

The application of electrical resistivity tomography (ERT), induced polarization (IP) and electromagnetic conductivity (EMC) methods for the evaluation of technical condition of flood embankment corpus

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Received: 4 January 2016; accepted: 10 November 2016

Abstract: A series of catastrophic floods that have occurred over the last twenty years in Poland brought an urgent need for taking preventive steps to monitor river embankment conditions. The main problem seems to be the development of efficient (i.e. fast and economical) measurements for controlling the condition of river embankments, because the execution of the full range of geotechnical measurements is both lengthy and costly. In this situation, a cheap and quick geophysical survey has been proposed to undertake this purpose. In this article the results of geophysical surveys are described which were performed using geoelectric and electromagnetic methods along a section of the Vistula embankment, located near the Maniów area in the Małopolska province. According to the archival data, this region is situated in a high-risk flooding zone. Three geophysical methods were used to recognize conditions of the levee: (i) Electrical Resistivity Tomography (ERT), (ii) Induced Polarization (IP) and (iii) Electromagnetic Conductivity (EMC). Geoelectrical measurement results were presented in the form of resistivity and polarization cross-sections. Results of conductivity measurement were presented in the form of plots. These parameters effectively supplement geotechnical testing, providing spatial information about the changes within the embankment and its substrate. It allows the prediction of potentially vulnerable areas to water percolation during flooding.

Keywords: conductivity methods, resistivity tomography, induced polarization methods, river flood embankment

INTRODUCTION

The damage caused by flooding in 1997, 2010 and 2012 indicated the need for a more detailed assessment of the technical condition of the levees. Economic constraints incline towards the wider use of geophysical methods as a cheaper option than geotechnical ones. The results obtained from shallow geophysical surveys as opposed to borehole methods

do not specify the detailed mineral composition of the body embankment, but the quasi-continuous information about changes in the physical parameters of the geological medium. Their proper interpretation and the linking of these changes with geotechnical conditions in specified areas allows the indication of vulnerable zones in the embankments. Such zones are exposed to a high break risk. The geophysical survey indicates the levee section

where performing anti-filtration screens or the careful monitoring of its condition are required, especially during flood risk. The geophysical surveys effectively supplement geotechnical testing, which determines the benchmark for geophysical methods and are the basis for the correct interpretation of geological and geophysical surveys. These preventive measures provide an opportunity to significantly minimize the effects of flooding. Several studies presented in the literature and performed by the PBG Geophysical Exploration Ltd. confirm the desirability of conducting geophysical surveys on such strategic objects as levees.

In 2014, the PBG Geophysical Exploration Ltd., for the purposes of research project No. POIG.01.04.00-00-363/13 entitled “Experimental adaptation of airborne geophysics methods to develop an effective tool for monitoring the condition of the levees and other onshore infrastructure objects” implemented under the Innovative Economy Operational Program performed a series of geophysical measurements using different land methods to determine the appropriate research methodology allowing the effective recognition of the properties of the levees and their substrate.

This methodology allows also changes of the levee properties in time to be monitored. This is made possible by changing the standard approach

for measurement performed on river embankments, based mainly on geotechnical survey. Test results indicated the desirability of performing integrated measurements using a set of various geophysical methods. This follows the physical basis of the used methods, the measurement specification and geotechnical conditions. All these reasons mean that the information obtained from one measuring method does not properly determine all of the properties of the geological medium that are responsible for levees stability during flood.

LOCATION AND GEOLOGY OF THE STUDY AREA

The methodological measuring profile is located on the right side of the Vistula River near Maniów village in the Dąbrowa Tarnowska district. This section of levee is under the jurisdiction of the Provincial Land Melioration and Water Units Board in Krakow (Małopolski Zarząd Melioracji i Urządzeń Wodnych), which provided the documentation concerning the technical state of the object. According to the borehole data, the flood embankment is underlain by indigenous deposits, consisting of alluvial sediments of the Vistula river composed of sands and gravels with claystone and mudstone intercalations (Fig. 1).

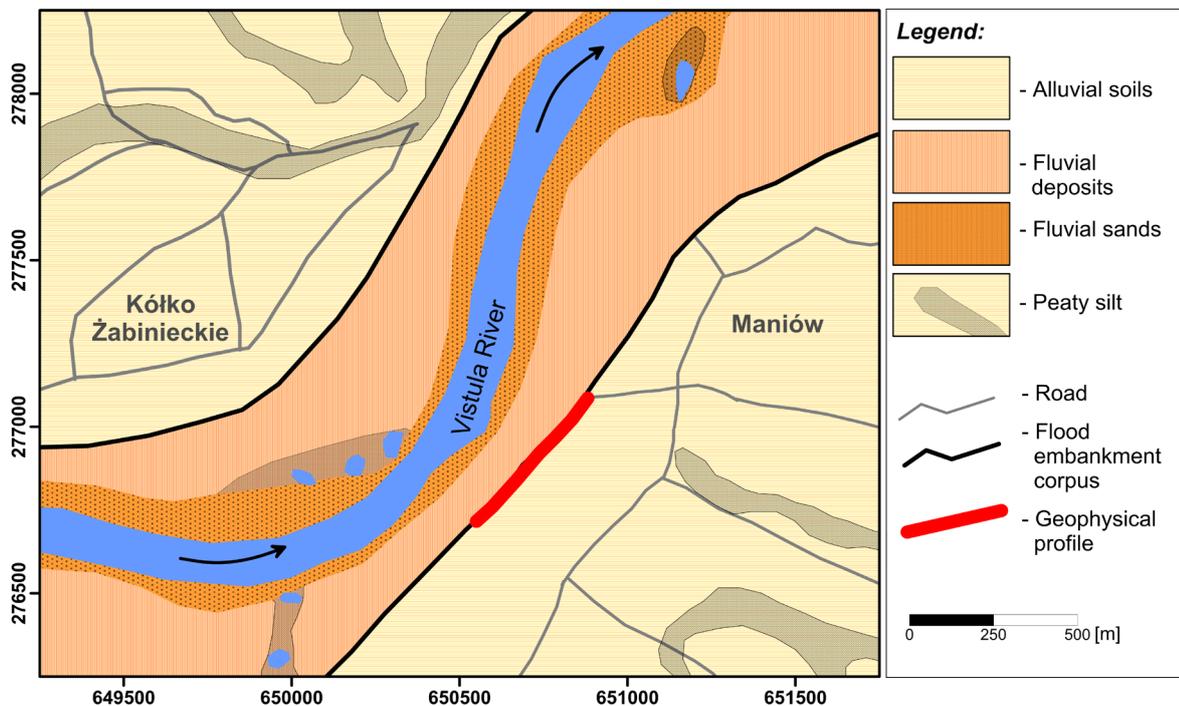


Fig. 1. Location of the study area and geophysical profile on a geological map background; sheet M34-67A Szczucin, 1:50 000 (edited by Rostowska 1967, changed)

The geological structure of the substrate is strongly deformed by the earlier erosion and accumulation activity of the Vistula River. Lithological components of the geological medium are classified as cohesive soils such as silt, sandy silt, silty loam and loamy sands. In the geological profile, the unconsolidated sediments (soils) such as non-cohesive silty sands, fine, medium and coarse sands, and sandy gravel (from loose to compacted) can also be found (Walczowski 1968, Mosiej et al. 2014).

Borehole data indicates that the embankment body consists of the material collected at the place of its origin (Mosiej et al. 2014, Cygal et al. 2015). It allows us to assume that lithogenic variability in the lithology of the embankment structure can also occur, a factor related to the presence of the sandy fraction. It poses a potential risk to embankment stability (Gołębowski et al. 2012).

METHODOLOGY

To achieve the task aims, three land geophysical methods were used: Electrical Resistivity Tomography, Induced Polarization and Electromagnetic Conductivity. From a physical point of view all of the methods are independent and based on the measurement of electrical parameters of the subsurface material. On the other hand, they vary in terms of the electric signal generation and signal recording as well as the physical nature of the recorded parameters of the geological medium.

Electrical Resistivity Tomography (ERT) is a non-invasive method based on the flow of direct electric current (DC) through the geological medium (Loke 2004). This method, according to the methodology and the measurement specification, is a sum of the soundings (and profilings) of electrical resistivity performed with an appropriate electrode spacing.

In the most common measuring array, during a single measurement we induce the electric field (current transmission) in the geological medium between two current electrodes A and B and measure the potential difference between two electrodes named *M* and *N*. Based on the relation (1) it can calculate the apparent resistivity of the medium:

$$\rho_{\alpha} = k \frac{U_{MN}}{I_{AB}} \quad (1)$$

where:

k – geometrical coefficient of measurement scheme,

U_{MN} – potential difference between two electrodes MN,

I_{AB} – the current emitted to the medium through the electrodes AB,

MN – the potential measuring dipole,

AB – the current injection dipole.

ERT measurements were performed using a Terrameter LS 64-channel recorder, manufactured by the Swedish company ABEM. This device includes a current generator with a maximum output power of 250 W and a high resolution receiver recorder that allows the registration of resistivity (function: RES), induced polarization (function: IP) or the registration of both these parameters at the same time (RES/IP). The research was performed using two measuring systems: dipole-dipole and the Schlumberger symmetric system for results comparison. In both variants, measurements were performed with the combined recording of the resistivity (RES) and the induced polarization (IP). To obtain high vertical and horizontal resolution of results, the distance between electrodes was set to 1 m. This assumption, combined with the equipment used, allowed us to obtain a maximum penetration depth ranging up to 8 m.

The article also presents the results obtained using the induced polarization method (IP) mentioned above. IP measurement is an extension of the electrical resistivity tomography method (ERT) that gives an additional electric parameter of the surveyed medium. This parameter is a measure of the rock's ability to separate electric charge in external electric field. IP methods were originally used for detecting ore deposits and now this method is widely used for hydrocarbon exploration as well as for environmental and engineering research (Zonge et al. 2005, Wojdyła et al. 2011). Relating to results published by Zonge, the authors applied this method to recognize the boundary interface between clay and sands or gravel.

The IP effect is, among others, a physical property called the chargeability (M) (Siegel 1959) and is expressed as:

$$M = \frac{V_s}{V_p} [\text{mV/V}] \quad (2)$$

where:

V_s – the OFF-time measured MN voltage

V_p – the ON-time measured MN voltage.

This article describes the IP effect observed in the capillaries, at the border of mineral grain – fluid. This kind of polarization is called membrane polarization. In this case, the IP effect is connected with the existence of clay particles contained within the pore structure of the rock (Parasnis 1973, Kiberu 2002). This phenomenon is caused by restricting the movement of ions in the capillaries. The surface of the clay is characterized by negative charge, so it attracts positive ions from the fluids which fill the capillaries. If the distance between positive charged zone and capillaries is sufficiently large, it effectively limits the flow of positively charged ions and results in impervious membrane formation impeding their movement through the capillaries (Fig. 2A) (Kiberu 2002).

Under the influence of electrical current flow, the clay minerals allow the positive charged ions to flow and stop the negative charged ions. Then, an excess of negative charge is created. When the current flow is interrupted, the positive charges return to their former equilibrium pattern. The process of charge redistribution can be identified with the IP effect, because it manifests itself as a decaying voltage between two electrodes in contact with the clay (Kiberu 2002). The model of charge redistribution is presented in Figure 2B.

During the analysis of measurements performed on the embankment, it is important to identify areas that are composed of dry sandy material. These zones are exposed to the risk of damage during the flood and should be characterized by a very low polarization effect. These zones are also linked with strongly marked anomalies determined from the measurements of electrical resistivity tomography and electromagnetic conductivity methods.

The last geophysical method applied in the tests is Electromagnetic Conductivity method (ECM) called also as induction profiling (Antoniuk 2004, Cygal et al. 2015, Klityński et al. 2015). It is a non-invasive surface method using the secondary electromagnetic field generated in the geological medium by a set of coils or dipoles. The measurement techniques are based on the emission of electromagnetic field into geological medium, called the primary field (Fig. 3) with a strength H_p (3). This field is created by low frequency alternating current in the transmitting coil T_x . Primary field generates a secondary electromagnetic field with a strength H_s (3) in geological medium. The intensity of the secondary field is measured using a receiver coil R_x . The variation of apparent electrical conductivity in the surveyed medium, can be determined according to the formula:

$$\sigma_a = \frac{4}{i\omega\mu s^2} \frac{H_s}{H_p} \quad (3)$$

where:

σ_a – apparent conductivity,

H_p – the primary electromagnetic field strength,

H_s – the secondary electromagnetic field strength,

s – distance between the emitter and receiver coils,

μ – magnetic permeability of the geological medium,

ω – angular frequency of the emitted signal.

The secondary electromagnetic field generated by the conductive structures mentioned above, correspond with the lithology changes, the presence of groundwater, soil contamination by conductive substances, the presence the infrastructure objects in the subsurface, foundations and steel elements. The measurement results in ECM method are two parameters: the apparent conductivity distribution and In-phase parameter. The second parameter gives information about ferromagnetic objects such as cables, pipes, etc., located below the subsurface (according to manufacturer's specifications and GF-Instruments). Based on the measurement results graphs, maps and conductivity and/or apparent resistivity cross-sections can be created, illustrating the variability of geoelectrical properties within the geological medium.

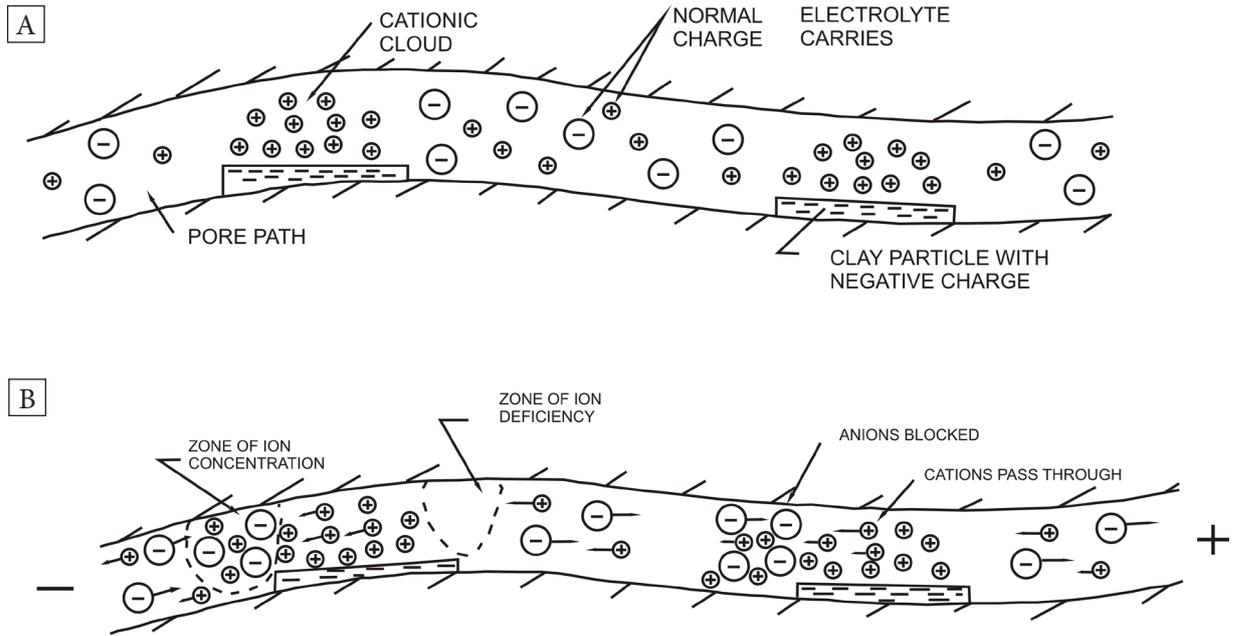


Fig. 2. Model of charge distribution in the geological space according to Fraser (Fraser et al. 1964, Morrison & Gasperikova 2015)

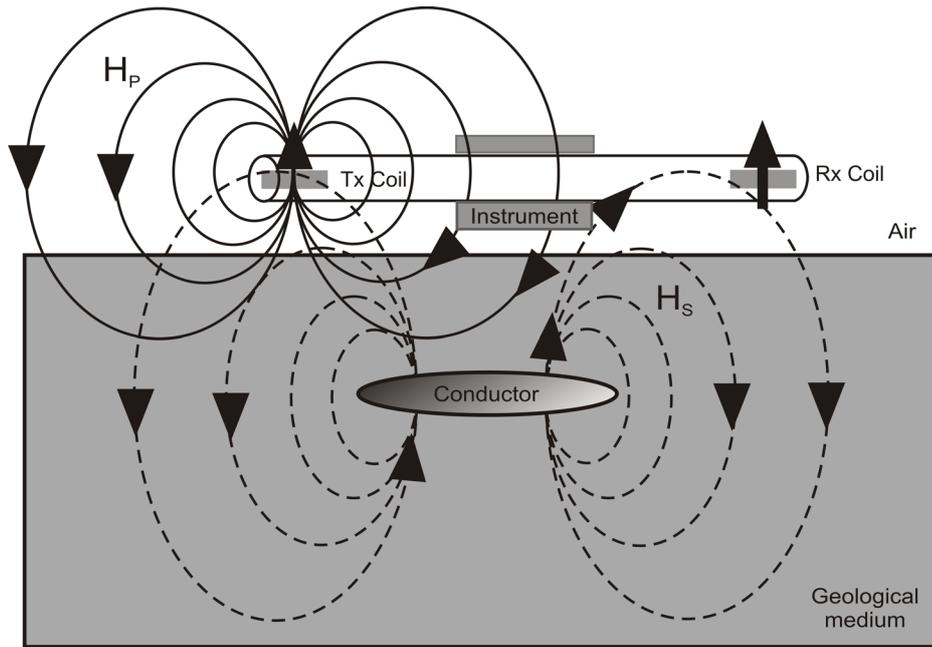


Fig. 3. Scheme of electromagnetic induction in confined conductor for model of conductivity meter. Explanations: H_p – the primary electromagnetic field strength, H_s – the secondary electromagnetic field strength, T_x Coil – transmitter coil, R_x Coil – receiver coil (Gilbert 1999, changed)

ANALYSIS AND INTERPRETATION OF RESULTS

The research results obtained using the electrical resistivity tomography method confirmed the earlier assumptions of the relationship between the

electrical parameter distribution and changes in the technical condition of flood embankments as well as the geological conditions of their substrate. Significant changes in resistivity suggest a large variability in the lithologic material from which the embankment body is built (Figs. 4 and 5). The

geo-electrical cross-sections generally show two quasilateral zones within the surveyed medium. The first one is characterized by high-resistivity values. This zone located below 164 m a.s.l is a natural substrate on which the embankment is situated. The second one is connected with the embankment body and this zone was precisely analyzed. The criterion of good embankment condition is low resistivity. This could be connected with the predominant participation of clay material, which makes the isolation of the embankment body. In contrast, a risk for the embankment breakage may be associated with the presence of intercalations with increased proportion of sandy fraction and – in extreme cases – gravels characterized by higher resistivity values. Meteorological conditions and low water levels during measurements allowed us to assume that zones with increased values of resistivity should be marked as anomalies. It should also be noted that the anomalous

regions are located above the groundwater level, what excluded the impact of water saturation on the ERT imaging result. The suggested locations of anomalies are shown in the sections by vertical lines and sequentially marked as zones from A to E (Figs. 4 and 5). The comprehensive interpretation of the results allowed the combination of the electrical resistivity tomography data and the apparent conductivity measurements data, that were performed along the same profile. The results of the induced polarization method were also helpful. The high resistivity zones correspond well to zones of low value of chargeability. This confirms the lithological changes in the structure of embankment corpus. Along the profile, the border between clay and sand was observed (Figs. 4 and 5). In zone E higher values of chargeability in comparison to the other anomalies can be observed (Fig. 5) and this was probably caused by the presence of clay in the sand deposits.

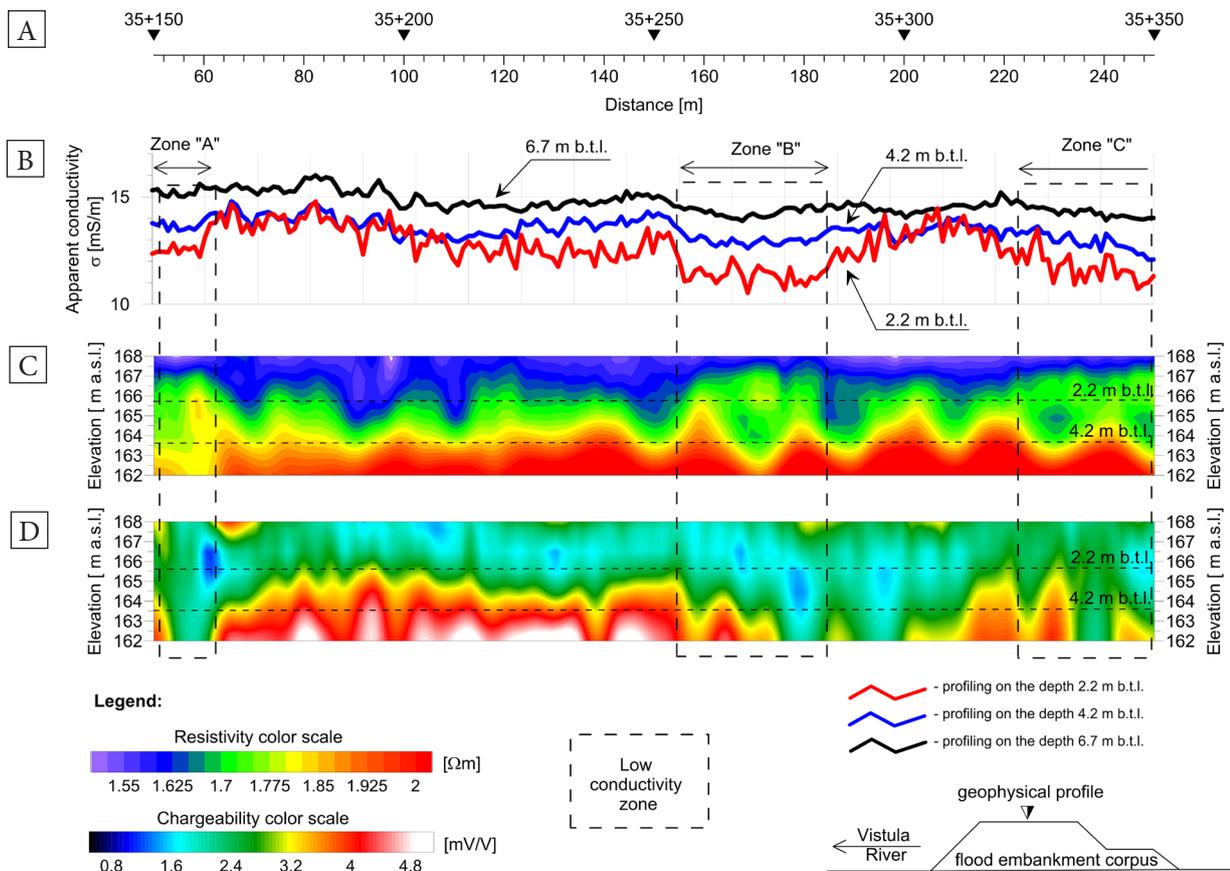


Fig. 4. Comparison of the ECM (B), ERT (C) and IP (D) data along the profile located on the crown of the embankment for the section from km 35 + 150 to km 35 + 350 of the embankment with an indication of anomalous zones. Vertical scale exaggerated

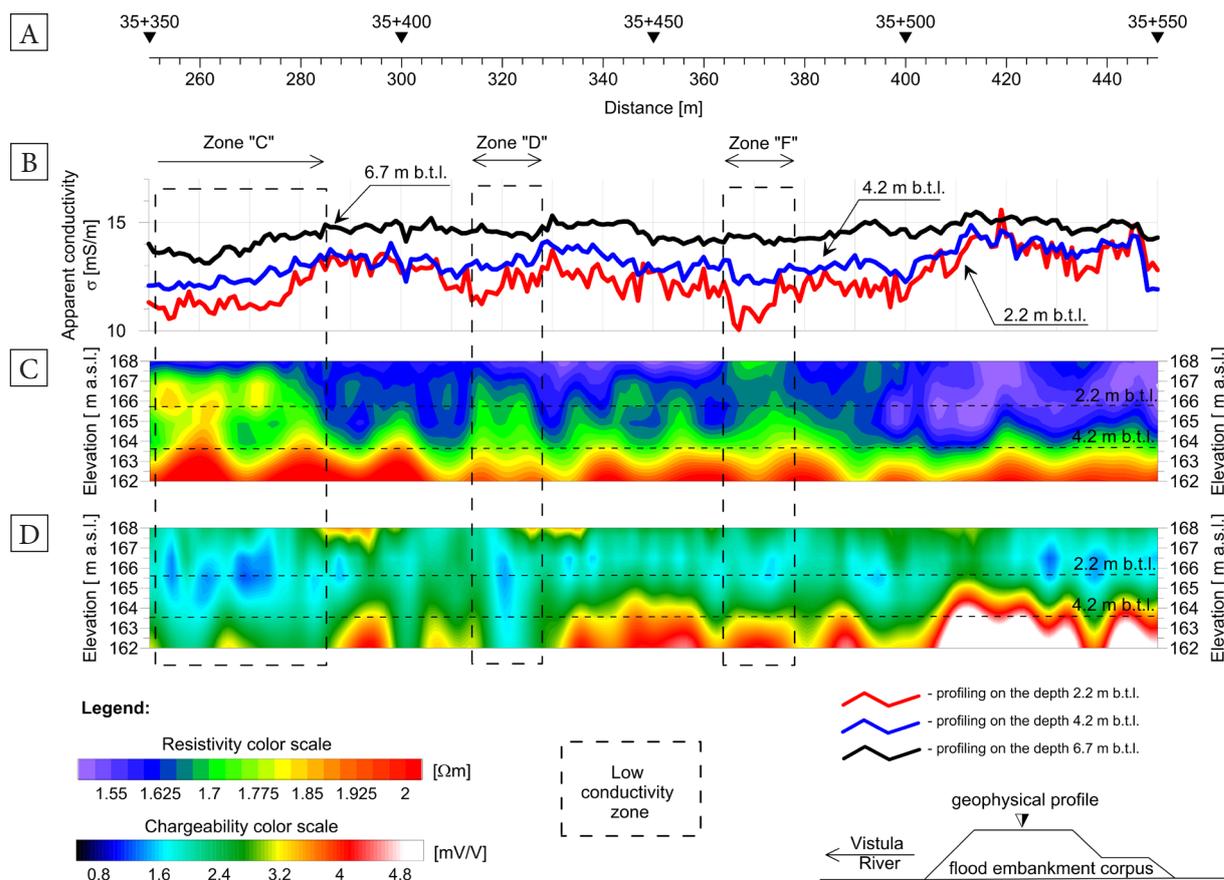


Fig. 5. Comparison of the ECM (B), ERT (C) and IP (D) data along the profile located on the crown of the embankment for the section from km 35 + 350 to km 35 + 550 of the embankment along with an indication of anomalous zones. Vertical scale exaggerated.

ERT and IP cross sections were compared with the selected results of apparent conductivity measurements (ECM). This approach allowed the verification of selected anomalies in the ERT and IP data. The conductivity data from three measurement levels in the domain of depth can be interpreted as follows, respectively: 2.2 m b.t.l., 4.2 m b.t.l. and 6.7 m b.t.l. The deepest level is associated with the levee substrate. The reduced values of conductivity should correlate with positive resistivity anomalies in geoelectrical data sets. On the described profile section five anomalous zones fulfilling the above assumption were observed. The most extensive areas are marked as zones B and C, where a local decrease of apparent conductivity is according with the resistivity increase and chargeability decrease. Zones A and E are exceptions, with zone A having very low IP results despite constant conductivity being observed. This is perhaps caused by changes in the mineral

composition of the geological medium which is the substrate of the flood embankment. Another example is the distribution of the described parameters in zone E, where the increase of the IP parameter for the low apparent conductivity and for the high resistivity could be observed. Despite the fact that assumptions were not fulfilled, the marked zones should be controlled because they could be a potential hazard for the stability of the flood embankment body.

The changes in the conductivity values at the profile plots for depth of 6.7 m b.t.l. indicates lithological variations in the subsurface, which may be prone for hydraulic perforation under the embankment during flooding. The protection procedure of the levees in crisis situations should include the monitoring of the indicated (geophysical anomalous) sectors, whereas prevention activities should lead to the sealing of the embankment body.

CONCLUSIONS

The geophysical images of the levee structure obtained at the test site show the distribution of electrical parameters in the flood embankment and its direct substrate. Analysis of the electrical tomography results allowed the zones characterized by high resistivity values to be contoured. This indicated local agglomerations of sandy fraction in the embankment body and its substrate. Such areas are potentially prone to hydraulic perforation. The resistivity anomalies are generally confirmed by conductivity ones.

The results of this study confirm the usefulness of geophysical methods as a quick and non-invasive tool to identify flood protection status and indicate the need for the implementation of standard preventive actions. As shown in the appended figures, borehole location was unsuccessful because it did not fully show the variability of the embankment body material. Shifting the borehole location by several meters could significantly change the result of the geological and geotechnical interpretation. It should be emphasized that it is necessary to perform a comprehensive interpretation of geological and geophysical data collected on the embankments and their direct substrate. The implementation of geophysical surveys into flood embankment investigation procedures will help in designing a more efficient location for geotechnical investigations which are necessary for the proper assessment of the technical condition of the object.

The results of research carried out by PBG Geophysical Exploration Ltd. were used in this article. The research works were performed within the framework of project No POIG.01.04.00-00-363/13 entitled "Experimental adaptation of airborne geophysics methods to develop an effective tool for monitoring the condition of the levees and other onshore infrastructure objects" (Operational Program of Innovative Economy). Materials provided by the Provincial Land Melioration and Water Units Board in Krakow, Branch Office in Tarnów, were also used.

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