Embankment dam seepage assessment by resistivity monitoring

Dahlin, Torleif; Sjödahl, Pontus; Johansson, Sam

2008

B13

Embankment Dam Seepage Evaluation from Resistivity Monitoring Data

T. Dahlin* (Lund University), P. Sjödahl (HydroResearch) & S. Johansson (HydroResearch)

SUMMARY

Methods for monitoring seepage are important for dam safety of embankment dams. Increased seepage may be associated with internal erosion in the dam, and internal erosion is one of the main reasons for dam failures. Internal erosion progresses inside the dam, and is difficult to detect by conventional methods. Therefore, there is a need for new or improved methods. The resistivity method is a non-destructive method that may accomplish this task. A method for evaluating the seepage from resistivity monitoring data is theoretically described and tested for four selected areas in the foundation of the Sädva dam. Seasonal resistivity variations are apparent in the reservoir as well as inside the dam. The four selected areas represent areas with low, via intermediate to high variations in the seasonal resistivity variation. The areas are compared qualitatively and thereby permeable zones within the dam may be identified. Quantitative assessment of the seepage flow is also carried out as an initial test of the described method. It is concluded that the experiences from the Sädva dam are valuable for the application of the resistivity method on embankment dams. The presented method is a promising first step for quantitative assessment of seepage.

Introduction

A main safety concern for embankment dams is to understand the seepage situation through the dam. Methods for monitoring the seepage and for detecting internal erosion give essential information for the safety evaluation of earth embankment dams. Together with overtopping, internal erosion through the dam or the foundation is the most frequent reason for embankment dam failures (ICOLD 1995; Foster et al. 2000). While overtopping scenarios might be difficult to predict, they are straightforward to understand and design monitoring systems for. An efficient monitoring system for internal erosion, on the other hand, is a far more complicated task to achieve.

Long-term resistivity monitoring is an unconventional method for dam monitoring that may have the potential to detect anomalous seepage through embankment dams. The method is non-intrusive, which is a major advantage for use on existing dams. Leakage detection and structural status control of existing dams using the resistivity method have been tried on many occasions. A more powerful approach of using the method is to carry out repeated measurements or long-term monitoring. This approach of evaluating resistivity monitoring data is based on its time variation. Deviations from the established normal background are taken to indicate anomalous conditions in the dam.

In this paper an approximate method of estimating seepage from such long-term monitoring resistivity data is presented. The method is based on a number of simplified evaluation concepts (Johansson 1997), and was originally tested on occasional repeated measurements from another Swedish dam (Johansson and Dahlin 1996). Excellent data quality from the resistivity monitoring of the Sädva dam now allows for a valuable test of this first approach on a dam with continuous long-term monitoring data. Identified inhomogeneities in the resistivity distribution along the Sädva dam is used as an example. Sädva was the second embankment dam to get a permanently installed resistivity monitoring system and daily measurements started in 2001.

Seepage induced resistivity variations in dams

All dams in their natural state experience some degree of seepage flow entering from the reservoir. The properties of the reservoir water will thus affect the inner part of the dam. Temperature and ion content (measured as Total Dissolved Solids, TDS) are two characteristics of the seepage water that vary seasonally in the reservoir. The seasonal variations in temperature and TDS in the reservoir water propagate with the seepage water and cause a time dependant resistivity variation inside the dam. As the resistivity of the soil is affected by temperature and ion content, the signature of the seepage water may be observed in the inner part of the dam by repeated resistivity measurements. Resistivity variation in the reservoir that is not caused by temperature variations is assumed to originate from variations in TDS. The seasonal variation of the absolute resistivity in the reservoir water is separated into two parts when the seepage water passes through the dam. The solutes penetrate into the dam with the pore velocity v_n, while the temperature travels with the thermal velocity v_T (Figure 1). The resistivity variation in the dam is therefore a combined result of these two transport processes.

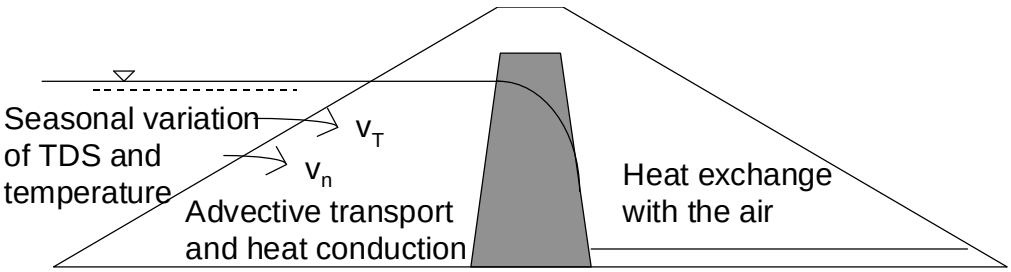

Figure 1. Cross-section of an embankment dam showing the important transport processes that affect the resistivity variation.

Site description

The Sädva dam is located in the upper part of the Skellefteälven River just south of the Arctic Circle. It has a reservoir storage volume of 625 million m^3. The dam and power plant was put into operation in 1985. The total length of the dam is 620 m, which is divided in a 210 m long main dam across the old river channel and a 410 m long dyke along the old river channel (Figure 2). The maximum height of the main dam is 32 m, but considerably lower for the dyke averaging around 10 m. The main dam is a rock fill embankment dam with a slightly inclined central core made of fine-grained glacial till. Annual water level variations are around 16 m (+460.7 - +477.0 m.a.s.l.), which is half the height of the dam. The high variations constitute a complication in the evaluation of the measurements, but at least the seasonal pattern is roughly the same from one year to another. The reservoir reaches top levels in autumn and is lowered over the winter to the lowest levels only to be filled up again over early summer with the vast snowmelt. The main dam is founded on bedrock, while the dyke is founded on moraine except where it connects to the main dam.

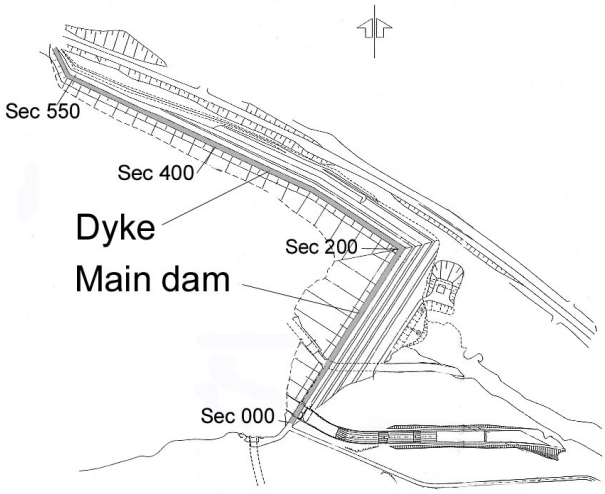

Figure 2. Plan over Sädva dam. The 210 m long main dam is crossing the river channel and the 410 m long dyke extend along one side of the river channel.

Resistivity measurements

Stainless steel electrodes (0.25 m x 0.25 m plates) with 6 metres spacing are used for the resistivity measurements, and in addition non-polarisable electrodes in between the steel electrodes are used for potential measurements on the main dam. Data acquisition is done with a version of the ABEM Lund Imaging System that is adapted for monitoring, which does fully automated measuring on a daily basis. Inversion of time filtered apparent resistivity data was done using the software Res2dinv version 3.54r (Loke 2004), using the robust (L_1-norm) optimisation method in combination with time-lapse inversion for the repeated data sets. Statistical paaremters were calculated from the inverted models.

Results and discussion

Monitoring data from Sädva dyke over the period from 2001-09-20 to 2005-11-25 is presented here (Figure 3). This whole evaluation period was divided in 7-day periods and one inverted model was created for each such 7-day period. The upper part of Figure 3 is the median of those models and represents an overview of the spatial resistivity distribution. Anomalous zones are of interest, and not much attention is paid to absolute values in the interpretation of data. This is because distortions from 3D effects caused by the embankment dam geometry are introduced in the inversion step, which makes absolute resistivity values and depth location somewhat unreliable. These effects have been demonstrated through numerical modelling (Sjödahl et al. 2006), but even so the 2D approach remains the most

practical option for handling large sets of data from long monitoring periods. The lower part of Figure 3 represents the relative variation, calculated as $(\rho_{max} - \rho_{min}) / \rho_{median}$, of the 7-day data sets. This is a very rough statistical measure, but serves reasonably well as a tool for indication of zones with high amplitudes in the seasonal resistivity pattern, which is the main interest.

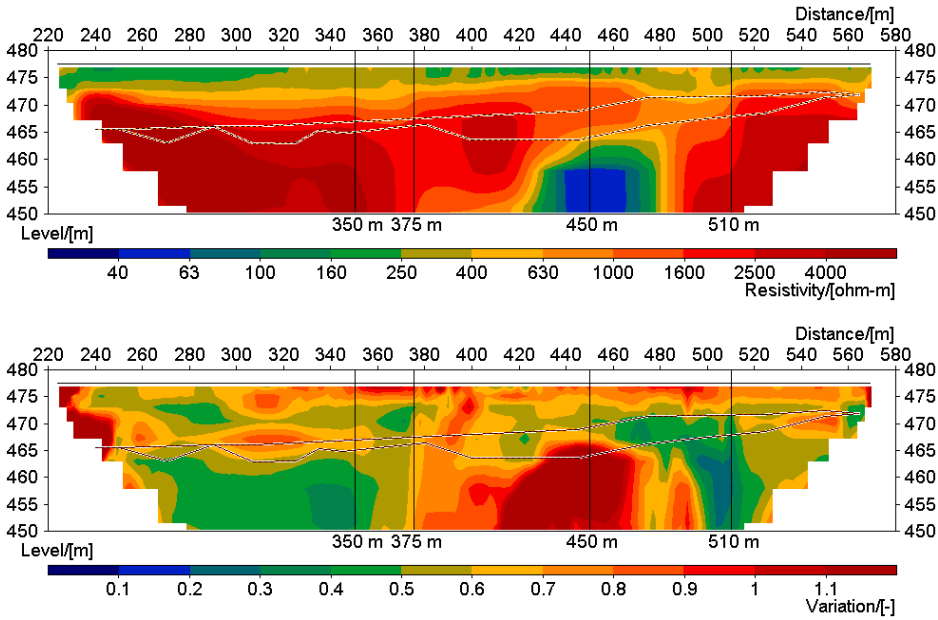

Figure 3. Sädva dyke model sections with foundation and bedrock level indicated (solid lines). Medium inverted model of resistivity distribution (top) and relative variation of inverted resistivity models (bottom), over the period from 2001-09-20 to 2005-11-25.

More detailed investigations of the variations in selected areas can be performed by studying the resistivity over time in specific parts of the dam. Four different zones were selected for seepage evaluation. These are all situated on the same depths but on different distances along the dam. The chainages at 350 m, 375 m, 450 m and 510 m, also marked out in Figure 3, were selected for testing of the seepage evaluation methods (Figure 4). The obvious seasonal variation is a consequence of the changing water level and seepage-induced variations due to the resistivity variation of the reservoir water. The variation in the selected zones is around 10-30%, with the exception of the zone in chainage 450 m, where the variation is approximately 75%. This is an indication of higher seepage in this area.

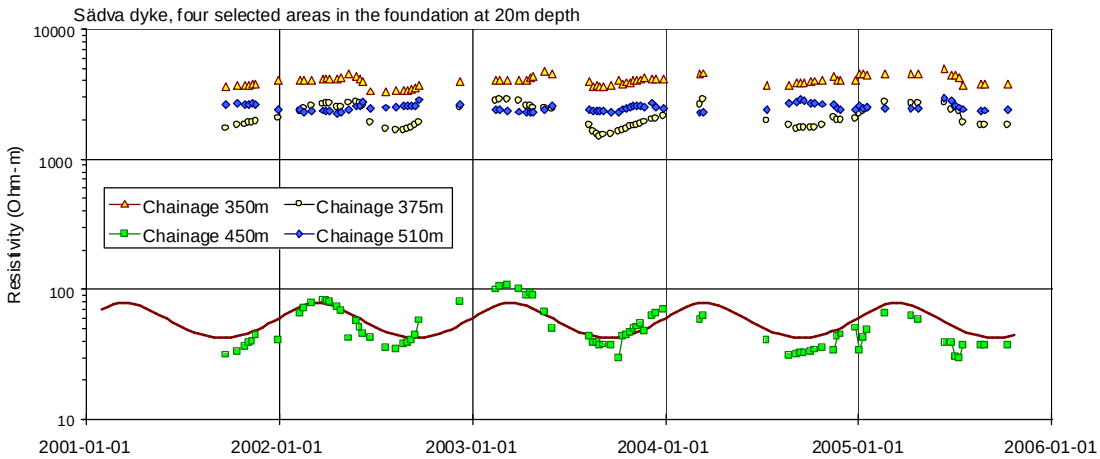

Figure 4. Four selected areas for seepage evaluation. All areas from depth 20 m, corresponding to 458 m.a.s..l The line represents an approximate method to quantify the seepage by fitting a calculated response from an assumed seepage flow rate of 3.0×10^{-5} $m^3/(s,m)$.

Comparing different areas along the embankment identifies the most sensitive areas. Such areas can then be given extra attention in the further monitoring. However, a quantitative evaluation approach can also be tested for the area around chainage 450 m. It is based on the assumption that the variation is solely dependant on the temperature. The resistivity response caused by a temperature variation in the same range as the observed variation in the reservoir, at an assumed seepage flow rate of 3.0x10-5 m^3/(s,m), is plotted and fitted to the measured resistivity data (Figure 4). A total seepage flow in the order of one litre per second was thus estimated for the whole area around chainage 450 m. This is reasonable, but at this stage, considering the amount of simplifications and assumptions in the quantitative evaluation method, it must be seen as an initial test. More work is needed to refine the method. However, in principle there are few or no reliable methods capable of quantifying the seepage flow along embankment dams, and a result merely in the right order of magnitude is valuable for dam safety purposes.

Conclusions

The resistivity monitoring system at Sädva dam is operating since 2001. The resistivity variations in the dam are mostly smooth and stable which indicates that the dam is performing well. Nevertheless, significant differences in resistivity and in the characteristics of the resistivity variation are found when comparing different locations along the dam. Comparably larger variations are present in the foundation at chainage 450 m, which is indicating the presence of a possible seepage path in the foundation.

Qualitative assessments of the seepage situation in the dam can be carried out by comparing different areas in the dam. This is a useful method for detecting weaker zones along the dam. An approach has been developed to quantify the seepage from resistivity monitoring data. Ongoing work is in progress of trying to improve the initial method of quantifying the seepage, as well as extending the evaluation period with the new data from 2006 and forward.

There are no indications from these observations that question the overall safety of the Sädva embankment dam. However, the zones with high resistivity variations will be kept under special observation in the future.

Acknowledgements

The work presented here was carried out with funding from Elforsk, Svenska Kraftnät and Dam Safety Interest Group (DSIG). Skellefteälvens Vattenregleringsföretag AB, who is the owner of Sädva dam, has given additional funding and valuable support.

References

Foster M, Fell R, Spannagle M (2000) The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal* 37: 1000-1024

ICOLD (1995) *Dam failures statistical analysis*. International Commission on Large Dams (ICOLD), Bulletin 99

Johansson S, Dahlin T (1996) Seepage monitoring in an earth embankment dam by repeated resistivity measurements. *European Journal of Engineering and Environmental Geophysics* 1(3): 229-247

Johansson S (1997) *Seepage monitoring in embankment dams*. Doctoral Thesis, TRITA-AMI PHD 1014, ISBN 91-7170-792-1, Royal Institute of Technology, Stockholm, p 49

Loke MH (2004) *Rapid 2-D resistivity & IP inversion using the least-squares method*, Manual for Res2dinv, version 3.54 (www.geoelectrical.com), p 53

Sjödahl P, Zhou B, Dahlin T (2006) 2.5D Resistivity Modeling of Embankment Dams to Assess Influence from Geometry and Material Properties. *Geophysics* 71: 107-114

Sjödahl P, Dahlin T, Johansson S (2008) Resistivity monitoring for leakage and internal erosion detection at Hällby embankment dam. Submitted to *Journal of Applied Geophysics*.