Investigation of shallow leakage zones in a small embankment dam using repeated resistivity measurements in Internal erosion in embankment dams and their foundations

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Investigation of shallow leakage zones in a small embankment dam using repeated resistivity measurements

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Resistivity measurements were carried out in order to identify preferential seepage paths in a small dam in central Sweden. Increased seepage flow had been observed at high reservoir levels. Repeated resistivity measurements were performed along the dam crest during 24 hours controlled rising of the reservoir. Each measurement data set was compared to the original reference data set using time-lapse inversion. Zones with gradually decreasing resistivity were identified inside the dam at the depth corresponding to the changed reservoir level. The zones were interpreted as preferential seepage paths. During a possible future repair of the dam this interpretation may be evaluated.

keywords: seepage, detection, resistivity, embankment dam

1. Introduction

Resistivity measurements have been used on embankment dams for different purposes and with an alternating degree of success. The traditional approach is the use of resistivity surveying as a tool to investigate defects or to map the extension of weak zones. Typically the method is, in this case, used for complementary examination of an observed weakness.

An additional approach has been to use permanent installations for long-term resistivity monitoring. The idea behind the latter approach is to examine the pattern of the seasonal variation and/or to identify small changes over time. These factors could be related to internal erosion or seepage changes.

The study in this paper is based on ideas from both of these approaches. The objective was to investigate a known problem of increasing seepage appearing at a certain reservoir level. Repeated measurements were performed over a short period, when the reservoir was filled to the level where the increasing seepage took place. Studying changes over time, particularly in combination with altering of the reservoir level, increase the amount of information for interpretation and thereby makes the method more powerful. A similar approach was tested in a

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blind test on a small embankment with known built-in defects (Sjödahl et al. 2010). The design of the field work was based on the intention of being able to map contrasts in resistivity between soils with different degree of saturation.

1.1 Site description

The plant is situated in central Sweden. It consists of a power plant, a concrete dam with gates, a workshop building and an embankment dam (Fig. 1). The embankment dam is less than 100 meters long and less than 10 m high.

Fig. 1 Plan view over from left to right: the power plant, spillways, workshop building and embankment dam (from Google maps).

The dam was originally built in the first part of the 20th century and has changed ownership several times. Existing documentation of the dam construction is limited. Only one old plan drawing (on which Fig. 2 is based) has been provided. Today the crest of the dam and a rather large area in front of the workshop building is paved with asphalt. According to personnel at the site the dam has been raised at one occasion, but the former crest level is not known. This is confirmed by information from the water rights that the retention level was raised by 0.45 m from El. 77.49 m to El. +77.94 m.

During operation with reservoir levels around El. 77.50 m and above leakages has been observed on the dam. Two outflow areas have been visually observed. The first observation is a leakage through the concrete wall into the workshop building and the other leakage outflow area has been observed in the downstream slope adjacent to the southeast corner of the workshop building. Furthermore, several settlements has been observed on the asphalted area in front of the workshop building as well as wet spots in the downstream area east of the workshop building. Even though the outflow areas have been observed the seepage path through the dam is unrevealed.

The dam is classified in consequence class 3 in the Swedish guidelines of dam safety (RIDAS), which means that it is the least prioritised group of dams. However, it is required that future operation of the dam will allow making use of the original retention levels.

2. Method

The embankment dam was cleared of vegetation. Two lines of electrodes were installed along the dam crest. Both lines started closed to where the embankment dam connects to the spillway dam. The first line then followed the dam curvature along the upstream side of the crest, whereas the second line was placed straight across the asphalted area in front of the workshop building. After a quick first test the second line was chosen for the repeated measurements due to lower noise levels. The position of this line is shown in Fig. 2. Each electrode location was carefully positioned and levelled.

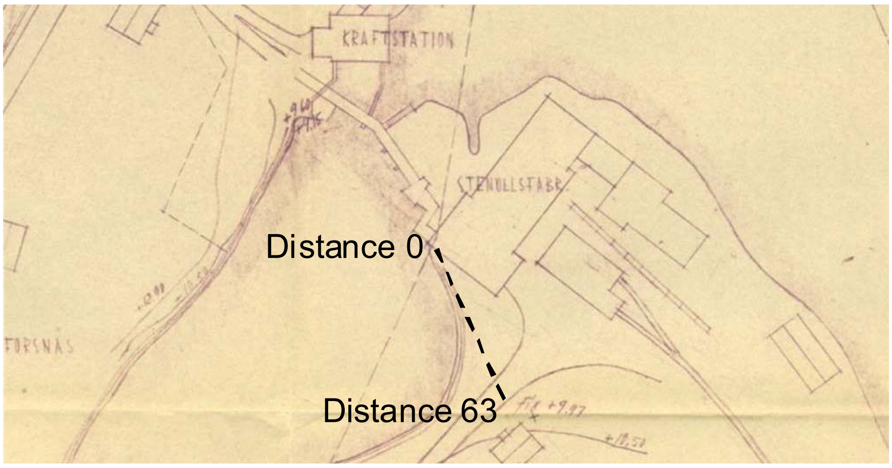

Fig. 2 Plan over the power plant and embankment dam with electrode layout.

Holes, with diameter 16 mm and depth 30 cm, were drilled through the asphalt every meter. The holes were filled with granulated clay and sufficiently wetted to ensure good electrode contact. In total 64 stainless steel electrodes were inserted and connected to the instrument via multicore cables. The instrument, an ABEM Terrameter LS, consists of a current transmitter and 12 measuring channels.

The measuring protocol was an expanded multiple-gradient protocol based on a combination of gradient and bipole-dipole arrays resulting in 2794 measuring configurations in each data set. However, the configurations that were most sensitive to noise were removed before data processing. Consequently, each processed measuring sequence is based on approximately 2250 data points. The multiple-gradient array (Dahlin and Zhou 2006) has good properties regarding noise sensitivity and efficient data acquisition and the bipole-dipole array makes a good complement increasing resolution towards the ends of the measuring line.

Repeated measurements were taken during a period of two days (Fig. 3). Each measurement sequence had an identical setup. Data collection time for one sequence was in the order of one hour. The first two measurements were taken with low reservoir, the third during filling and the following with high reservoir level. In total 13 measurements were taken.

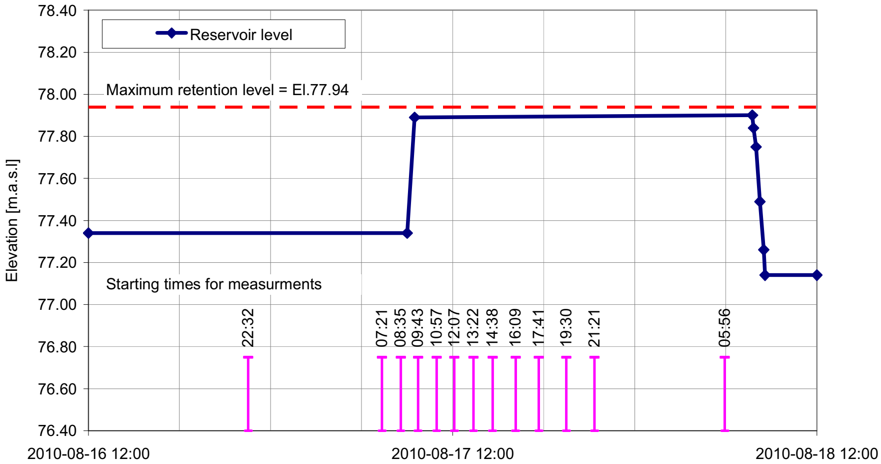

Fig. 3 Reservoir levels and starting times for measurements.

Inverse modelling was carried out with commercial software, Res2dInv version 3.59 (Geotomo Software 2010). The subsurface is divided into a large number of rectangular cells and an iterative process is applied to determine the resistivity of each cell that minimises the differences between the calculated and measured apparent resistivities. L1-norm optimization has been used (Claerbout and Muir 1973), which means that the absolute changes is minimised rather than the square of the changes. This is preferable when sharp interfaces between different regions may be expected. Moreover, time-lapse inversion (Loke 2001) was used to focus on changes in resistivity between measuring occasions. Model residuals in the range of 2-5% indicate good data quality and good measuring conditions.

3. Results and discussion

Measurements were taken at 13 occasions. The results demonstrate good repeatability and excellent data quality.

The resistivity distribution in the dam indicates homogeneous conditions along most part of the dam (Fig. 4). In the shallow parts there is an approximately 2 m deep layer with higher resistivity (ca 1000 Ωm), which most likely is representing dry earth material above the groundwater level. Due to the asphalt covering the ground this material has been protected from rainwater. Consequently, there is a rather large contrast in resistivity to the underlying material where the resistivity is significantly lower (ca 100 Ωm).

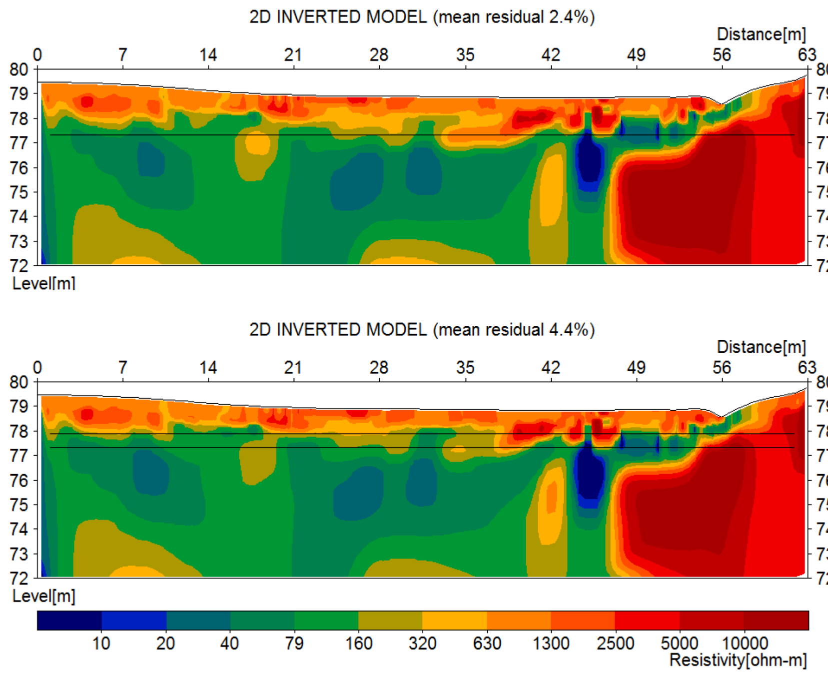

Fig. 4 Resistivity distribution in the dam from the first measurement 2010-08-16, 22:32 (above) and the last measurement 2010-08-18, 05:56 (below). Marked lines show reservoir level at first and actual measurement.

Between distance 0 and 40 m the resistivity is uniform down to El. 72-73 m, where an increase in resistivity can be inferred. In the right part of the measured line (ca distance >46 m) there is an extensive zone with very high resistivity, which is interpreted as bedrock. At the end of the line the bedrock can be seen at the ground surface, which coincides with the interpretation as the high resistivity zone is clearly reaching the surface in this part.

At distance 44-45 m there is a small zone with very low resistivity. There are no observations or documentation to explain this zone. Rather, it is likely an artefact from the inverse modelling. In the inversion process it is often difficult to correctly map zones with large such high contrast in resistivity as is likely to appear close to a bedrock soil interface. In such zones the model may overshoot and produce resistivities lower than what would be expected. Similar tendencies can be seen in the area above the supposed bedrock level around distance 47-55 m.

Estimating the differences in modelled resitivities from the displayed sections in Fig. 4 is challenging. To emphasize on the dissimilarities of the models difference plots has been composed (Fig. 5). The first data set is used as a reference and the change in resistivity for the subsequent data sets are examined. The change in resistivity is shown after 2 hours (Fig. 5 above) and 21 hours (Fig. 5 below) respectively. Blue areas represent a decrease in resistivity and red areas represent an increase. Areas where the change is less than 20% have been blanked out as white.

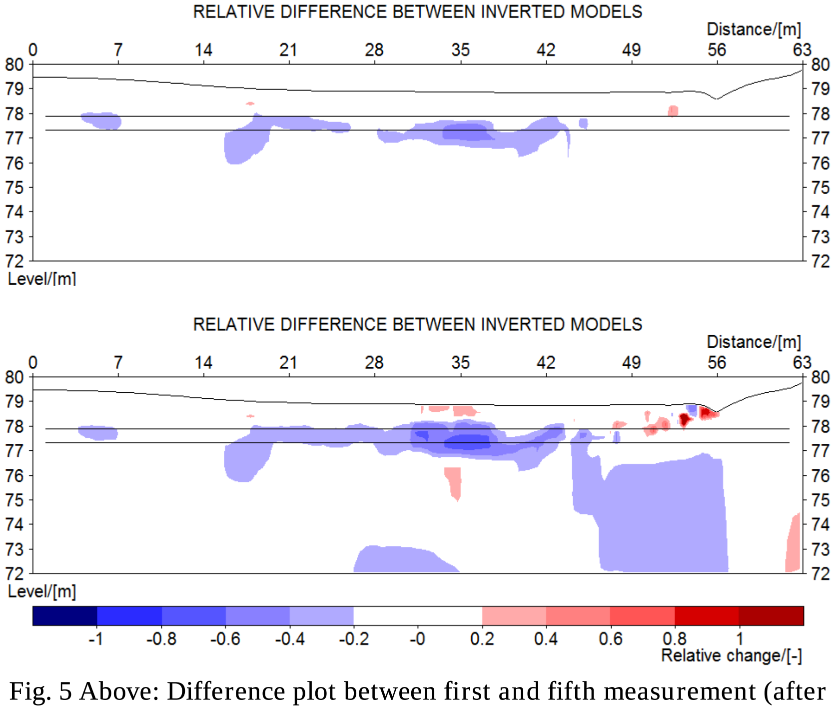

Fig. 5 Above: Difference plot between first and fifth measurement (after approx. 2 hours). Below: Difference plot between first and last measurement (after 21 hours). Marked lines show reservoir level at first and actual measurement.

Almost immediately after raising the reservoir the resistivity started to decrease along the dam at El. 77.34-77.89 m. The difference at this level, corresponding to the raise in reservoir level between the two measurements, is definitely the most apparent. This resistivity decrease corresponds well with the anticipated change in resistivity due to wetting of the soil and may be related to seepage. At this elevation the most prominent zone with decreasing resistivity is found with the centre at distance 35 m. By analysing the differences from all measurements one after another, the wetting process can be followed. A quick response is noticed at distances 5-6 m, 15-20 m and 30-40 m. The resistivity continued to decrease throughout the monitoring period in the area at distance 35, while in other areas the decrease stagnated.

The resistivity decrease in the presumed bedrock is probably caused by 3D effects, or inversion artefacts. In a few small areas a resistivity increase was noted. It might be due to drying out of shallow soil that was wetted by the intense rain that occurred in the days before the measurements started, as these areas were all situated outside the asphalt that protected most of the line from being wetted by the rain. Other possible explanations are noise or inversion artefacts in connection with the high contrast zones.

4. Conclusions

Repeated resistivity measurements in combination with changing of reservoir levels increases the amount of information achieved from the measurements and thereby makes the method more powerful.

Reference measurements were taken when the reservoir level was low and subsequent measurements after the water level was raised. The data sets from the repeated measurements were processed and evaluated jointly using time-lapse inversion.

The most obvious changes in resistivity were observed at the level corresponding to the reservoir increase. The resistivity of the soil decreases with increasing saturation, which enables an analysis of the seepage through the dam at this level. The most prominent zone with decreasing resistivity was found with the centre at distance 35 m. This zone has been interpreted as a preferential seepage path. The interpretation has not been possible to confirm yet, due to lack of reference data since no other type of investigation has been carried out. However, during a possible future repair of the dam this interpretation may be evaluated.

No clear indication of seepage was found on deeper levels.

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