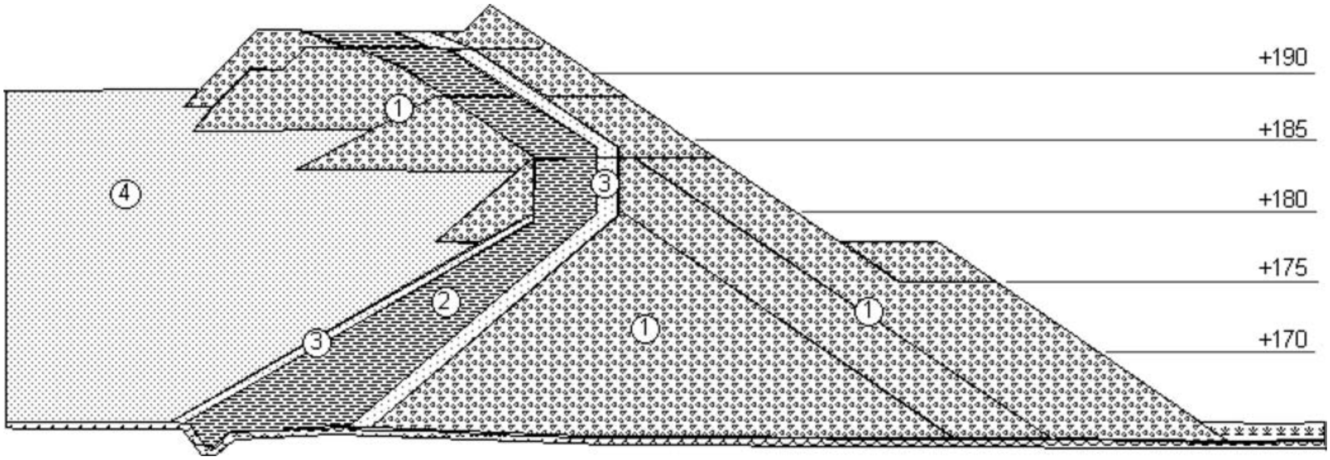

Fig. 1 Cross section of the X-Y dam. 1 Support fill (downstream and upstream), 2 core, 3 filter, 4 tailings. Level refers to meter above sea level

There is only one filter zone, with a minimum width of 1 m, between the till core and the downstream support rockfill. The filter material consists of gravel smaller than 14 mm. Downstream and upstream support fill consists of mixed fractions of crushed rock from the mining. The tailings, remaining from the mining after separating zinc and lead, consist of fairly loose, well-sorted, quite homogenous fine sand with around 20–35% contents of silt. It has a low hydraulic conductivity of about 10^{-5}–10^{-6} m/s (SWECO 2003).

As a part of the dam safety, work at Enemossen piers of rockfill has been constructed parallel to the dam 30–40 m upstream in the tailings. In the area between the dam and the piers, tailings are deposited 0.5 m higher than the reservoir water level. Furthermore, to increase stability, a 7-m-wide zone of downstream support fill was put out starting in 1997. Currently, the level of this supporting berm is at elevation 178 masl (Fig. 1).

Several incidents and sinkholes have been reported on the X-Y dam, especially between chainage 0/250 and 0/350 m (1977—failure between 0/250 and 0/350 m, 1990—sinkhole at 0/250 and 0/350 m, 1993—crest settlements at 0/260 m, and 1995—sinkhole at 0/270 m). Sinkholes were also observed at chainage 0/400 m in 2000 and at chainage 0/500 m in 2002.

In Enemossen the tailings were distributed over the tailings area via water in a system of pipes. The electrical conductivity of the outflow water from the tailing is about 100 mS/m with a variation between 94–102 mS/m during the last 5 years. This corresponds to 10 Ω m and is very low for Scandinavian conditions where water in rivers may be as high as several hundred Ohm m. This is explained by the high amount of total dissolved solids (TDS) in the tailings water compared to the low TDS levels of the extremely fresh river water in northern Sweden. Regarding the other materials, the till core is also expected to show low-resistivity ranges due to the high amount of fines, whereas the support rockfill typically has a very high resistivity, especially in the downstream dry area. Keeping this in mind it is likely that an area with increased seepage will stand out as a low-resistive zone.

Resistivity measurements and evaluation

Resistivity surveying was carried out with 5 m minimum electrode separation along the entire length of the two dams with the electrodes placed on the surface of the dam core 1 m from the downstream filter. Part of the line (0/225–0/575 m) was also surveyed using 2 m electrode separation in order to enhance the resolution in the areas where most incidents have been reported. On the basis of the information from the layout along the core and historical seepage areas, three cross lines, each around 150 m long, using 2 m electrode spacing were carried out at chainage 0/310, 0/471 and 0/492 m.

Measurements were taken with a prototype version of the ABEM Lund Imaging System. Gradient array surveying with multiple current electrode positions was employed. The maximum depth of investigation in the inverted depth sections was around 50 m, which was more than enough to reach the bedrock. The number of data points collected for each line were around 2,500 for the long line with 5 m spacing, around 2,900 for the detailed line with 2 m spacing and 850–1,050 each for the three lines crossing the dam.

Evaluation of the field data was done via 2D inverse numerical modelling (inversion), using the software Res2dinv[1], version 3.50b. In the inversion, 2D structures are assumed; i.e., the ground properties are assumed

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[1] Developed by M.H. Loke, available for example at http://www.geoelectrical.com.

constant perpendicular to the line of the profile, while the current electrodes are modelled as 3D sources. This is valid for cross section measurements as topography is taken into account. However, evaluation of surveying along the dam will result in severe 3D effects, but nevertheless the approach is valuable for detecting anomalous zones. The inversion is done through the generation of a finite element model of the resistivity distribution in the ground, which is adjusted iteratively to fit the data so that the differences between the model response and the measured data (the model residuals) are minimised. This can be done by either minimising the absolute values of the differences (inversion with L_1-norm or robust inversion), or minimising the squares of the differences (inversion with L_2-norm or smoothness-constrained least-squares inversion) (Loke et al. 2003). Robust (L_1-norm) inversion is more capable of handling sharp boundaries in the model and was used for all measurements, due to the expected large contrasts in electrical properties of the involved materials. Resistivity data from the inverted models were plotted with the software Erigraph by using linear interpolation between neighbouring cell values. Erigraph comes with the ABEM equipment.

Results

The resistivity measurements along the dams as well as the cross lines provided data of high quality, resulting in low model residuals (≈1–3%) for the inverted sections. The upper part of Fig. 2 shows an inverted section from the 5 m spacing survey along the entire dam X-Y. Data from the 2 m spacing and the 5 m spacing survey along the central part of the dam were combined and inverted jointly (Fig. 2).

A high-resistive bottom layer is evident throughout the section, at depths that correlate well with the somewhat sparse and uncertain information available about variations in bedrock level. The high-resistivity bottom layer comes close to the surface at the ends of the line. The central part the line exhibits three principal layers above the high-resistive base layer. Starting from the top; a couple of metres thick layer of around 100 Ω m, a medium-resistive layer of a few hundred Ohm m down to approximately 10 m depth, and below that a layer around 100 Ω m reaching circa 30 m depth.

The cross section at chainage 0/471 m (Fig. 3) shows a sequence of zones with different resistivity with steep to vertical interfaces, going from low (≈40 Ω m) over intermediate (≈200 Ω m) and rather low (< 100 Ω m) to very high (> 1,000 Ω m). These zones correspond well with that which can be expected from the way the dam is built. Starting from the upstream side on the left in the diagram, the low-resistive zone that continues up to –20 m corresponds to saturated sand, and with a resistivity of 10 Ω m of the pore water, a resistivity of 40 Ω m is reasonable if Archie's law is applied to the high porosities that can be expected for well-sorted sand. Thanks to the well-sorted character of the sand, it is possible to identify the groundwater surface in the diagram, being at the surface in the upstream edge of the diagram and decreasing to a relatively stable level of 185 masl going in the downstream direction. This fits perfectly with the observation wells at chainage 0/500 m that show a level of 185–186 masl. The higher resistivity above the level 185 masl corresponds to the tailings sand above the groundwater level. The zone with higher resistivity next to the low-resistive zone matches up with the position of the upstream support fill of the dam, with a water level at 185 masl visible as a decrease in resistivity. The next zone, of relatively low resistivity, corresponds to the core of the dam, where the inclined shape at the top followed by a more vertical part is well visible. There is also an indication of a reverse slope for the lowest part of the zone that can be interpreted as the core, however, not as inclined as on the drawing (Fig. 1). The highly resistive downstream zone corresponds to the downstream rockfill, whereas the filters cannot be readily identified.

The cross section at chainage 0/492 m (Fig. 3) agrees well with the one at 0/471 m, but the top high-resistive part corresponding to the upper part of the upstream support fill is not so well developed. The latter explains the high-resistive zone at 0/471 m in the sections measured along the dam (Fig. 2). The extra low-resistive part of the zone interpreted as the core might be an indication of a change in the properties connected to the sinkhole development. The groundwater level was recorded at elevation 165 masl at + 3 m on the cross section (chainage 0/500 m).

The cross section at chainage 0/310 m (Fig. 3) is similar to the one at 0/471 m with one important exception. The high-resistivity zone corresponding to the upstream filter is interrupted by a large zone (around 10 m high) with resistivity below 100 Ω m. This can be interpreted as an effect of anomalous seepage through the dam, which fits well with the occurrence of old sinkholes. Measured groundwater levels at elevation 187 masl at –40 m and elevation 185 masl at –20 m fit well with the image. At + 3 m the measured groundwater level at 171 masl is not visible, as would neither be expected in fine-grained material. The bedrock level at elevation 165 masl at –15 m may be situated below the depth penetration. At + 20–25 m the bedrock at elevation 171 masl appears to be slightly less resistive than the downstream support fill.

When comparing the longitudinal sections and the cross sections, it is evident that the former, which are measured along around –10 m in the cross section, will suffer from severe 3D effects. The top layer observed in

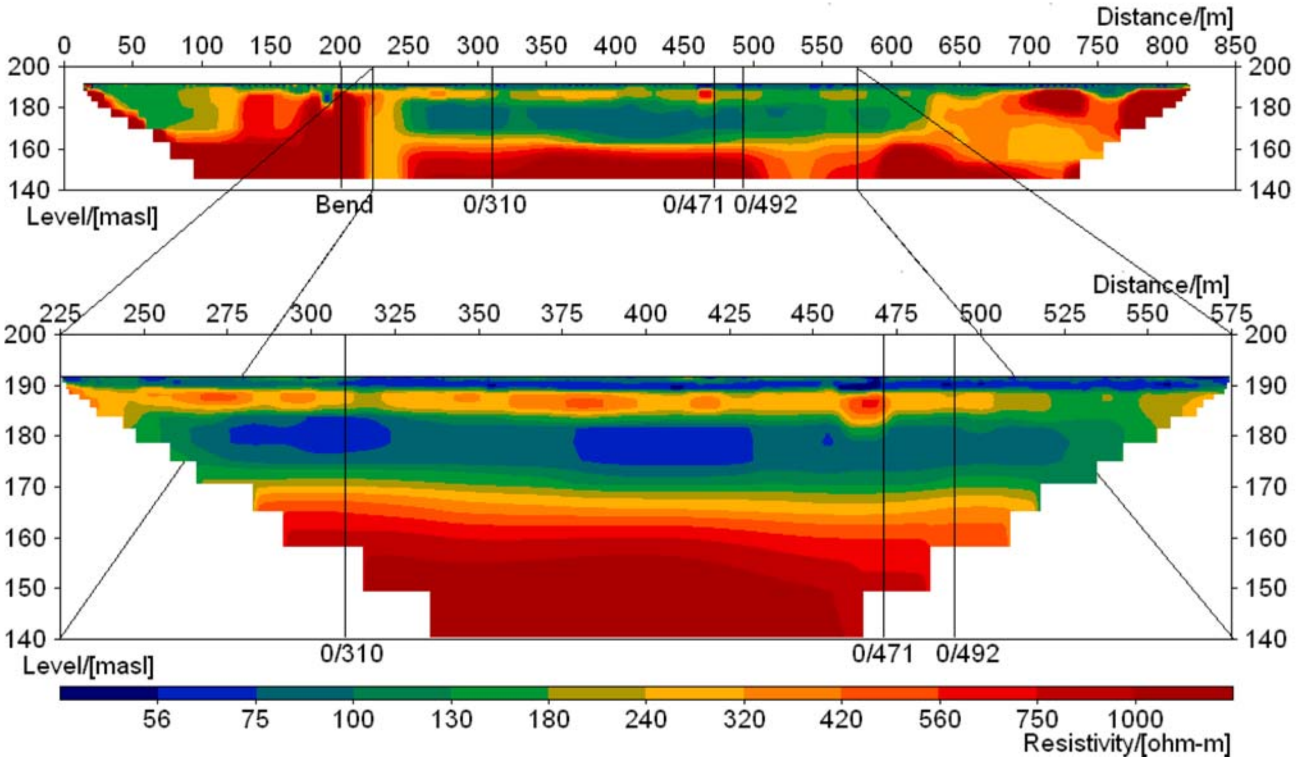

Fig. 2 Inverted resistivity section from the X-Y dam. Above: based on measurements from the 5-m spacing survey (mean residual 2.5%). Below: based on measurements from both the 2-m electrode spacing and the 5-m spacing survey (mean residual 1.4%). Cross section profiles at 0/310, 0/471 and 0/492 m are marked out. Level refers to meters above sea level

Fig. 2 corresponds to the uppermost part of the dam core, and the second layer corresponds to the upstream support fill. The third layer in the length sections show the combined effect of the dam core, the water-saturated support fill and the saturated tailing sand.

Discussion and conclusions

Good measuring conditions with high contrast in resistivity between soil and the low resistivity of the water disposed in the tailings dam give good possibilities to detect areas with high water content. Possible leakage zones will be observed as low-resistivity areas. The measurement accuracy is good as well as the model residuals after inversion. This accounts for credible results and several known features are also confirmed. The combination of longitudinal sections and cross sections is recommended. Measurements along the dam give a good overview and are capable of locating anomalous zones. Cross sections, which are in many cases not possible to carry out, give more detailed information about the resistivity in the dam.

The resistivity profiles along the dam show low-resistivity areas at chainage 0/280–0/340 m, 0/390–0/425 m, and 0/525–0/550 m. The resistivity in the area of the latest sinkhole (at chainage 0/500 m) is similar compared to the other parts of the dam. The cross section at chainage 0/492 m shows, however, a lower resistivity in the downstream part of the core. This is similar to the result at chainage 0/310 m where a high-resistivity zone (corresponding to the upstream support fill) is interrupted by a large low-resistive zone. This can be interpreted as an effect of anomalous seepage through the dam, which fits well with the occurrence of previous sinkholes. The overall conclusion, based on the result from these investigations, is that none of the detected resistivity or temperature anomalies immediately need any further investigation, but the result shows the importance and need of the ongoing monitoring program for the dams.

Known problem areas were associated with low resistivities even though the resistivity measurements alone did not provide enough information to confidently come to a decision about the status of the dams. However, repeated measurements would provide possibilities to detect changes in the material or seepage-induced resistivity changes, the latter mainly due to temperature changes. This approach is used in an ongoing dam-monitoring programme at two Swedish embankment

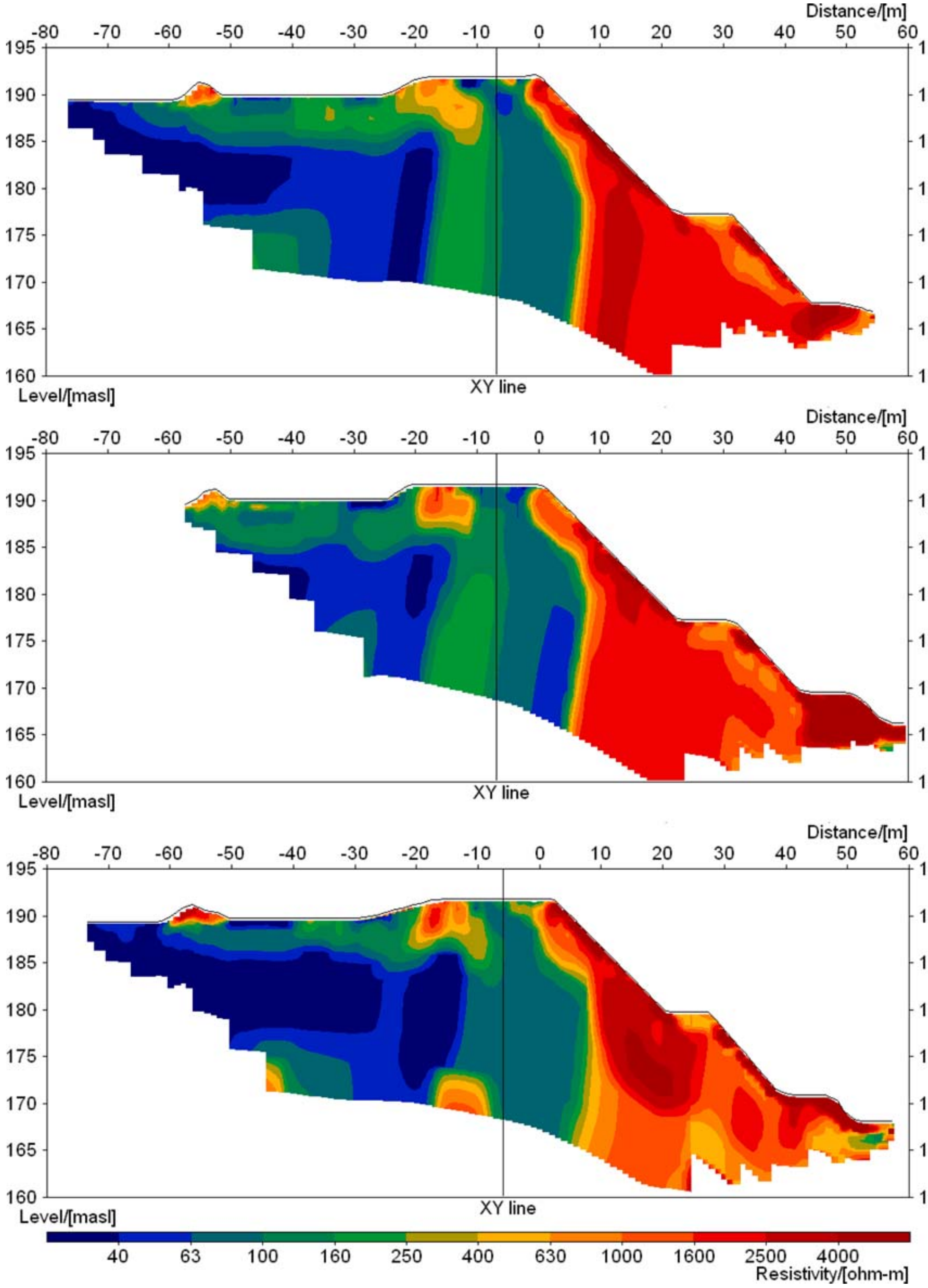

Fig. 3 Inverted resistivity cross sections from the X-Y dam. Above: chainage 0/471 m (mean residual 3.1%). Centre: chainage 0/492 m (mean residual 3.3%) Below: chainage 0/310 m (mean residual 1.7%). Level refers to meters above sea level and chainage to length along the dam in meters

dams. Experiences from that project show that repeated measurements or preferably regular monitoring is needed to detect internal erosion or anomalous seepage (Johansson and Dahlin 1998; Dahlin et al. 2001). There are, however, important differences between the monitoring program and this investigation at Enemossen. Firstly, here the conductive water is ≈10 Ω m compared to the resistive water that is ≈500 Ω min northern Sweden power station reservoirs. Secondly, thanks to the possibility to reach the upstream reservoir and get enough grounding contact in the downstream fill, good cross sections could be measured at Enemossen. In addition, a smaller electrode separation was used at Enemossen leading to higher resolution, thus giving us useful information about the geoelectrical situations in zoned embankments constructed with these characteristic earth materials.

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