POST FLOODING DAMAGE ASSESSMENT OF EARTH DAMS AND HISTORICAL RESERVOIRS USING NON-INVASIVE GEOPHYSICAL TECHNIQUES.

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KEY WORDS: Electrical Resistivity Tomography, Electromagnic profile, Self Potential, Gravimetry, Reservoirs, Embankments.

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Highlights

- Combined Electrical Resistivity Tomography (ERT) with electromagnetic self-potential and microgravimetry to assess reservoir dam integrity
- Validation of Geophysical techniques for detecting damages and seepage in reservoir embankments
- Time lapse Resistivity subtraction changes in the embankment soil matrix between 2010 and 2013
- Discussion on the effect of pre and post flood conditions on soil resistivity

Abstract

This paper describes the use of four geophysical techniques to map the structural integrity of historical earth reservoir embankments which are susceptible to natural decay with time.

The four techniques that were used to assess the post flood damage were 1. A fast scanning technique using a dipole electromagnetic profile apparatus (GEM2), 2. Electrical Resistivity Tomography (ERT) in order to obtain a high resolution image of the shape of the damaged/seepage zone, 3. Self-Potential surveys were carried out to relate the detected seepage evolution and change of the water displacement inside the embankment, 4. The washed zone in the areas with piping was characterised with microgravimetry.

The four geophysical techniques used were evaluated against the case studies of two reservoirs in South Bohemia, Czech Republic. A risk approach based on the Geophysical results was undertaken for the reservoir embankments. The four techniques together enabled a comprehensive non-invasive assessment whereby remedial action could be recommended where required. Conclusions were also drawn on the efficiency of the techniques to be applied for embankments with wood structures.

Keywords: Slingram; Electrical Resistivity Tomography; Geophysics; Microgravimetry; Seepage; Piping; Earth Dam; Reservoirs

1. Introduction

Currently only visual inspections are routinely performed to appraise earth flood embankments condition. Defects however can be masked by the presence of vegetation and seasonal variations, moisture can reduce fissures or erosion that were apparent. Previous studies into embankments condition have required the use of trenching in order to compare surface anomalies with those in the subsurface. Cooling and Marsland (1954) dug trenches into various embankments following the 1953 flooding in order to examine the effect of fissuring on the soil in breached flood embankments. Dyer et al (2009) conducted trenching to a depth of 1.5 m in order to observe the extent of desiccation fissuring.

Trenching is a work intensive, time consuming process and destructive to the embankment structure, there is also a high risk that the trench does not reveal the full extent of the damage or misses it completely. Geophysical techniques such as Electrical Resistivity Tomography (ERT) and Electromagnetic scanning have been suggested as non-invasive methods for examining internal embankment conditions (Jones 2014, Castellanza 2014, Sentenac 2013, Zielinski 2010). These are among other Geophysical techniques used to scan embankments. Hadley (1983) used common offset seismic refraction technique to scan a dam axis and toe. The anomalous areas were then targeted for drilling. The technique was successfully applied to about 15 dams in the USA.

Modern geophysical surveys often require the use of two or more complimentary techniques in order to verify the locations of anomalies (Nguyen 2005, McDowell 2002, Reynolds 1997). Sjödahl et al. (2006) investigated an embankment in southern Sweden by taking temperature, ERT, induced polarization (IP) and self-potential (SP) measurements together with standard visual inspections and piezometer readings.

They found that ERT was a good non-destructive technique, which gave the possibility of detecting internal erosion processes and anomalous seepage at an early stage before the stability of the dam was compromised.

Chao et al. (2006) combined seismic and electric resistivity to locate potential seepage locations in an embankment along the Yangtze River, in China. They used S-wave velocity for their seismic profiles to identify anomalies and used the resistivity profiles to study the moisture content inside the selected embankment. An anomaly detected in a section of the embankment was verified as a previous location of piping during flooding in 1998.

More recently Cho and Yeom (2007) used ERT to find out anomalous seepage pathways in an embankment dam in Korea. Two seepage pathways with low resistivity zones were identified using a dipole-dipole resistivity section obtained from a line survey along the crest of the dam. One pathway was confirmed by visual inspection of the dam, and afterward, by trenching.

Benes et al. (2011) used the repeated geoelectrical measurement (SLINGRAM, ERT, SP) during the dry season and flood event for more precise interpretation of seepages through embankment and dams.

Di Prinzio et al (2010) preferred the use of Ground Penetrating Radar (GPR) for the monitoring of river embankments. Since air-filled voids provided an excellent dielectric constant contrast, GPR revealed to be suitable for identifying animal burrows in earthen embankments and levees. The GPR technique is an extensive investigation method that enables one to rapidly cover a wide area, locating voids and it is easy to use with the possibility to inspect the collected data in real-time. Nevertheless GPR analysis needs expertise and modeling skills and the embankments material is also very important. Clay for instance is more difficult to characterize. Mydlikovski et al (2007) also used high frequency electromagnetic methods: GPR or measurements of mutual impedance. The depth of penetration of electromagnetic waves was small due to the fact that, in this medium electromagnetic

waves are strongly attenuated. As the structural weaknesses of levee caused by high level of ground water are characterized by high level of electrical permittivity and low resistivity, they also used Electrical resistivity Tomography (ERT) to increase the accuracy of inhomogeneity detection.

It is more and more frequent to see in the literature reviews and evaluations of Geophysical techniques. For example Niederleithinger et al (2012) evaluated resistivity, electromagnetic, seismic and GPR techniques at a test site along the Mulde River in eastern Germany, giving advantages and inconvenient of the techniques reviewed.

Although the four techniques used in this study have been used previously and are described in the literature, it is unusual for more than two techniques to be combined therefore this is the first study that brings together these four techniques for a comprehensive non-invasive post flood damage assessment of historical embankments. An examination of the literature discussing Geophysical techniques applied to surveying flood embankments have shown the use of ERT to be common, due in part to the suitability of the construction materials (normally compacted, fine grained soils) and its sensitivity to changes in moisture as well as its ability to detect discontinuities in the material.

The potential of two conventional Electrical and Electromagnetic methods with microgravimetry coarse resolution investigation was assessed against two reservoirs in South Bohemia (Czeque Republic). The electromagnetic survey (EM) was used to cross check and validate resistivity values and to evaluate quickly possible areas of high fluctuations in conductivity that may be an indication of structural defect or piping. The microgravimetry was used for the detection of material transport in the zone of piping. The interpretation of geophysical measurement was made more accurate by comparing measurement carried out at the same locations in 2010 (under normal condition) and in 2013 (after flooding).

The embankments surveyed were located in South Bohemia, Czech Republic. These dams are historical and were built during the second half of the 16th century. Table 1 summarizes each Geophysical technique, and how they can help for a non intrusive ground investigation prior to trenching and drilling boreholes in the dams.

Table 1. Geophysical techniques used and applications relevance

Highly applicable / Partly applicable	Stratigraphy	Voids/cavities	Ground Water	Seepage	Mine Workings	Contamination/ Utilities	Services/ Utilities	Foundations/ obstruction
ERT								
Electromagnetics								
Microgravimetry								
Self Potential								

2. Methodology

Four complementary geophysical techniques were used to scan the embankments following the same methodology and procedure.

2.1 Electromagnetic Surveying

The first technique used was the Electromagnetic Slingram profiling which is based on the measurement of induction of the primary electromagnetic field of the transmitting coil in the surrounding investigated medium. The primary field induces a secondary field whose intensity depends on the conductivity (resistivity) of the medium surrounding the transmitting coil. The depth to obtain the information on the conductivity of the medium depends on the frequency of the primary electromagnetic

field or on the length of the transmitter coils. High frequencies reach lower depth penetration than low frequencies. The sensor GEM2 (GEOPHEX USA) operating as broadband digital multi-frequency electromagnetic device was used at 4 frequencies. These frequencies were selected as the most appropriate, based on the analysis of electromagnetic noise at the site. The respective frequencies were 6525 Hz, 13025 Hz, 27025 Hz and 47025 Hz. These frequencies represented approximate depth penetrations of 6 m, 4 m, 2 m and 1 m. The measurements were conducted with stacking of 5 (i.e. the average of 5 consecutive measurements was stored in the memory). They were carried out “continually” at a walking pace. The results density was approximately 3 to 4 scans per 1 m of profile. The device was connected to GPS navigation, hence recording the measurement positions automatically. The measured data were analysed with the programme DIKINS_analyzer (MEASProg – Czech Republic).

The Electromagnetic method (EM) provides significant advantages for shallow environmental characterization. Unlike seismic or ground-penetrating radar methods that involve heavy logistics and labour-intensive field work, GEM-2 requires only a single operator, is contactless with the ground (thus, is less intrusive), and can operate at stand-off distance. The relative high-frequency signal can travel only a short distance and thus, "sees" only shallow structures. Therefore, scanning through a frequency window is equivalent to depth sounding and is particularly interesting for flood or reservoir embankments.

2.2 Resistivity Surveying

Electrical resistivity tomography (ERT) is a well-established geophysical technique that is commonly applied at the ground surface and has particular promise in complementing conventional methods of site investigation towards spatially improved

characterisation of subsurface water, soil layers and pollutant transports (as reviewed e.g. in Slater, 2007). Aside from delivering improved spatial information, in-situ ERT surveys are also rapid and cost-effective compared to traditional methods of access-hole sampling and analysis.

The resistivity arrays technique is routinely used to map ground water and contaminated flows, it is also regularly used to located buried artefacts or structures. ERT performs particularly well in soils media consisting of clay or silty soils due to the excellent contact between electrodes and the soil, and the high concentration of charged particles that facilitate electrolytic conduction through the soil. Modern resistivity surveys involve the use of computer controlled multi-electrode arrays in order to efficiently obtain resistivity measurements over the surveyed section. The inversion of this data with software like Res2dinv or Res3dinv gives a tomography contour model of the subsurface in two or three dimensions (Griffiths and Barker, 1993).

The principle of the method is based on the measurement of the soil resistivity, using a large number of electrodes placed along the profile or in the area. The electrodes are interconnected by a special cable that enables to connect the electrodes as current ones and potential ones step by step. This allows performing the measurement for a large number of variants of a 4-electrodes array with differing geometry and penetration depth. The measurement proceeds automatically, everything is PC-controlled. For the resistivity tomography measurements, the device ARES (GF Instruments, Czech Republic) was used. The distance between the electrodes was 2.5 m on longitudinal profiles of the embankments and 1 m on the perpendicular profiles. 2D resistivity sections were compiled using the programme Res2Dinv (GEOTOMO Software - Malaysia). A Schlumberger electrode arrays configuration was chosen for the ERT measurements. The results were collected using the 3rd iteration of least squares method.

2.3 Self-Potential method

The SP method measures the natural electrical potential of soils and rocks. In dam surveying, the filtration potential produced by water through a porous medium can often be detected. The principle of this phenomenon consists in unequal mobility of anions and cations transferred by the liquid medium through the porous material. This inequality generates measureable negative potential at the point of infiltration and positive potential at the point of outflow. When interpreting SP potentials, it is necessary to distinguish a natural filter electric field from interfering fields caused by the natural electrochemical process or artificial fields (for example near railways, cables and tubes). The outcomes of the measurement using the SP method are profile curves – graphs of electric potentials. Based on their analysis, the locations of potential seepage paths through the levee can be identified. To assess the presence of seepage, it is convenient to take measurements on the land side during dry season (decreased water level in the reservoir) and during the flood (maximal water level in the reservoir). The method is suitable also for repeated – monitoring measurements aiming to monitor long-term changes in the seepage regime of the levee and its underlying layers. The measurements were performed with the device GEOTOR I (Czech Republic), using the non-polarized electrodes with spacing of 2,5 or 5 m.

2.4 Microgravimetry

Gravimetric method is sensitive to the changes of bulk densities of the medium at the point of measurement. This allows assessing places in the dams disturbed by water seepage or piping with transport of fine soil material. Cavities are most often caused by sediments washing out along zone of piping or seepage. On the ground surface there is a risk of occurrence of progressive deformations or sudden collapses. For

the measurement, a gravimeter SCINTREX CG5 was used. The step of measurement was 2 or 4 m.

All the gravimetric data were corrected. They were processed to the values of relative Bouguer anomaly without topographic correction. Therefore, the dam and the profile position were symmetrical, there were no hills and we were only interested in shallow local anomalies.

A 2,5D density modelling software called MAG with Talwani formula was used. The software was evaluated by Geofyzika Brno s.p. Differential densities were used, meaning that the normal mass had density "0" and local gravity anomalies presented some +/- differential densities.

The regional trend of Bouguer anomaly, which corresponds to deeper geological structures and effect of relief, was calculated on the basis of polynomial regression of the measured profile data. The difference between the measured data and their regional trend corresponded to the residual Bouguer anomaly. This anomaly represented the gravitational effect of shallow deposited dense inhomogeneities. In our case, it described best the position of the washed zone in the dams. The residual Bouguer anomaly was used for the modelisation of the density model.

3. Surveys Results

The geophysical survey of the Velky Hroch reservoir in South Bohemia (Czech Republic) was made in 2 stages: In October 2010 it was part of the of the project no. 60023529 – Norway grants, and in June 2013 it was part of the current project no. 324426 – MAGIC FP7 – PEOPLE. The aim of the first stage was the characterization of material homogeneities and the detection of possible weak zones of the embankment.

A site map indicating the location of all geophysical surveys is presented in Figure 1.

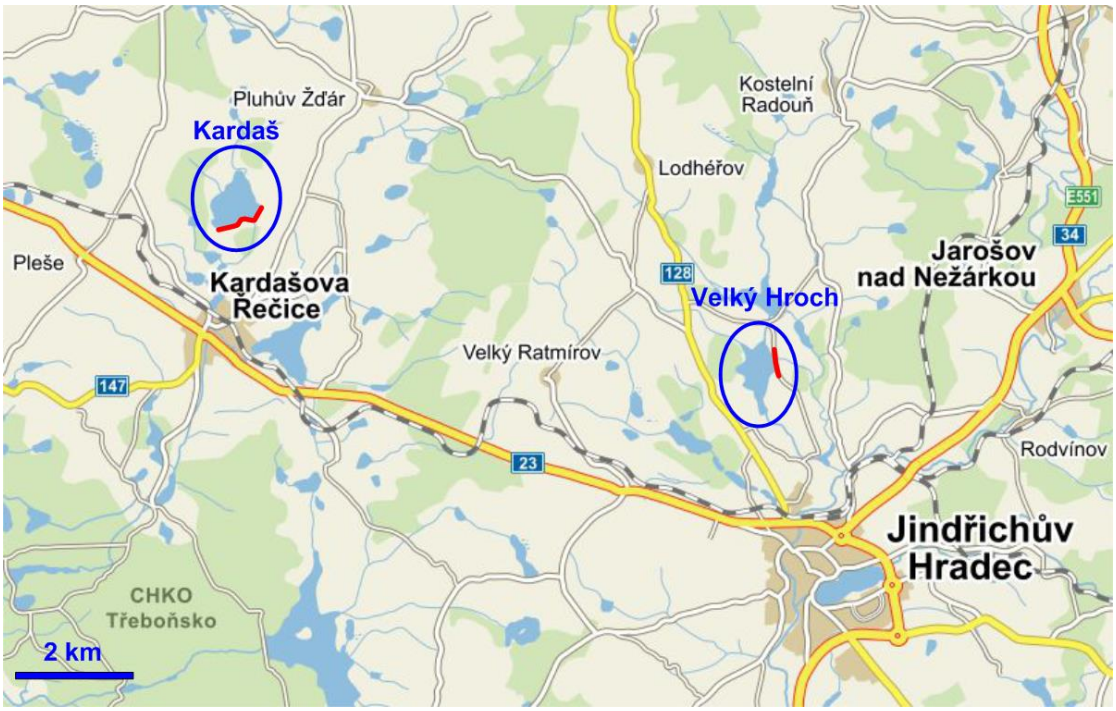


Figure 1. South Bohemian ponds and location of all geophysical surveys as red lines.

The Velky Hroch dam was built from material with resistivity ranging from 200 to 300 ohm/m (as seen on resistivity curves of Slingram on Figure 3). It is typical for sandy clay with higher permeability. The dam dimensions are: lenght app 300 m, max. elevation app. 7,5 m, slope 1:1,5 to 1:2. The local materials used for the construction at that time were mainly sand and sandy clay. Oak trees were used to improve the

stability of the land side slopes. The original outlet was also made from oak wood. Total replacement was cost prohibitive therefore identification of damage and repair was the current choice. The Meadow sediment is mainly silty sand and gravel, clayish sand and gravel with a thickness or approximately 1-3 m. The Bedrock is made of paragneiss or mignatitc. A Geological map is presented on Figure2.

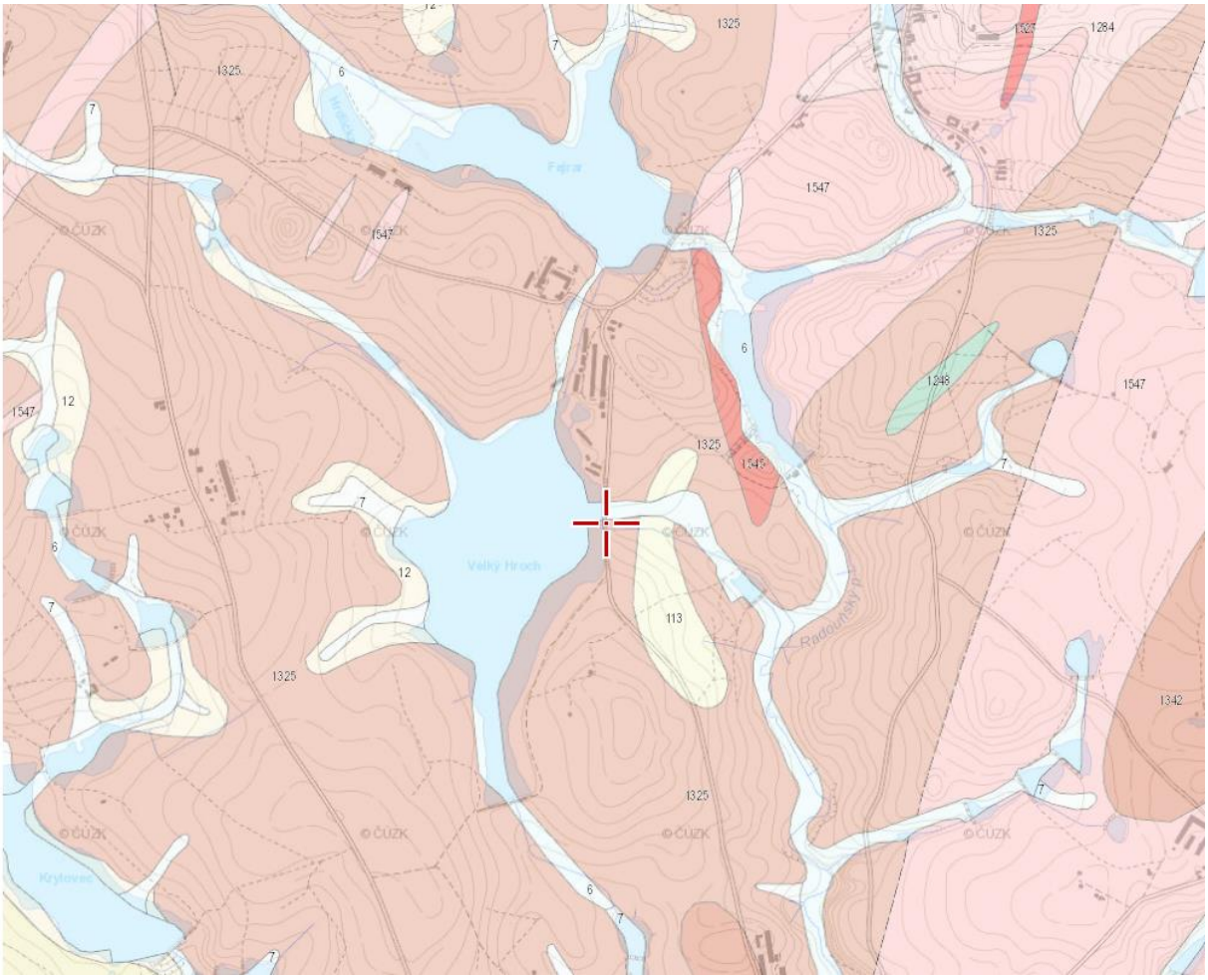


Figure 2. Geological map of the Vely Hroch pond. (6: loam, sand, gravel, 12: = clayish sand, gravel, 1325: paragneiss, migmatite, 113: sandstone, claystone

Electromagnetic survey:

Some local decrease of resistivity on the profile near the dam toe was interpreted as local seepages.

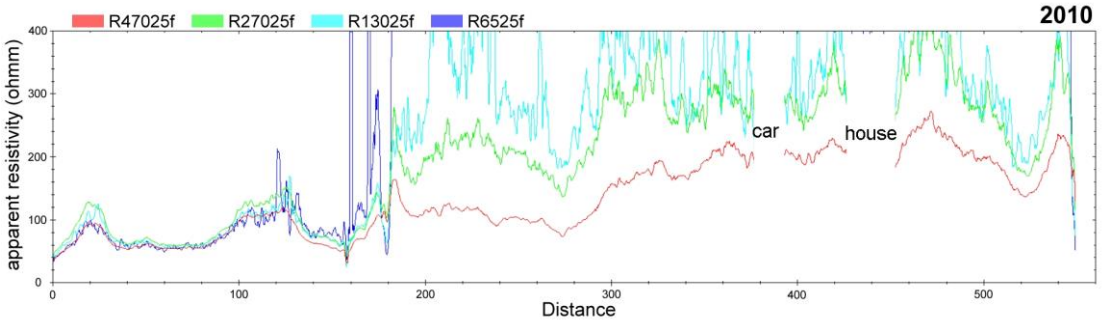


Figure 3. Graphs of apparent resistivity by Slingram method (GEM-2 sensor). Longitudinal Profile in the dam axis, repeated measurement for 2010

The most concerning anomaly was detected by microgravimetry above the outlet wood pipe (see Figure 4). The local minimum of residual Bouguer anomaly was interpreted like a disturbed zone characterised by the washing effect of the water and the assessment of cavities near the outlet pipe due to piping process.

The embankment section was therefore categorized with a high risk of breach. This interpretation was verified during the flood in June 2013 when the collapse of a cavity occurred on the land side slope of the dam (see corresponding picture in Figure 4).

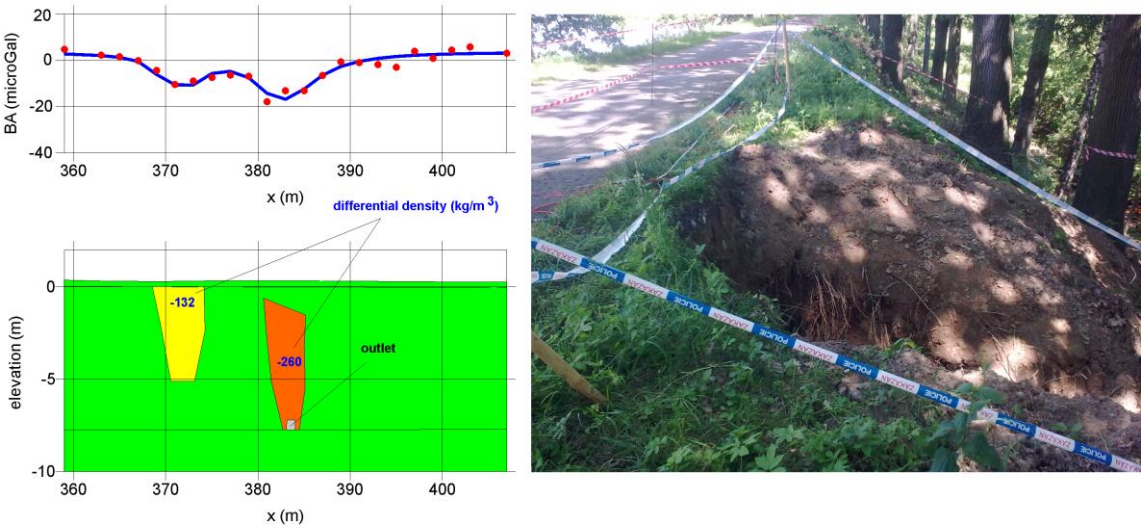


Figure 4. Density model by microgravimetric measurement. Profile above the outlet, detection of piping with cavity in 2010.

The second stage of the geophysical survey was arranged after flooding in June 2013 to see the changes of water saturation in the dam body. The repeated Slingram measurement is presented in Figure 5 for 2013. There is a good agreement between the initial and repeated measurements. A decrease in resistivity was observed on the deviations chart resistivity curves mainly in the central part of the dam near the outlet (symbol SV in the middle graph).

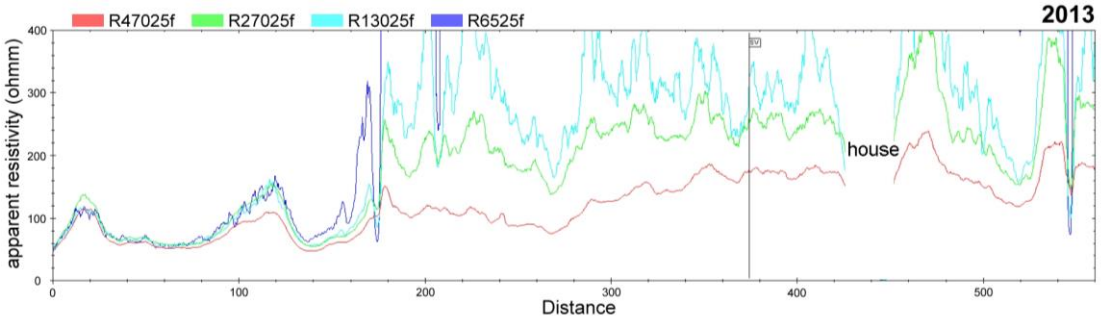


Figure 5. Graphs of apparent resistivity by Slingram method (GEM-2 sensor). Longitudinal Profile in the dam axis, repeated measurement for 2013

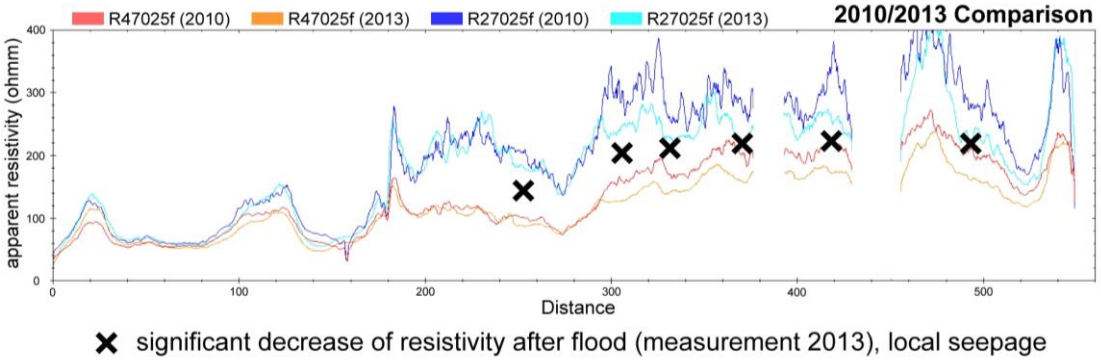


Figure 6. Comparison of apparent resistivity between 2010 and 2013 by Slingram method (GEM-2 sensor). Longitudinal Profile in the dam axis

The significant anomalies detected on Figure 6 are represented by small crosses and they are interpreted as a manifestation of preferential seepage that occurred during floods in 2013. The decrease in resistivity here reached 20% of the baseline values. In other parts of the dam, residual deviations in resistivity generally decreased by

10% of measured values. This can be explained by the effect of higher water saturation after the flood.

Self Potential (SP) survey:

The seepage detection was checked with SP measurement too. SP curves are presented on Figure 7 from the profile near the dam toe on the land side. They were interpreted as two zones of local decrease of SP potential after the 2013 flood. Both zones are in good correlation with the anomalies detected with the Slingram method.

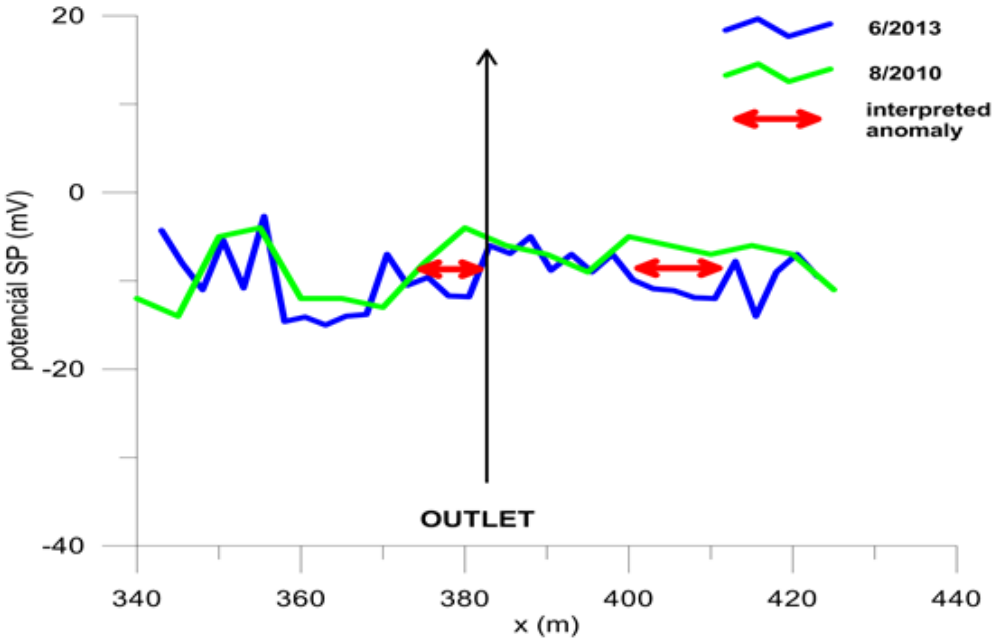


Figure 7. Comparative graphs of SP potential between 2010 and 2013. Profiles at the dam toe, land side (seepage detection).

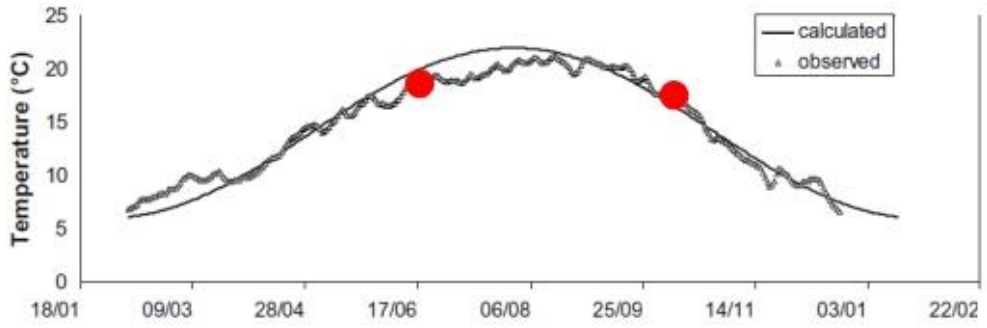
Electrical Resistivity Tomography (ERT) survey

Velky Hroch pond:

Repeated ERT measurements were carried out for a better description of the changes in the dam body near the outlet after the 2013 flood and compared with the 2010 surveys.

It was assumed that during late spring and early autumn the weather condition was similar with an air temperature around 20°C. The temperature in the soil at a depth of

more than 1 m during the year changed very smoothly with a long delay (approximately 1 month) similarly to the plot showed in Figure 8 for another survey exhibiting the same temperature trend line. Therefore it was accepted that the temperatures changes in the dam body could be neglected and there was no need for temperature correction in the resistivity data.



Example of measured and calculated temperatures at 65 cm depth ($R^2 = 0.96$).

time of stages geophysical survey (10/2010, 6/2013)

Brunet et al. 2008: Monitoring soil water content and deficit using Electrical Resistivity Tomography (ERT). A case study in the Cevennes area, France. Journal of Hydrology 380 (2010) 146–153.

Figure 8: Temperature effect on resistivity, related to similar seasonal effect.

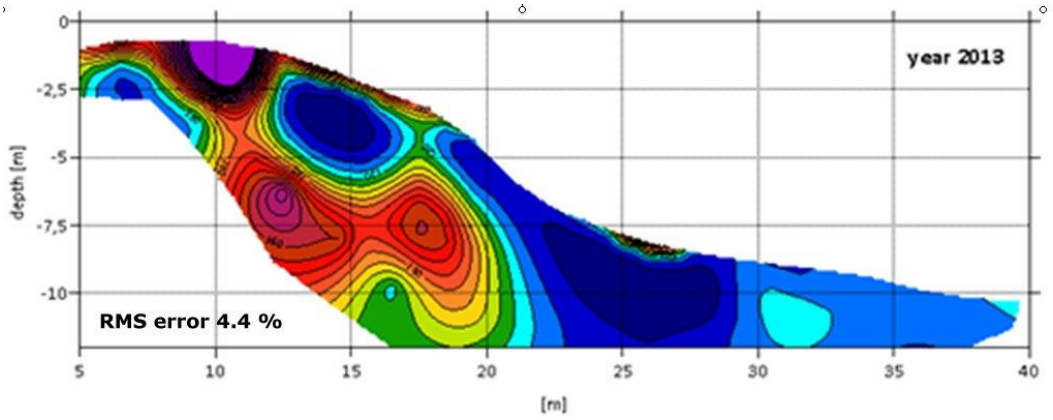
The Schlumberger array configuration was chosen for the ERT survey as it is the more adequate for the study of geological conditions with mostly horizontal layers. Earth embankments are generally constructed by horizontal layers and the boundary of the dam body with bedrock is mostly horizontal too.

The position of electrodes was very close during both stages. There were some geodetic points on the dam to help the layout using the measuring tape. The position of the profile was 5 m to the side of the outlet and 2 m away from the collapse boundary at the surface. It has to be noted that it was possible to compare structures at depth down to 5 m very well if the electrodes position error is less than a 1 m.

A L2-norm approach (Standard method) was used. It was assumed that the L1-norm approach (Robust method) is better for noisy area and for a geological body with sharp boundary and a much contrasted resistivity.

The 3rd iteration used for the inversion offered the best description of normal and smooth geological conditions based also on the development of the RMS Error. Usually 5 iterations were carried out. If the difference of RMS Error between 3 and 4 iteration w similar and the value of RMS Error for 3rd iteration is less than 8%, it is assumed that the model for the 3rd iteration is the closest to real conditions. Using higher iterations with higher resistivity contrast and shifting the resistivity boundaries near surface can reduce RMS error but it very often a mathematic effect only.

The tomographic subtraction between 2010 and 2013 (Figure 9) revealed some embankment resistivity changes over time. In general, the ERT results showed also good agreement between the initial and repeated measurements. The increase in resistivity located near the surface could be explained by the drying process of the dam top soil during hot summer time. The collapse of part of the embankment is shown as a large increase in resistivity (general signature of a cavity). The dam body around the large increased anomaly presented lower resistivity in year 2013. It could be explained as the effect of higher water saturation after the flood period. An area of decreased resistivity in the dam body is clearly visible on the 2010 scan, which is in good correlation with the curve of the surface water. The “spot” of low resistivity at the surface near the position 30 show the seepage above the outlet pipe.



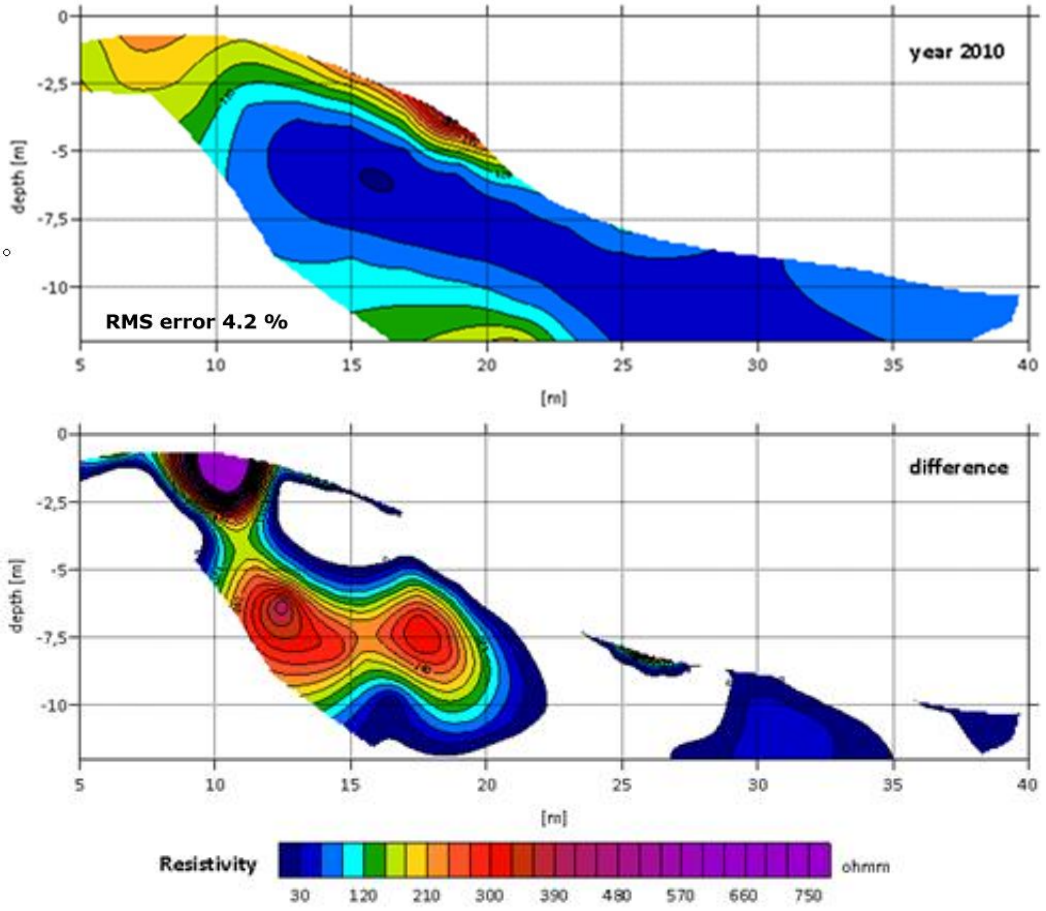


Figure 9. Resistivity cross-section by ERT. Perpendicular profile near the outlet, scans subtraction for the years 2010 and 2013.

The mapping of all interpreted anomalies is shown on Figure 10

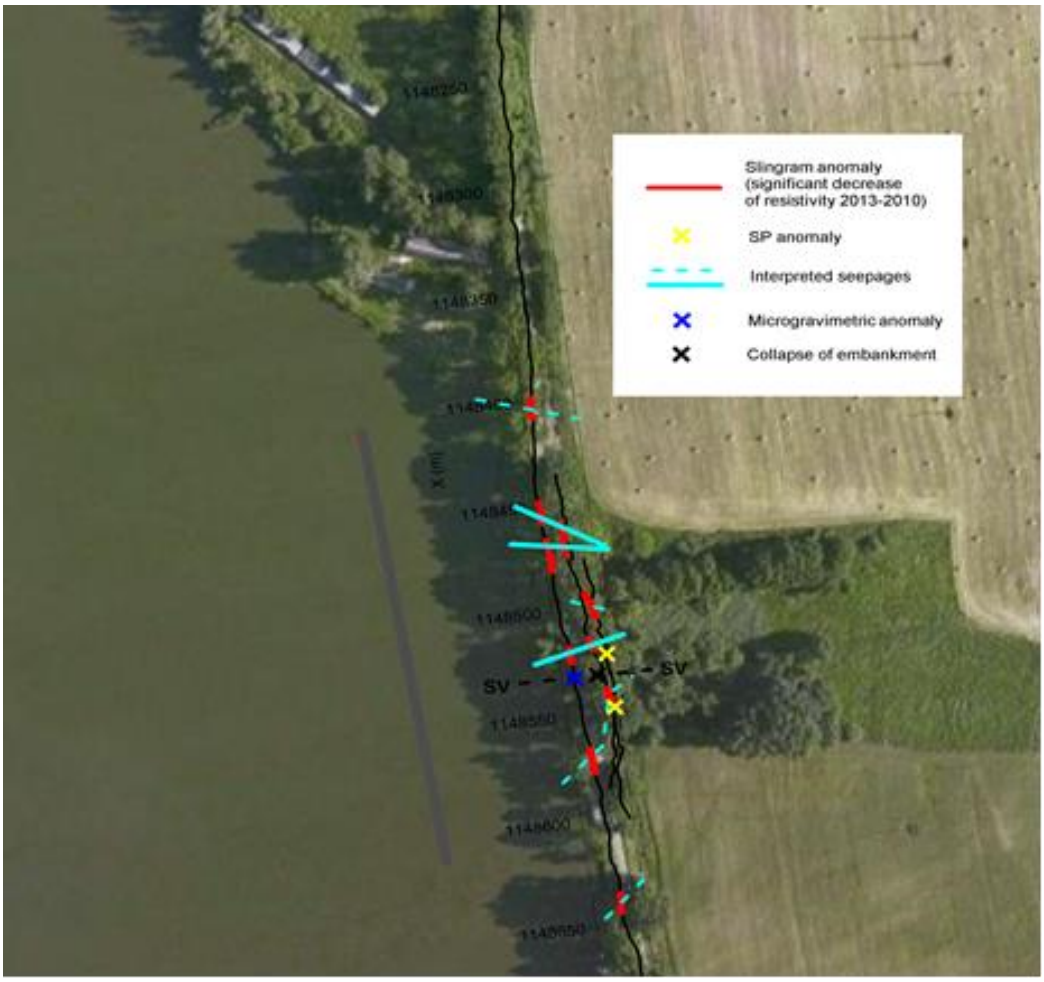


Figure 10. Mapping of interpreted geophysical anomalies. Repeated measurement years 2013 – 2010.

Kardas reservoir

The Geophysical survey of Kardas reservoir embankment was carried out following the same methodology. The dam was built with materials with typical resistivity ranging from 80 to 400 ohm/m, as shown on the graphs of apparent resistivity obtained by the Slingram method (The western part of the dam (upper dam) is mainly made of heterogeneous material (clay sand and gravel). The dam is located in a shallow valley filled with sediments. The base layer of the dam comes from granites, gneisses and magmatites. The dam is layered with less permeable local materials

(related to the geology characteristics of the dam surroundings). The boundary between blocks is sub-vertical. The sealed core of the dam is not continuous. The Slingram fast survey showed on Figure 11 revealed 2 anomalous zones. The first one was near the main outlet where the dam was dug over and where the outlet tube was changed. The second anomaly corresponds to a local decrease in resistivity which was interpreted as the effect of shallow seepages.

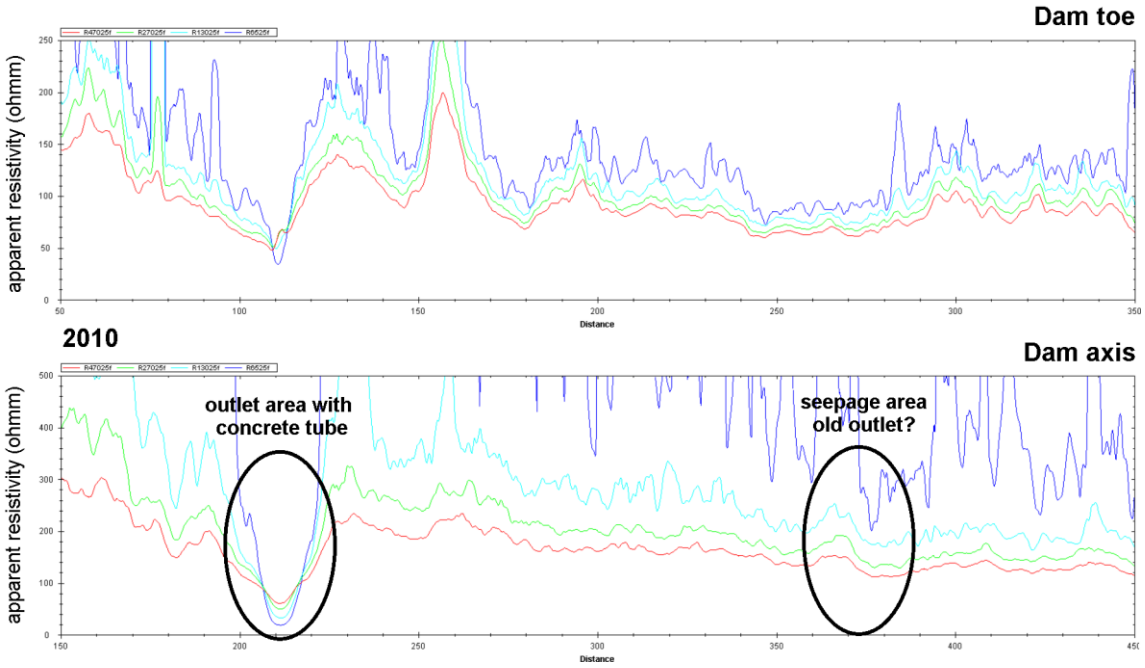


Figure 11. Graphs of apparent resistivity obtained by Slingram method. Profile along the dam length.

For both zones , local microgravimetric measurements (Figure 12) revealed the same anomaly and can be explained as the effect of density, decreasing. The anomaly was interpreted the same way as for the Velky hroch dam as a result of material transport in the piping zone. The anomalies also appear more important after the 2013 flood, meaning that the piping process was very active during the flood.

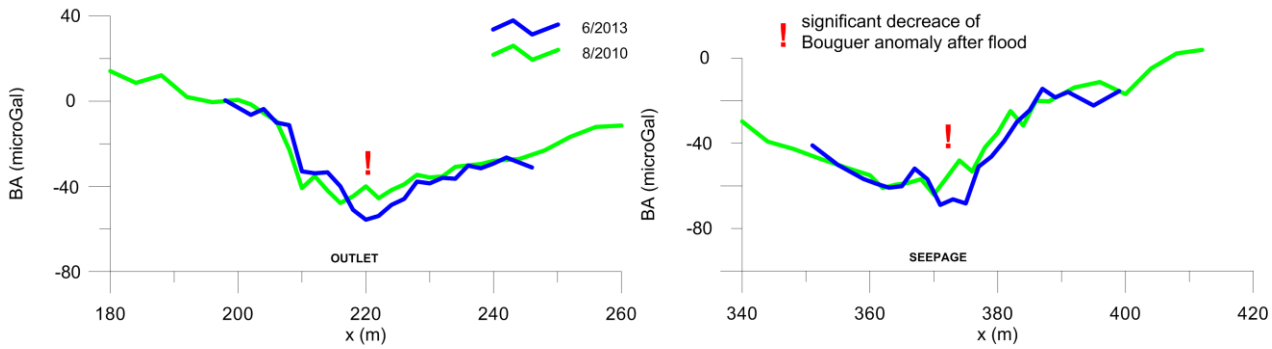


Figure 12 Repeated microgravimetric measurement. Graphs of Bouguer anomaly. Profiles along the dam axis.

The seepage detection was checked with SP measurements too. Figure 13 shows SP curves from the profile near the dam toe on the land side. There were zones with significant changes of SP potential during the 2013 flood. In general, the data obtained during flood were smoother due to high water saturation in the dam body. All zones are in good correlation with the anomalies detected by the Slingram method.

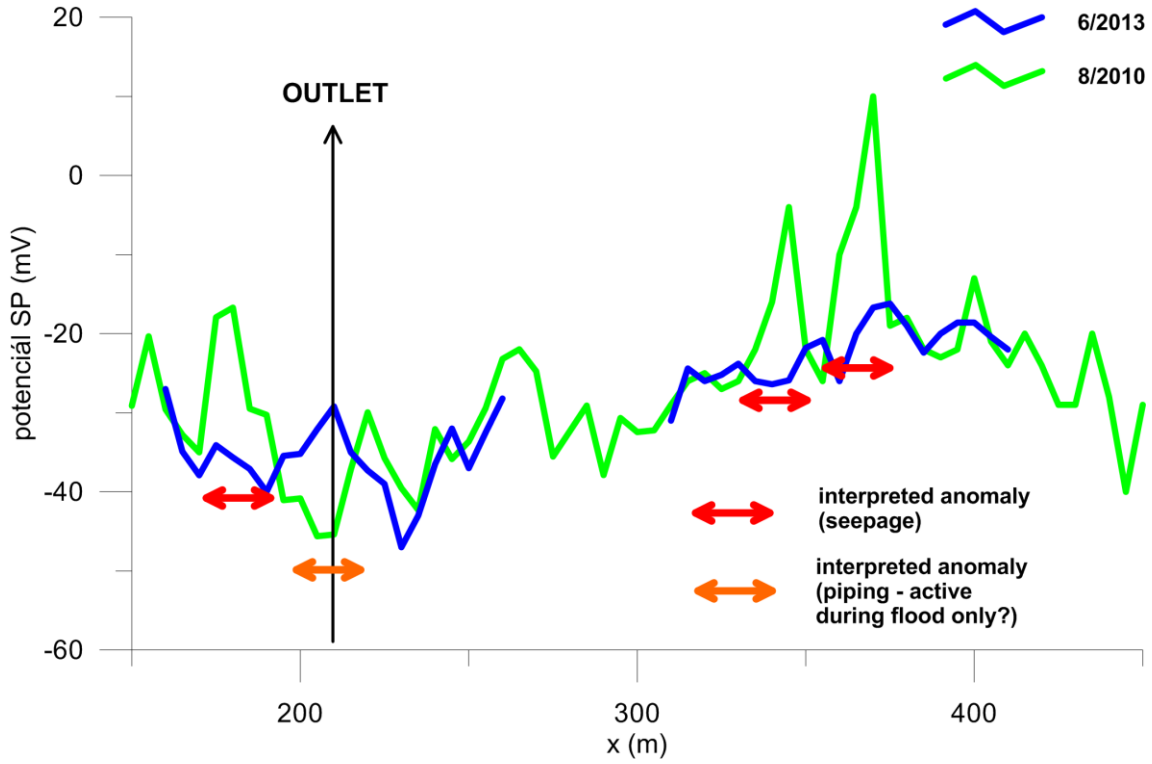


Figure 13. Graphs of SP potential for seepage detection. Profile at the dam toe on the land side.

ERT measurements were carried out to refine the detection of changes in the dam body in the zones previously discussed after the 2013 flood. The tomographic subtraction showed on Figure 14a and Figure 14b revealed resistivity changes over time between 2010 and 2013. In general, the ERT results showed good agreement between the initial and repeated measurements. Near the main outlet, there was an obvious decrease of resistivity in the dam body (Figure 14a), partly from the surface due to saturation of soils after the rain, and in the bedrock zone under the dam. Both anomalies were interpreted like a seepage effect around the outlet tube.

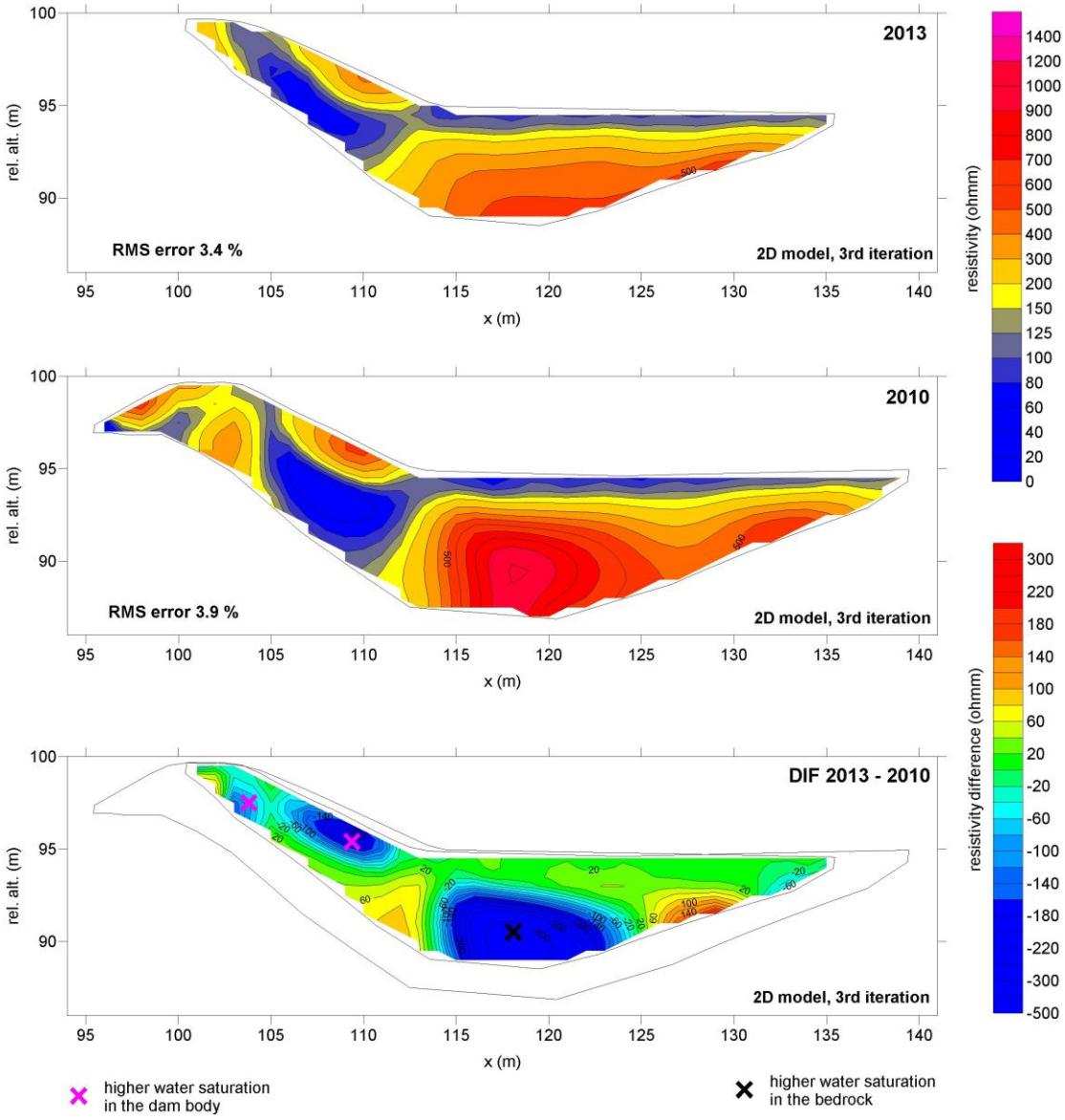


Figure 14a cross-section ERT. Perpendicular profile near the outlet, scans subtraction for the years 2010 and 2013.

The differential resistivity anomaly in the interpreted seepage zone (Figure 14b) showed small changes. Nevertheless, the higher water saturation of the dam and bedrock underneath the dam after flood 2013 is shown as lower resistivity contours. The old outlet with the original wood tube was probably based at this location and was used to supply water to small annex fish pounds near the main dam. The tube was probably obstructed. Hence, It could have work as a seepage/piping preferential pathway. A similar mechanism could have occurred with old roots from dead trees.

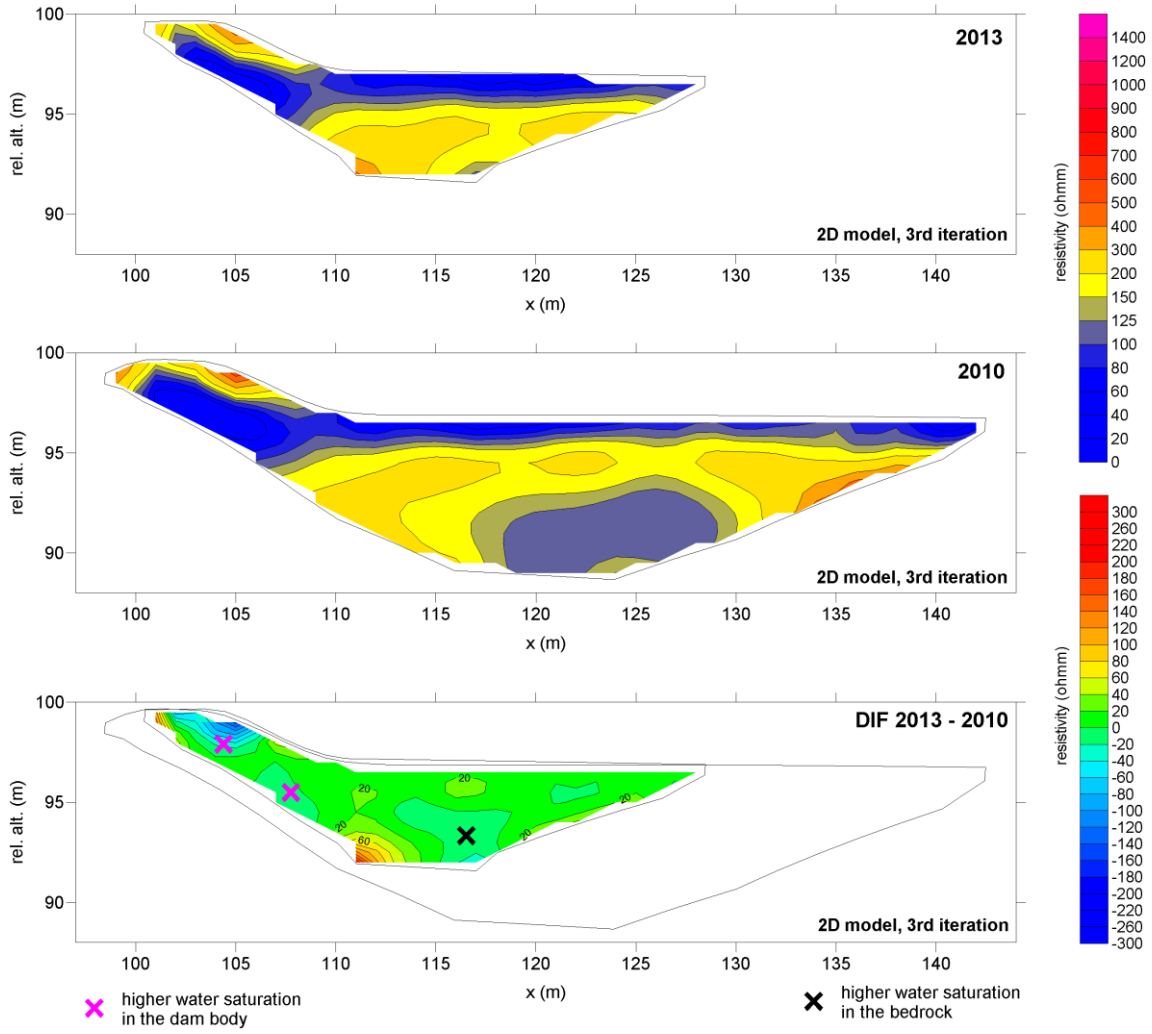


Figure 14b ERT cross-section . Perpendicular profile near interpreted seepage area. Scans subtraction for the years 2010 and 2013.

The anomaly in the bedrock near the outlet (Figure 14b) is distinctively larger than the seepage area. The cause may be due to the difference in sediment type in the meadow and its bedrock. Sand and gravel predominate in the area of the outlet, the

bedrock is mainly made of orthogneiss. Loam and clay sand are mostly present in the seepage zone and weathered granite can be found in the bedrock. The resistivity changes between flood and dry season is higher in the area with sand and bedrock, as seen of Figure 14a.

4. Conclusion

By using all four techniques much more information is gathered than by individual techniques. The fact that these tests are all non-invasive means that the integrity of the embankment has not been breached. Furthermore these tests are far more economical than traditional trenching or borehole investigations and also the whole embankment is assessed and no hot spots are missed, which could have catastrophic results in both social and economic terms.

The value of using these combined techniques cannot be underestimated for both flood prevention and damage remediation. The quantity and quality of information covers fast scan assessment of the whole embankment which can identify weak zones or damaged zones not apparent by visual examination. These require further investigation which can be done by the application of high resolution techniques (ERT/SP/MG) at the specified locations.

The Slingram method is effective and fast and gave a basic description of material homogeneity and helped in the identification of the problematic zones. Self-Potential (SP) and Electrical Resistivity Tomography (ERT) provided the best interpretation of seepages with higher resolution. They were especially valuable when compared in a “time lapse” manner between the years 2010 and 2013. Changes in resistivity and conductivity related to drying or wetting process were subtracted after inversion. The zones affected by the resistivity changes could then be related to the post 2013 flood effect. On the other hand, the microgravimetry (MG) technique was able to detect the piping process with material transport and large cavity propagation and confirmed

SP and ERT results. The repeated measurements during changes in hydraulic regime (dry season versus flood events) made the interpretation of defects more accurate as proved on ERT time subtractions scans and Slingram, SP and MG comparative results between the year 2010 and 2013. Repeated geoelectrical measurement revealed the relative changes of water saturation in the selected reservoirs embankments. By using all four techniques together the assessor has a degree of certainty and confidence in the results meaning that the most appropriate and economical solution can be applied.

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