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Repeated geophysical measurement – the basic principle of the GMS methodology used to inspect the condition of flood control dikes.

V. Beneš[1], M. Tesař[1], Z. Boukalová[2]
[1]*G IMPULS Praha spol. s r.o., Czech Republic*
[2]*VODNÍ ZDROJE, a.s., Czech Republic*

Abstract

Geophysical Monitoring System GMS is a modern and complex methodology of investigation serving as a complement to the classical techniques of inspecting the condition of flood control dikes. It is based on a combination of fast and cheap techniques for the basic description of long dike segments with more sophisticated methods serving for detailed description of problematic dike segments. Especially a combination of suitable geoelectrical methods – dipole electromagnetic profiling (DEMP) and resistivity tomography (RT) is applied and, where appropriate, complemented by another independent method (mostly some of the seismic methods or microgravimetry). One of the innovations of the GMS methodology is the execution of repeated geophysical measurements at various levels of dike saturation with water. The interpretation of such measurements may detect the existence of anomalous seepage zones in the dikes. When performing the analysis of repeated measurements, it is important to eliminate the effect of “natural” (seasonal, climatic) changes in the measured parameters. In the case of the DEMP method which serves for the basic description of long dike segments it is calculation of the so-called residual resistivity anomaly and mutual correlation of these anomalies in a series of repeated (monitoring) measurements.

Key words: dike (levee), inspection, geophysical investigation, GMS, DEMP, RT, monitoring

1 Introduction

In the majority of advanced countries, the condition of flood control dikes is inspected by means of 3 basic techniques:

- visual inspection
- analysis of airborne or satellite photographs
- repeated levelling of fix points on the top of the dikes

These techniques, neverthelesss, mostly fail to bring the information on the inner structure and material composition of the dikes or on hidden defects that also may be the reason leading to dike failure during floods. These may include material defects in the dike body or subsoil (such as contact of heterogeneous materials, the occurrence of highly permeable layers, etc.) or the existence of “illegal” distribution systems inside the dike body. The knowledge of the material composition and inner structure of the dikes is one of the important prerequisites allowing to prepare the optimum design of the dike reconstruction and repair. The effective tool which may complement the information on the inner structure and material composition of the dikes is the geophysical measurement.

2 A description of the GMS methodology

The Geophysical Monitoring System GMS is an advanced and complex methodology of investigation, properly complementing the above mentioned techniques of dike inspections. The basis of the GMS methodology is a combination of fast and cheap techniques for the basic description of long dike segments with more exacting methods for detailed description of problematic dike segments. In particular, a combination of appropriate geoelectrical methods, such as the method of dipole electromagnetic profiling (DEMP) [1-2] with the method of resistivity tomography (RT) [3], in case of need complemented by another independent method such as one of the seismic methods or microgravimetry, is used. Detailed description of the GMS methodology is included in outcomes of the European projects IMPACT [4] and FLOODSite [5].

The main result of the measurements using the GMS methodology is the division of the dikes within a river basin to so-called quasihomogeneous blocks. These blocks are dike segments (or segments of their underlying layers) that are built up by a certain type of material and show similar geomechanical properties. Such information is important for the planning of engineering-geological investigations using direct methods, and also for proposing the extent and the techniques of dike repairs. We distinguish 5 basic types of quasihomogeneous blocks according to the predominant materials in the dike body (underlying layers). Their description is presented in the following Table 1. Due to a variegated geological pattern of central Europe, it is usual that within one river basin there alternate dikes built up by all of the materials described below and, furthermore, transitions between the individual material types are often abrupt [6].

Table 1: a description of quasihomogeneous blocks of the dikes

Code of the quasihomogeneous block	Resistivities DEMP (ohmm), measured in dry conditions	Predominant material
-2	< 40	Clays to slightly sandy clays
-1	40 - 80	Sandy clays
0	80 - 140	Clayey sands and gravel sands
+1	140 - 250	Slightly clayey sands and gravel
+2	> 250	Sands and gravel sands

It is advisable to perform the basic measurement in dry conditions, when resistivities of the medium are more contrasting and allow to better describe the material composition of the dikes. The interpretation of the geophysical measurements further focuses on the identification of potentially problematic dike segments. In particular, the following events and anomalies are concerned:

- local material changes (often places of repairs of old ruptures)
- abrupt material transitions
- occurrence of permeable materials in the dike or in underlying layers
- occurrence of purely clayey materials with increased plasticity
- occurrence of unknown distribution systems in the dike body

3 Repeated geophysical measurement

One of the innovations of the GMS methodology is the execution of repeated (monitoring) geophysical measurements in risk posing dike places that were estimated on the basis of the basic geophysical investigation or the results of visual inspection. The measurements are conducted at different levels of the dike saturation with water (ideally in a dry period and during flood), which may detect the existence of the anomalous leakage zones in the dikes. In analyzing the repeated measurements, it is important to suppress the effect of “natural” or seasonal (climatic) changes in the measured parameters.

For the DEMP method, which serves for the basic description of long dike segments, this means calculation of the so-called residual resistivity anomaly and mutual correlation of these anomalies in a series of the repeated (monitoring) measurements. Such a method of interpretation of repeated measurements requires the application of apparatuses showing high resolution, high-quality repeatability of the measurements and a possibility of connection to the GPS. For the DEMP method, a multifrequency apparatus GEM2 manufactured by GEOPHEX (USA) turned out well. To perform analyses of the repeated measurements, we have developed special software called GMS_analyzer, which to a great extent facilitates calculation of the residual resistivity anomaly and their mutual correlation [7].

When analyzing the repeated measurements we mostly assess a pair of repeated measurements. The first set of data shows the initial condition (measurement conducted in dry conditions or the preceding phase of measurement), the latter corresponds to the monitoring measurement (preferably measurement at an increased water level or during flood). The mutual general shift of both resistivity graphs may indicate a showing of seasonal variations and corresponds to the total change in the dike saturation with water. We focus on the detection of local shape variations of the measured resistivity curves that may indicate a local change in the level of the dike saturation with water. We logically consider „questionable“ such areas, where the measurement at a high water level, compared to the preceding phase, showed an anomalous decline of resistivity values (local seepage, increased intensity and pace of the dike saturation with water). When analyzing the repeated measurements, we use the mutual correlation of the so-called relative residual resistivity anomaly, which is calculated according to the relationship (1).

$$R_{res} = 100 * (R_{meas} - R_{reg}) / R_{meas} \ [\%] \quad (1)$$

R_{res} - relative residual resistivity anomaly
R_{meas} - resistivity values measured by the apparatus GEM2
R_{reg} - regional trend of R_{meas}

Regional trend R_{reg} mostly involves „usual“ seasonal variations of the measured resistivity values. Shape variations of the residual anomaly then indicate the searched risk posing segments. In calculating the regional trend, for example polynomial regression or runing average of the measured data can be used. Polynomial degree or a length of filter of running average needs to be chosen with regard to an expected length of the searched anomalies (seepages). To perform the analysis of the repeated measurements we mostly use the regional trend which is calculated using the running average with two filter lengths. We use a filter in a length of approx. 50 m for local events, and a filter in a length of approx. 250 m for wider anomalies. The places where a decline of the residual resistivity anomaly occurs at an increased water level or over time, we consider to be risk posing (so-called unstable anomalies). Such places also show a decline of the function of the mutual correlation of the residual anomalies. The correlation function serves as an appropriate guidance in the interpretation of the repeated measurements.

In principle, we proceed similarly in comparing the repeated measurements also for other methods, such as resistivity tomography (RT), the method of spontaneous polarization (SP) and microgravimetry (MG). We consider risk posing those places where after suppressing the seasonal effects on the measured data local anomalous changes in the monitored parameters occur, especially those indicating worsening of the dike properties (for example, gradual deepening of the local anomalies of SP or the gravimetric minimum). Risk posing as well is of course the occurrence of new local anomalies.

4 Examples of anomalies of the repeated geophysical measurements

The following examples show typical anomalies of the repeated geophysical measurements conducted at flood control dikes or small water reservoir dams.

4.1 The locality of Lednice

The example from the locality of Lednice includes data from the historical flood control dike on the Dyje/Thaya River (Czech Republic), which protects the Lednice – Valtice site (architectural landmark on the UNESCO list). The dike reaches a height of 3 to 4 m and its material composition is very variegated. The dike is established on old meanders of the Dyje/Thaya River. Local sediments from the river flood-plain were used as building material. The dike includes segments with the predominance of clayey material (organic filling of the meanders, flood-loams), at places the dike is built up by sandy and gravelly stream sediments. The locality is regularly affected by spring floods caused by snow thawing, there also occur occasional summer flash-floods. The last extensive flood in this locality occurred in 2006. It was a spring flood, the dikes were flooded as high as the dike top, with frequent seepages through the underlying layers and at the toe of the dike having occurred.

In the top part of Figure 1, a set of resistivity graphs according to the DEMP method from the locality of Lednice is shown. It is a dike segment in a length of 3 km. The graph includes two sets of data acquired by the measurements in two phases (summer 2005 - red lines and spring 2006 – blue lines). In each of these two phases, resistivity values for 4 operating frequencies were measured. At first sight we can see a good repeatability of the measurements and also the general shift of the data caused by increased dike saturation with water at the time of the measurements during the flood in 2006. Furthermore, graph 2 shows a broken line taking the values of between -2 and +2, which describes the extent of the individual quasihomogeneous blocks presented in Table 1.

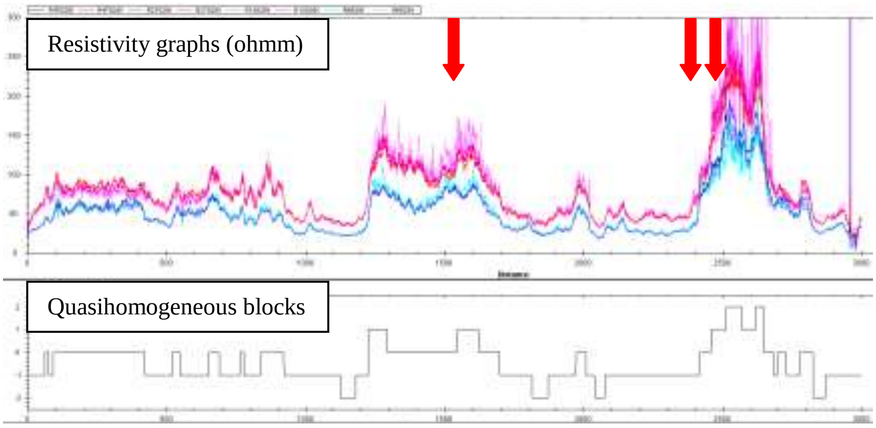

Figure 1: An overview of resistivity graphs from the locality of Lednice
(two phases of measurements)

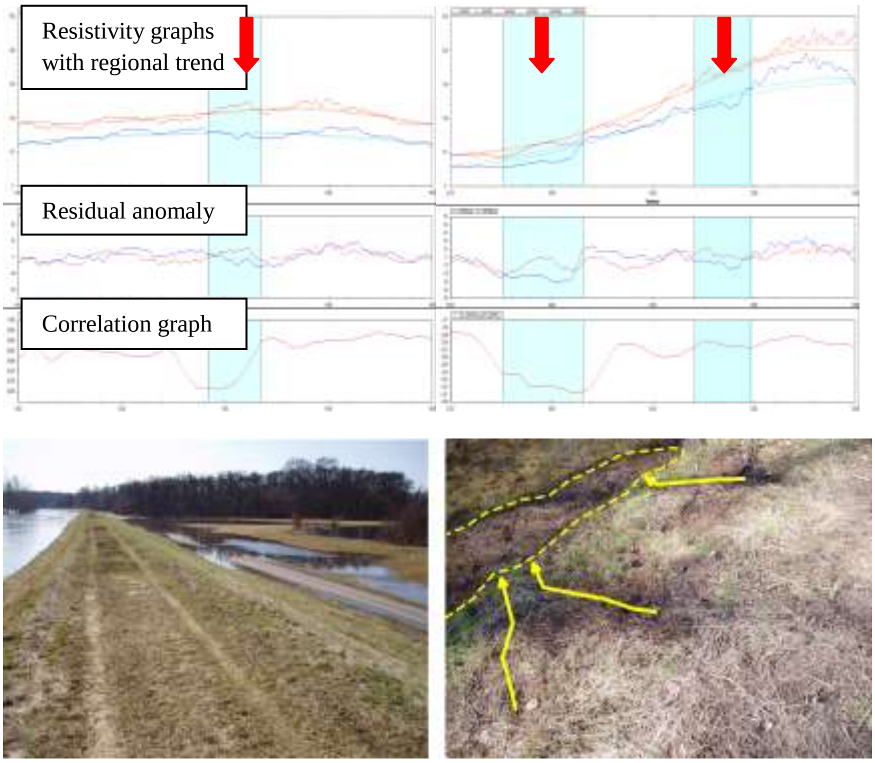

Figure 2: Example of a detailed analysis of the measured data and seepages
in anomalous dike segments

In a detailed comparison of shapes of the measured curves we may find places with the occurrence of more distinct local variations. Figure 2 shows a detail of such places, their position in Figure 1 is marked with an arrow. The graph in the top of Figure 2 shows a comparison of the chosen operating frequency from both phases of the measurements and a course of the calculated regional field. Graph 2 shows residual resistivity anomalies. Graph 3 corresponds to the function of their mutual correlation. The segments highlighted by arrows show places of anomalous declines of resistivity values in measurements performed at an increased water level and, at the same time, places of reduced correlation of residual anomalies. From the viewpoint of occurrence of seepages, these are risk posing places. The correctness of the interpretation was confirmed at the time of flood culmination in 2006, when in these places a distinctive seepage at the toe of the dike occurred (see Figure 2). The given examples of anomalies are typical also from the viewpoint of their occurrence with regard to the entire resistivity and thus also the material composition of the dikes. The anomalies to the left and to the right were detected at a place of increased resistivity values (i.e. increased permeability), the middle anomaly is at a place of resistivity/material transition.

4.2 The locality of Panský dolní pond

We apply the GMS methodology also for the inspection of dams of small water reservoirs – ponds. In Figure 3, results of the repeated measurements using the method of resistivity tomography (RT) on the Panský dolní pond dam in South Bohemia are shown. The results are in the form of resistivity cross sections measured in the longitudinal dam axis at a place of the bottom water outlet, the repeated measurements were performed after approx. 6 months. The position of the bottom water outlet is marked with a blue arrow, the conduit is located in a depth of approx. 7 m. It is a historical dam, the bottom water outlet conduit is made of hollowed oak trunks. The aim of the measurement was to confirm a suspicion arisen on the basis of camera inspection that the conduit is disturbed and that through an increased river flow water „pushing“ into the dam body and its underlying layers occurs. Thís might lead to washing out the material and to the occurrence of piping, followed by the dam collapse.

The top cross section shows a resistivity model of the dam and underlying layers at a standard regime. The bottom cross section was measured at the time of increased water flow through the conduit during the summer flood. In the bottom cross section, the occurrence of a new distinctive resistivity minimum in the area of the bottom water outlet conduit is easily noticeable. This anomaly corresponds to a showing of increased moisture content in the dam body near the conduit and confirms a disturbance of the conduit. Based on the performed measurements, the conduit was repaired. During the repair, a disturbance of the conduit along with the dam saturation with water as well as incipient process of the material washing out were proven.

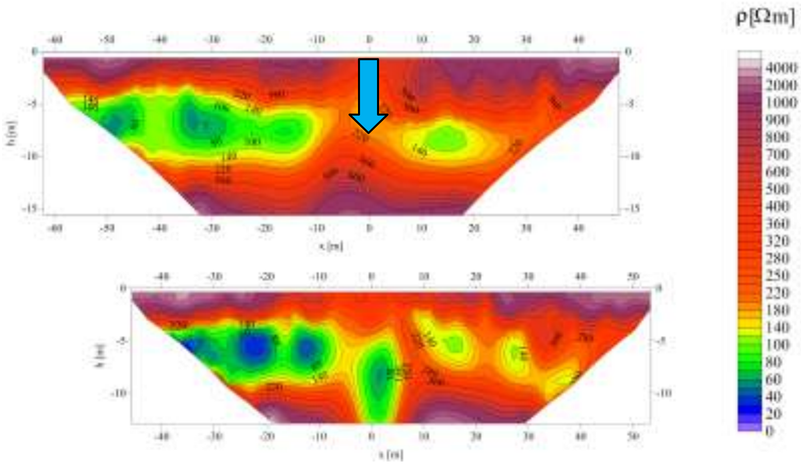

Figure 3: Results of the repeated measurements using the method of resistivity tomography on the Panský dolní pond dam.

4.3 The locality of Buck Chute

The locality of Buck Chute is situated in the USA in the Mississipi River Basin. The demonstration geophysical measurement using the GMS methodology was conducted there in 2009 and 2010 and called GMS_bank under the project KONTAKT. The objective of the project is international exchange of experiences in performing inspection of flood control dikes/levees using the geophysical methods.

At the locality in question, the repeated measurements using the DEMP method were performed at the main levee of the Mississippi River at the places where seepages through the levee underlying layers with water outflows (sand boil) on the air-side frequently occur. The levees are built up by fine-grained clayey sands to clays, in the levee subsoil there occurs a layer of flood-loams which performs a sealing function. Coincidentally, in the period between the two phases of the measurement a new zone with seepages of sand boil type occurred in the locality. The following graph in Figure 4 shows a comparison of the measurements using the DEMP method in the given area from the profile at the air-side toe of the levee. At the top, resistivity graphs of the repeated measurements for the chosen frequency (27025 Hz) are shown. Blue arrows indicate a position of the main water outflows occurring approximately 20 m from the air-side toe of the levee. The resistivity graphs at these places show an evident anomalous decline of resistivity values in the repeated measurement (with active seepages – a blue curve). The segments distinguished in the bottom graph show a position of the main interpreted anomalies, i.e. the local shape variations. They are easily noticeable also in graph 2 with the residual resistivity anomaly. It has to be stated that in the repeated measurement conducted in the same segment on the top of the levee no shape variations in excess of measurement error were not recorded. This is given by a considerable height of the levee (approx. 8 m) and by a limited penetration depth of the measurement using the DEMP method. The anomalous area could only be detected at the profile at the toe of the levee.

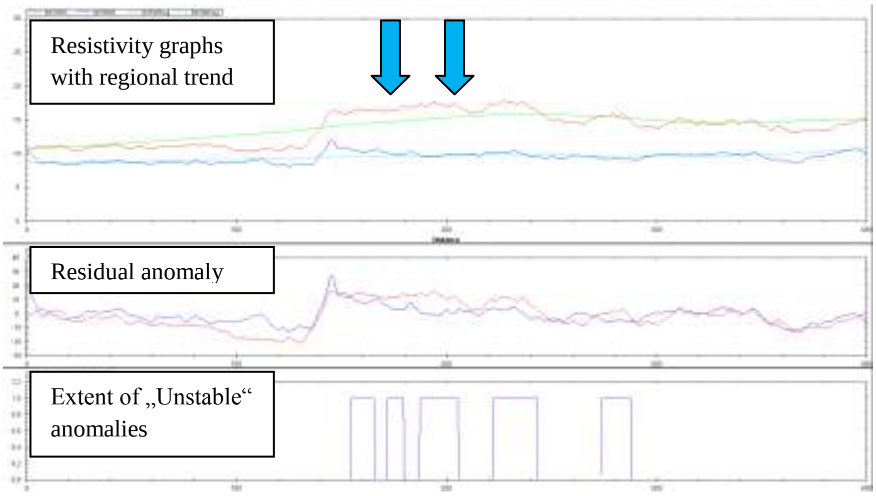

Figure 4: The anomalous area with the occurrence of seepages of sand boil type.

The changes in resistivity values of the sediments in the river flood-plain in dependence on seepages from the river channel according to the water level fluctuation in the Mississippi River can be perfectly documented on the data from the repeated measurements using the method of resistivity tomography, which at the locality of Buck Chute are conducted by colleagues from the Research & Development Center of US Army Corps Engineers in Vicksburg. Herewith, the authors of this paper thank for the provision of data for their analyses which will continue in 2011 under the project GMS_bank. The presented example (see Figure No. 5) documents a distinctive change in the resistivity values in the permeable layer of the river flood-plain (it is probably an old river bed) in dependence on the water level increase in the Mississippi River during the flood. The presented data are from the year 2008, the monitored area probably represents a water supply „canal“ for seepages of sand boil type in the given area.

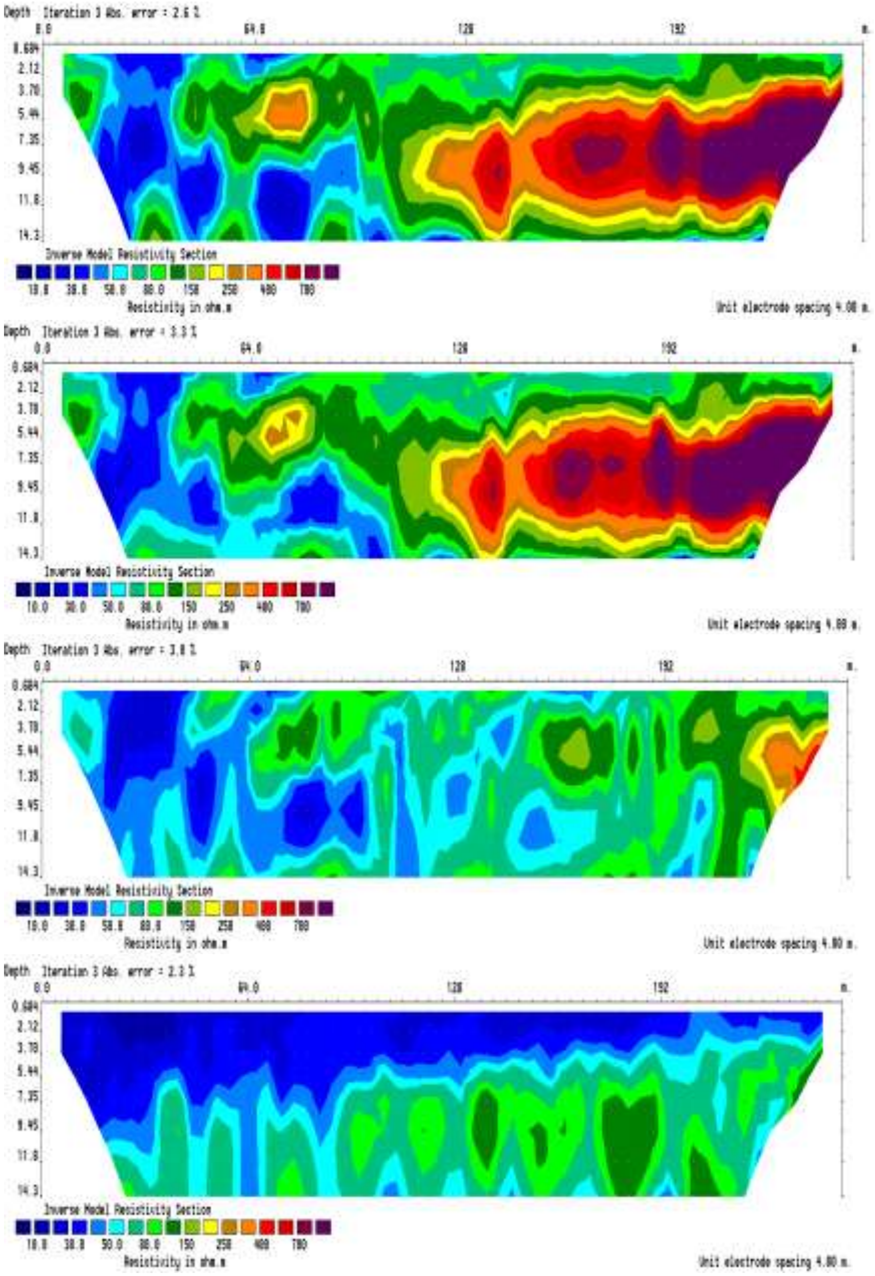

Figure 5: The repeated measurements using the method of resistivity tomography at a place of old river bed (water supply canal for seepages) recorded 2.1.2008, 10.1.2008, 15.3.2008, 13.4.2008 water level in the Mississippi River 7.56 m, 5.61 m, 11.37 m, 15.15 m

5 Conclusion

The presented examples show that the repeated geophysical measurements and their detailed analyses may contribute to the identification of the risk posing dike/levee segments or their underlying layers. Those concerned are most often areas posing risks of seepages. The geophysical methods can also be applied to monitor the geomechanical properties of the dikes/levees and their potential changes. In conducting the measurement it needs to be particular about keeping to the position of the profiles and it is necessary to use apparatuses with a high level of repeatability and small measurement error. In the interpretation, the identical procedures and identical set-up of the interpretation programmes need to be applied. Experience in the interpretation of the repeated (particularly geoelectrical) measurements can be summarized in the following points:

1. we recommend to conduct the basic description of the material composition of the dikes using the geoelectrical methods (such as the DEMP method or the RT method) in a dry season, when the resistivity structure of the medium shows a larger contrast.
2. it is advisable to perform the repeated measurements at the time of increased water level.
3. as regards the effect on the resistivities of the medium, it is necessary to distinguish the effect of a „normal“ change in water content in the dike body caused by a higher water level and the effect caused by climatic conditions at the time of measurement. For this, procedures leading to a calculation of residual resistivity anomalies and their shape correlations may serve.
4. local changes/declines of a shape of the resistivity anomalies in the repeated measurements probably often correspond to the places showing a higher level or a higher pace of saturating the medium with water. Such places, from the viewpoint of seepage occurrences during floods, can be considered risk posing.
5. it is necessary to appropriately define the limit beyond which we consider shape variations anomalous. For the DEMP method and residual resistivity anomalies expressed in per cent we consider anomalous shape variations showing a difference > 10 % (clayey medium) or > 20% (sandy medium).
6. it is evident that suggested or estimated anomalies mostly exceed the number of real seepages. „False“ anomalies may arise due to measurement errors, due to failing to keep to the geometry of the measured profiles, etc. Nevertheless, we believe that the analysis of the repeated geophysical measurements is a useful guidance for the detection of risk posing segments of flood control dikes.

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