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THE APPLICATION OF GEOPHYSICAL METHODS AND NUMERICAL MODELING FOR THE EVALUATION OF EMBANKMENT TECHNICAL CONDITIONS

ZASTOSOWANIE METOD GEOFIZYCZNYCH I MODELOWANIA NUMERYCZNEGO DO OCENY STANU TECHNICZNEGO WAŁÓW PRZECIWPOWODZIOWYCH

A b s t r a c t

The paper focuses on selected geophysical methods, which may be applied for the evaluation of the technical conditions of flood banks. The paper presents and discusses results of geophysical tests (refractive seismic, geo-radar, vertical electrical sounding and electrical resistivity tomography) obtained from the Kobylnica research test site, i.e. for parts of flood banks on the Vistula River in the Mazovia Region. For a part of the flood bank, where geophysical anomalies were presented, and where cones of hydraulic leakages were observed, numerical calculations of the filtration processes (suffosion) were performed. The obtained results of the geophysical investigations were compared with geotechnical investigations.

Keywords: Geophysical Methods, Electrical Resistivity Tomography (ERT), Ground Penetrating Radar Method (GPR), Vertical Electrical Soundings (VES), refractive seismic, numerical modelling, suffosion

S t r e s z c z e n i e

W artykule skoncentrowano się na wybranych metodach geofizycznych, które można zastosować do oceny stanu technicznego wałów przeciwpowodziowych. Przedstawiono i zinterpretowano wyniki badań geofizycznych (sejsmiki refrakcyjnej, georadaru, pionowych sondowań elektrooporowych oraz tomografii elektrooporowej) uzyskanych z poligonu badawczego Kobylnica, tj. fragmentów wałów przeciwpowodziowych na rz. Wiśle na Mazowszu. Dla fragmentu wału przeciwpowodziowego, gdzie wskazano anomalie geofizyczne oraz wcześniej wykryto strefy przebić hydraulicznych, wykonano obliczenia numeryczne procesów filtracyjnych (sufozji). Uzyskane wyniki badań geofizycznych skonfrontowano z wynikami badań geotechnicznych.

Słowa kluczowe: metody geofizyczne, tomografia elektrooporowa (ERT), metoda georadarowa (GPR), metoda pionowych sondowań elektrooporowych (VES), tomografia sejsmiczna, sejsmika refrakcyjna, modelowanie numeryczne, sufozja

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1. Introduction

Phenomena of filtration, moistening or loosening of grounds in the body of a flood bank are well visible during periods of rising waters or floods. Observations performed in this field are highly valuable for the evaluation of the technical conditions of flood banks. The possibility of locating such phenomena during other periods is complicated, since some defects are not visible from the terrain surface. The important parameters which influence the quality of the flood banks are its stability, impermeability and the quality of its foundations. The important issue concerns inspections of the technical conditions and safety of flood banks. Investigations performed with the use of geophysical methods have recently become more important. Such methods allow for pointing to weakened places within the investigated structure of the flood bank, where more detailed geotechnical tests should be performed. Such tests are non-invasive into the tested medium, their costs are low and a relatively short time is required to obtain the results of such tests. Geophysical methods were, among others, recommended as dedicated methods for the detection and observations of internal erosion processes [3].

At present, geotechnical methods such as dynamic soundings (Dynamic Probing Light), soundings (Cone Penetration Test) and small-diameter drilings, are the most important methods of investigation of the technical conditions of flood banks in Poland. Such approaches allow for stating whether the ground is soaked with water or whether it is compact or characterised by the high porosity in a given place. It is an effective test, but to perform it in places located within long distances may result in overlooking in the structure of flood banks.

Investigations of technical conditions of flood banks are more efficient when monitoring using geophysical methods are performed prior to preparation of geotechnical documentation. Geophysical methods allow for continuous, instrumental observations (2D or 3D) of the flood banks and its foundations based on changes in the physical parameters of embankment grounds, such as electric resistance, the dielectric constant, the velocity of seismic waves propagation etc. This means that measurements are not performed at given points, but instead, they are made along measuring lines. Therefore, it is possible to initially point, basing on geophysical anomalies, to places which are potentially threatened by breakdowns and to continue geotechnical investigation and strengthening of these places. The important advantage of these investigations concern their non-invasive characteristics. When investigations are performed using these methods, there is no physical intervention in the construction of banks.

This paper presents results of geophysical investigations performed in 2012 for the selected test site, *Kobylnica.* The obtained results of geophysical investigations were compared with the results of geotechnical investigations, performed in 2011, within the Rector's Grant of the Warsaw University of Technology, *Analysis of possibilities to utilise geophysical surface seismic methods for evaluation of technical conditions of flood banks.* Comparison of the results of investigations allowed for the determination of the correctness of results obtained with the use of geophysical methods and for evaluation of their accuracy. Based on the results of geophysical and geotechnical investigations, numerical modelling of the stability of escarpments of flood banks, as well as processes of filtration within the banks and under them, with consideration of the high water level in the river bed, was performed [5].

2. Description of a flood bank within the Kobylnica research test site (43+285 km)

The works were focused on the selected research test site, i.e. the part of the flood bank on the Vistula River, located south of Warsaw, in Kobylnica. This location was selected because of alarming events, which were observed on the flood bank and in its foundation during the flood of 2010. They included transudation through the flood bank body and hydraulic leakages in the bank foundation. The location of the test site is presented in Fig. 1.

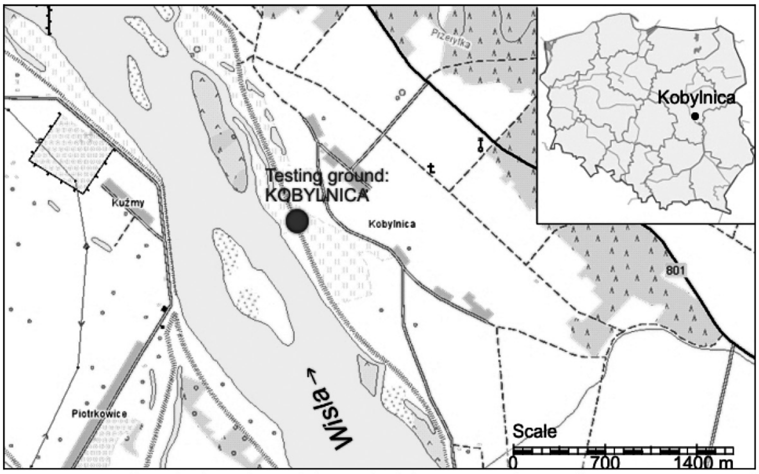

Fig. 1. A map presenting the location of the Kobylnica research test site (www.geoportal.gov.pl)

The flood banks within the area of Kobylnica are hydrotechnical structures of the 2nd class. They were modernised in 2007. The characteristic feature of this area is the close neighbourhood of old river beds and marginal lakes both located between the banks and behind them. The body of the flood bank is constructed of materials which are available locally, i.e. fine and dusty sand, with dust and clay. Although refurbishment works were performed, which included construction of the anti-filtration diaphragm in the flood bank body with a thickness of 15 cm and a depth of 7 m, suffosion phenomena was observed during the flood of 2010. It could be noticed in the form of the zones of water outflows close to the bank foundation, on the back side of the bank. This phenomenon is presented in Fig. 2.

The following investigations were performed within the Kobylnica test site:

1) borings to the depth of 6 m, DPL, Multichannel Analysis of Surface Wave (MASW) Continuous Surface-Wave System (CSWS) (2011 r.) [1, 4],
2) *vertical electrical soundings (VES)*, *electrical resistivity tomography (ERT),* ground penetrating radar (GPR) and refractive seismic [5].

The objective of these investigations was to determine the physical and mechanical parameters of the ground and types of geophysical anomalies at the place of existing suffosion phenomenon and weakening of the flood bank. The location of the performed works is presented in Fig. 4.

Fig. 2. Suffosion phenomena close to the bank foot, the area at the back of the flood bank, Kobylnica 2010 (photo. M. Marszałek)

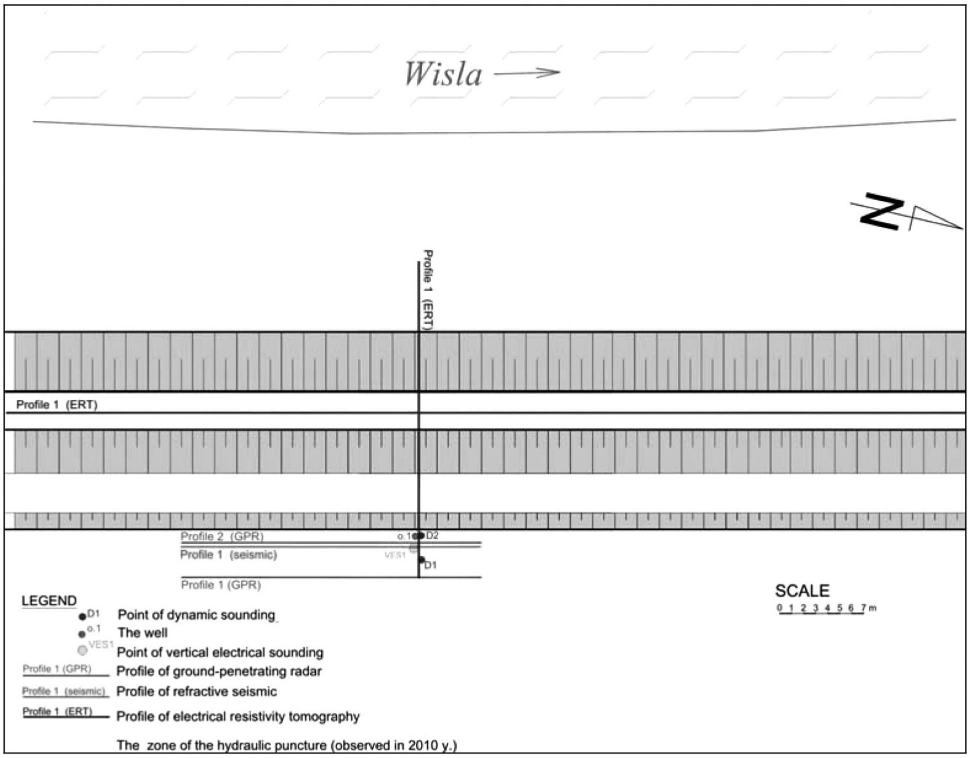

Fig. 3. A documentary map of geotechnical and geophysical tests

3. Geophysical tests

3.1. Vertical electric resistivity soundings

Assumptions of the method of vertical electrical soundings (VES) were formulated at the beginning of the 20th century by two brothers, Conrad and Marcel Schlumberger. The theoretical description may be found, for example, in [9, 16]. In general, this method is aimed at observations of properties of the electric field, which is artificially generated in the soils by a system of electrodes. This method is used for measurements of the apparent resistivity of soils which occur within the generated field. Basing on these measurements, the way of location of soils, which differ in the ability to conduct the electric current, is interpreted in the 1D system.

3.2. Electric resistivity tomography (ERT)

The method of the electric tomography (ERT) was developed at the end of the 20th century; is has been widely discussed, for example in: [6, 10–12]. This method is performed in such a way that it allows for recognition of the distribution of electric resistivity in the soils, in the 2D and/or 3D system. The Terrameter LS, produced by ABEM from Sweden, was utilised for investigations of the electric resistivity performed within the discussed works.

3.3. The ground penetrating radar method

The concept of geophysical investigations performed with the use of ground penetrating radar systems is based on reflection of high frequency electromagnetic waves emitted by special transmitting antennas into the geological medium. The issue of geo-radar investigations is widely discussed in [7, 8, 10].

In total, 20 geo-radar profiles were performed in the selected test site shield antennas of frequency 250 MHz were used for this purpose. For further discussions in this paper, two selected profiles have been used which were characterised by highly visible anomalies. In order to perform investigations using radar profiling, the universal RAMAC GPR system, produced in Sweden by Mala GeoScience, was used. The maximum range of depths of investigation for the existing geological conditions, was equal to almost 5 m.

3.4. The refractive seismic method

The physical basis for the utilisation of seismic measurements in geological-and-geotechnical prospecting is the relationship between the velocity of seismic waves, which propagate within the medium and mechanical parameters of this medium, which are connected with lithology, the level of densification or the level of damages of the primary structure of the medium [16].

Seismic refraction investigations use refractive seismic waves, i.e. waves refracted under the limit angle, at the border of two media, out of which the lower located medium is characterised by greater velocities of seismic waves. Measurements were performed using the profiling method of the length of 21 m (distances between geophones every 1 m). Seismic waves were generated at both of ends and along its lenght, spaced every 2–3 geophones). The applied methodology of measurements allowed for detailed diversification of the velocity of seismic waves in the subsurface layers of sediments, in the foundation of the flood bank. Calculations were performed with the use of ReflexW, the licensed software package. Seismic waves were generated percussively by using the 8 kg hammer. The registration of vibrations was performed using geophones of 28 Hz frequency and the seismic installations DMT Summit, with digital recording and the possibility to sum up the energy of seismic vibrations.

4. Results of geophysical testing

Data obtained from geophysical tests were processed and interpreted. Results were presented in the form of diagrams and cross-sections with appropriate descriptions.

4.1. The vertical electrical soundings

The paper presents results of one sounding operation (VES) which was performed close to the zone of the hydraulic leakage (location: Fig. 4). Sounding was performed in the Schlumberger system. The estimated range of prospection was equal to approx. 8 m below the terrain surface. Measurements were performed using the PMG102 device; the DC converter of the voltage up to 400 V was used for supplying the AB (current electrodes) line. The obtained VES curves were processed and quantitatively interpreted using the INCEL software. As a result of processing and quantitative interpretation of the VES1 curve, the image of the system of geological layers was obtained on the basis of the distribution of real resistivity values at the scale of the real depth. Interpretation of VES1 soundings (Fig. 4) was correlated with the profile of the drill openings (Fig. 4) and with the diagram of the dynamic sounding DPL (Fig. 4). Increased values of the electric resistivity are clearly visible on the VES1 curve – approx. 190–240 Ωm from the terrain surface to a depth of approx. 2 m. This separation corresponds to wet, medium and coarse in medium-density conditions. Deeper, between 2.0–3.0 m the layer of very high resistivity is visible, equal to approx. 1700 Ωm – it corresponds to coarse, loose sands. At a depth of 3 m, the free level of groundwater occurs in coarse sands; loose conditions – the resistivity of these sediments is equal to 80 Ωm. At a depth of 7 m, the floor of cohesive sediments was interpreted; its resistivity is equal to 28 Ωm; it was impossible to reach this levels by drilling. In the case of performed VES1 sounding, it is important to ensure correlation within the interval of depth between 2–3 m below the terrain surface, of the separated geological layer characterised by the high electric resistivity of 1700 Ωm, with the geotechnical layer, which corresponds to coarse sands in loose conditions. This layer is the privileged path for suffosion processes.

Within the Kobylnica test site, one geotechnical drilling was performed to a depth of 4 m below the terrain surface, as well as two DPL soundings to a depth of 6 m below the terrain surface. In the profile of drilling loose sediments of the river origin (fine sands, coarse sands and gravels). The free level of the groundwater was drilled to a depth of about 3 m, which coincides with data obtained from geophysical tests.

DPL soundings (Fig. 4) proved that the grounds are in a medium-dense condition, from the terrain surface up to the depth of about 1.8–2.0 m below the terrain surface; deeper they are in loose conditions.

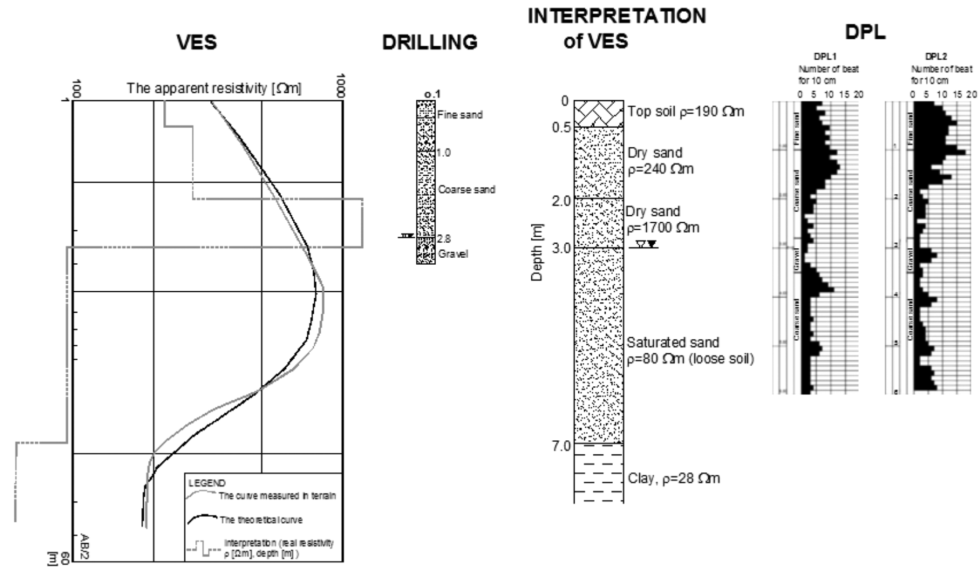

Fig. 4. Presentation of the results of investigations: VES, drilling, DPL. Kobylnica (2012)

4.2. The electric resistivity tomography

Field data was processed using the Res2Dinv software package [14]. All measurements were performed in a system of 41 electrodes, following the gradient protocol. Measuring profiles were located in parallel and perpendicularly to the axes of the flood bank – Fig. 3. The interval between electrodes along the traced measuring profiles was equal to 2 m (measurements along the bank) and 1 m (cross measurements). The maximum range of the depth of recognition of the medium resistivity obtained in measurements, equalled about 10 m below the flood foundation. Distribution of the electric resistivity within the flood bank body is uniform within the prevailing part of the examined sections of banks. Only in the northern part is the anomaly relating the increased resistivity value visible. Below the flood bank foundation, in the ground, measurements point to two anomalies of the increased resistivity: between 24–34 m and between 56–66 m of the profile length (Fig. 5). The increased values of the ground resistivity may result from changes in the lithology of grounds or of the increased porosity. The drilling profile made in the foundation of the flood bank (in the ground) to a depth of 4 m proves that within the given area, loose sediments occur of variable granularity (fine sands, coarse sands and a small layer of gravel). In such conditions, the considerable increase of the ground resistivity which was obtained in the ERT tests, results from the increased porosity of sediments. This result confirms the thesis, which was formulated during the measurements performed, with the use of the method of vertical electric resistivity sounding that the layer characterised by the increased resistivity value is the privileged path for the suffosion processes. There was no anti-filtration diaphragm during ERT measurements in the embankment.

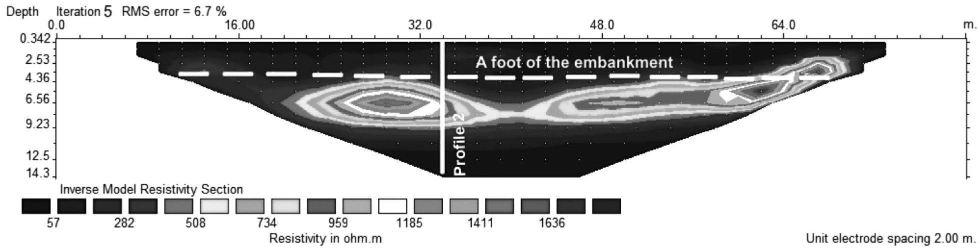

Fig. 5. The ERT – Profile 1 along the bank axis, Kobylnica

The measurements, which were performed transversely to the axis of the flood bank (Fig. 6), allowed for the separation of two distinct zones of the increased value of resistivity; at the eastern side, in grounds, below the bank foundation and at the westerns side, within the flood bank body.

The location of anomalies at the eastern side correspond to the occurrence of the zone of the hydraulic leakage (suffosion) of 2010 (Fig. 2, 3). This anomaly extends under the bank and it presents the expansion of grounds, within which, suffosion processes are generated. The anomaly in the bank body at the western side, may result from the increased porosity of the embankment grounds and/or their shrivelling processes.

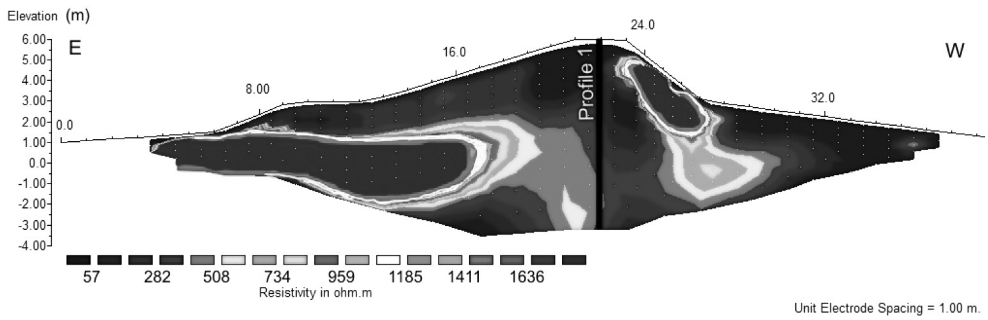

Fig. 6. The ERT method – Cross-section 2, perpendicular to the bank axis, Kobylnica

4.3. The ground penetrating radar method

Results of the ground penetrating radar data were processed with the use of the system for advanced data processing and interpretation: ReflexW by Sandmaier Co. Geo-radar data processing aimed at gain the signal of the electromagnetic wave and elimination of noises. There were applied the following procedures of the processing: move starttime, subtract-DC-shift, bandpassfrequency, background removal and gain. Interpretation of results of geo-radar testing was mainly performed with respect to location of anomalies related to zones of electromagnetic waves attenaution (Fig. 7, 8), which are visible on radargrams. They may be caused by: moist grounds or their attenaution, or adding the fraction of dusts or silt. In order to verify the origin of the anomalies, geotechnical investigations were performed

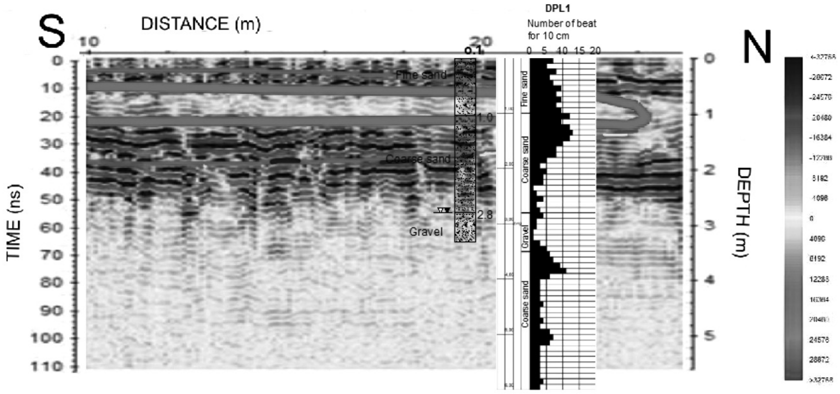

Fig. 7. Profile 1 – geo-radar radargrams with presented zone of electromagnetic waves attenaution

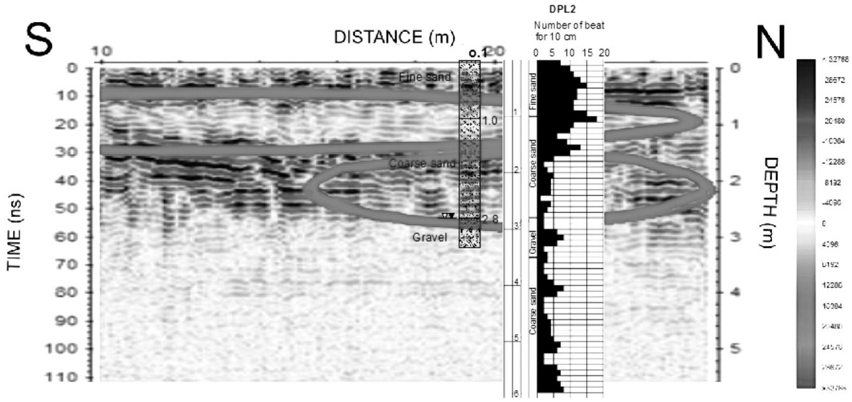

Fig. 8. Profile 2 – geo-radar radargram with presented zone of electromagnetic waves attenaution

(drilling and DPL sounding). Correlation of geotechnical data and GPR radargrams proves the correlation of zones of electromagnetic waves attenaution with sand in loose conditions. The lack of reflections in Profile 1 between depths of 0.5 m to 1 m is caused by the presence of fine sands. Appearance of reflections in coarse sands is obvious because the porosity of such a medium is higher and the porous space is filled with air. Along profile 2 decreasing of reflections amplitudes between depths of 1.5 m and 3 m might by caused by the increase moisture of the soil.

It was accepted for time-depth conversion that velocity is 0.07 m/ns).

4.4. The method of refractive seismic

Analysis of data obtained from the refractive seismic allowed for the separation of two seismic layers (Fig. 9). The layer 1: the velocity of the seismic wave is c.a. 386 m/s. In layer 2 the velocity of the seismic wave is c.a. 834 m/s. The seismic border between layers (no. 1 and no. 2) corresponds with the maximum value of the soil density.

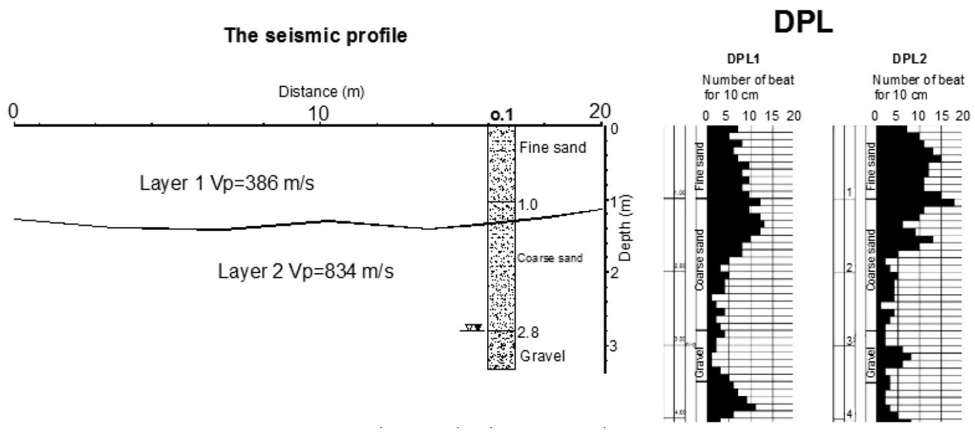

Fig. 9. Seismic cross-section

The method of refractive seismic did not give good results in this problem because the zone of suffosion is shallow and probably is small in size.

5. Numerical analysis

The investigated sections of the flood bank were numercally modelled (Fig. 10). The geological structure, parameters of the filtering diaphragm and grounds were assumed based on results of the performed boreholes, dynamic probing and the design of the modernisation of flood banks [13].

In order to evaluate the filtration and stability of flood banks, the specialised software package, Z_Soil.PC, was applied for engineering calculations. The model of untraced filtration was used for calculations. The function which describes variations in the water table level was specified based on hydrograms of passing of the flood wave in 2010. The total raised water stage lasted for 33 days. Coefficients of the stability were determined using the method of proportional reduction of resistance parameters (c-ϕ reduction) [15].

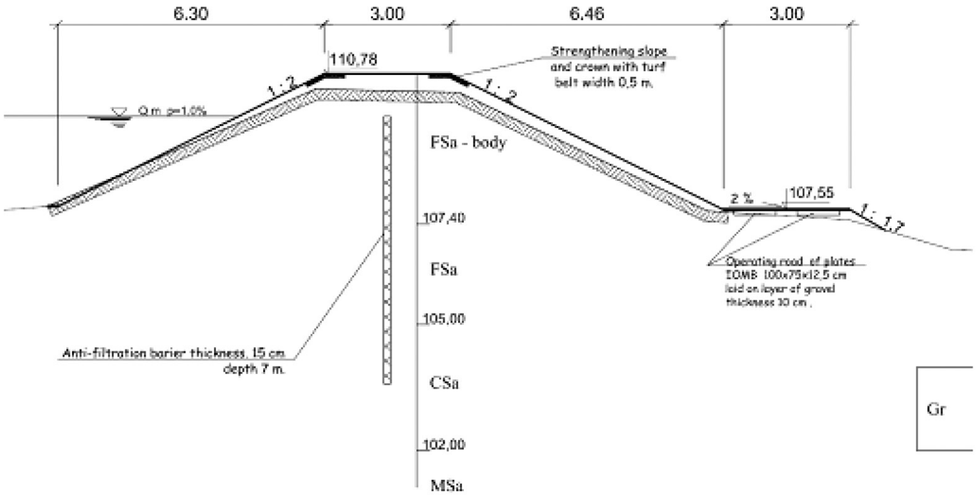

Fig. 10. Cross-section of the flood bank in Kobylnica

Due to considerable water leakages observed during the flood of 2010, numerical simulations were implemented concerning the insufficient depth of the constructed anti-filtering diaphragm to the assumed level in the flood bank foundations, as well as the existing hydraulic leakages. Three numerical models (Fig. 11) presenting various stages of the development of hydraulic leakages were generated, which specified these leakages.

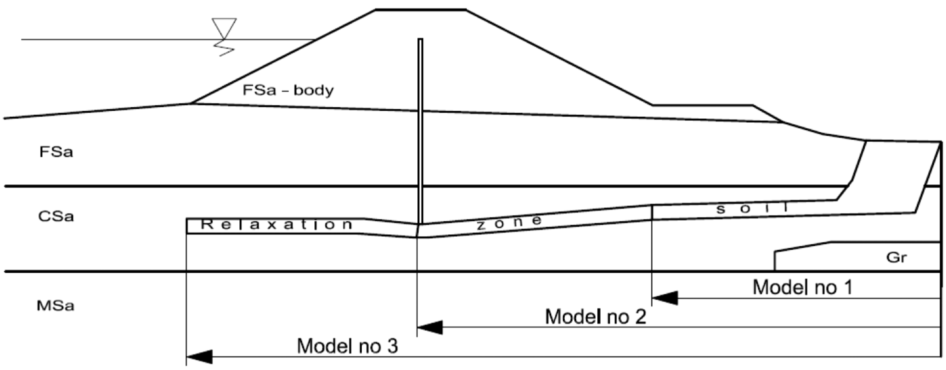

Fig. 11. Computational model – variants of calculations

Below, selected results of filtration (Fig. 12, 13) and stability (Fig. 14) are presented for model no. 3; the best compliance with observations performed during the high water stage in 2010 were obtained for this model.

The results of geophysical research proves that the modernization of flood embankments in the area of Kobylnica is. In the vicinity of the levee the anomalies in the ground were detected. On the basis of measurements field can be assumed that these areas are loosened or damp soil. This suggests the occurrence of subsidence which can be due to the presence of increased filtration phenomena (sufossion, hydraulic leakage). During various phases of the high water stage (rising or falling down of water between flood banks) the downstream face may lose its stability.

The obtained results of calculations should be considered with the tolerance resulting from the assumed theses, the level of accuracy of recognition of material zones of the flood bank body and the foundations, as well as from the assumption of the plain conditions of the numerical analysis. Computations considered the effect of the internal erosion, generation of

Table 1

Summary of material parameters

Type of Soil	E	ν	γ	γ_D	k	C	ϕ
	[kN/m^2]	[–]	[kN/m^3]	[kN/m^3]	[m/day]	[kN/m^2]	[deg]
Fsa – body	80000	0.3	18	18	5	3	27
Fsa	80000	0.3	18	18	5	3	27
Msa	120000	0.25	16	16	20	3	31
Csa	95000	0.25	18	18	30	3	32
Gr	155000	0.2	18	18	50	2	36
RZS*	120000	0.25	16	16	100	3	17

* Relaxation zone soil

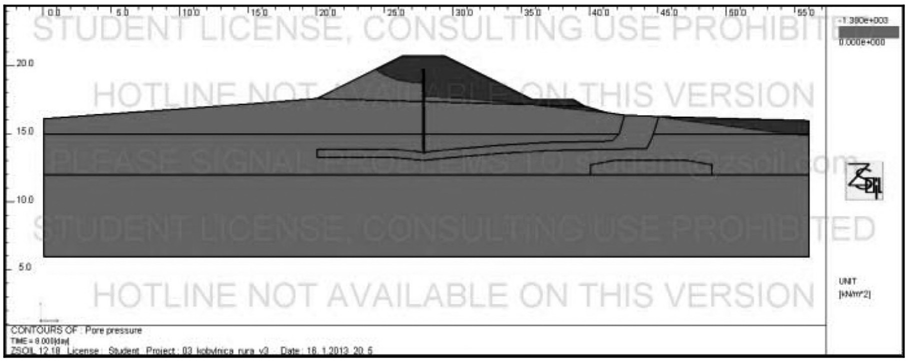

Fig. 12. Location of the depression curve

zones of grounds of modified values of parameters; for such an assumption the compliance of quality with observations performed during the flood was obtained. Thus, the extension of changes in the foundations, assumed for the analyses, was confirmed. It should be realised that during the successive raised water stage, in the same place, the development of the disadvantageous phenomenon of internal erosion will take place and the stability of the flood banks may be threatened.

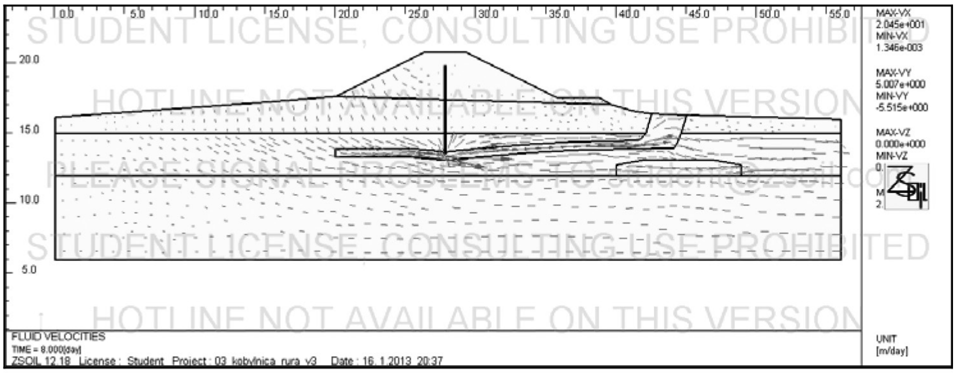

Fig. 13. Distribution of water flow speed vectors

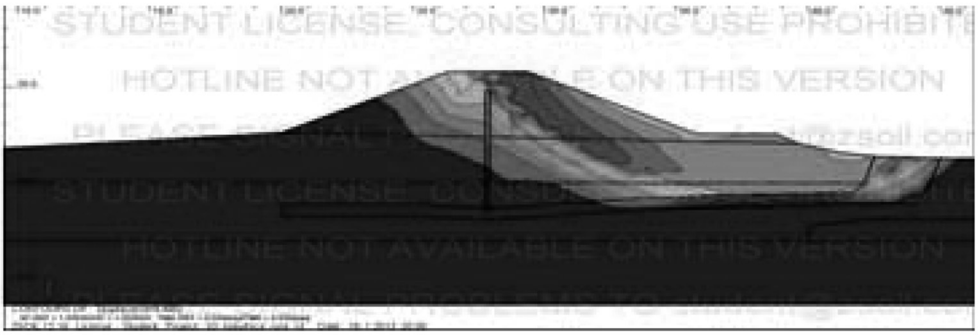

Fig. 14. The slippage area SF = 1.60

6. Final remarks

- Based on the performed tests, the usefulness of geophysical methods for recognition of technical conditions of flood banks may be stated, together with the possible specification of zones of diversified density, stiffness, parameters of filtration within the flood bank body and in the foundations.
- For the low water level in the river bed, the following geophysical anomalies were stated:
  – the increase of the electric resistivity of loose grounds, as well as grounds of increased porosity, threatened by the processes of suffusion,

  – the occurrence of zones of damping in geo-radar echograms within loose grounds, probably as well as grounds of increased wetness and porosity (suffosion phenomena),
  – the visible decrease in the velocity of propagation of seismic waves in loose grounds, as well as in grounds of increased porosity.
- Detailed geotechnical investigations should be preceded by geophysical tests; due to their non-invasive features, they allow for the fast location of anomalies which occur within the investigated grounds. Therefore, it is possible to correctly locate research openings within the areas of anomalies and in typical places of the investigated flood bank.
- Geophysical methods, although their applications for the evaluation of technical conditions of hydrotechnical structures are relatively new in Poland, become more important in practice. The high potential of these methods, which can become an additional source of data, results from their non-invasive features. It is also possible to amend data concerning the specified area of interest between the places of testing (drilling, sounding) by verification of the variability of parameters of the ground medium using various geophysical methods.
- Multi-variant numerical analysis allowed for the utilisation of the results of the geophysical investigations, and next, for the determination of the location of the depression curve and places of flow concentration, variable in time, as well as calculation of the stability coefficient and location of the slippage zone of the escarpment in particular days of the raised water stage.
- Comaring results of investigations performed with the use of various methods allowed for the determination of the correctness of the results obtained with the use of geophysical methods, as well as the evaluation of their accuracy and possible scope of utilisation.

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References

[1] Barański M., Kłobukowski D., Makowski R., Popielski P., Szczepański T., *Analysis of possibilities to utilise geophysical surface seismic methods for evaluation of technical conditions of flood banks*, Czasopismo Techniczne z. 3-Ś/2012, Kraków 2012.

[2] Fajklewicz Z. (ed.), *Zarys geofizyki stosowanej, An outline of applied geophysics*, Wydawnictwa Geologiczne, Warszawa 1972.

[3] Fry J.J., *How to Prevent Embankments from Internal Erosion Failure?*, International Symposium on Dams on Changing Word, Kyoto, Japan, June 5, 2012.

[4] Grant Rektorski PW: *Analysis of possibilities to utilise geophysical surface seismic methods for evaluation of technical conditions of flood banks*, Koło Naukowe Inżynierii Wodnej Politechniki Warszawskiej, Warszawa 2011.

[5] Grant Rektorski PW: *Analysis of possibilities to utilise modern methods of researches of grounds and numerical modelling for evaluation of technical conditions of hydro-*

technical structures, Koło Naukowe Inżynierii Wodnej Politechniki Warszawskiej, Warszawa 2012.

[6] Griffiths D.H., Barker R D., *Two-dimensional resistivity imaging and modelling in areas of complex geology*, Journal of Applied Geopgysics, no. 29, 1993, 211-226.

[7] Jol H.M. (ed.), *Ground Penetrating Radar: Theory and Application*, 1st ed., Elsevier, 2009.

[8] Karczewski J., *An outline of the geo-radar method*, Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Wydanie I, Kraków 2007.

[9] Keller G.V. Frischknecht F.C., *Electrical methods in geophysical prospecting*, Pergamon Press Inc., Oxford 1966.

[10] Kirsch R., (ed.), *Groundwater Geophisics, A Tool for Hydrogeology*, 2 vol. ed., Springer, 2009.

[11] Loke M.H., Barker R.D., *Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting*, no. 44, 1996, 131-152.

[12] Loke M. H., *Tutorial: 2-D and 3-D electrical imagining surveys*, Geotomo Software, Malaysia 2012.

[13] Projekt wykonawczy – *Modernisation of the flood bank, 2nd class in km 35+000 to 45+000, of the right-hand bank of the Vistula River valley, at the section: Antoniówka Świerżowska-Wróble Wargocin, Maciejowice Municipality, Garwolin District*, BIPROMEL, 2003.

[14] *Res2DINV Manual*, GEOTOMO Sofware, 5 Cangkat Miden Loroung 6, Miden Heights, 11700 Gelugor, Penang, Malaysia, 2003, (www.geoeletrical.com).

[15] Sanecki L., Truty A., Urbański A., *On the possibilities of computer-asissted modelling of stability of complex geotechnical systems*, Materiały XLV Konf. Nauk KILiW PAN Krynica 99, Wrocław 1999.

[16] Szymanko J., Stenzel P., *Metody geofizyczne w badaniach hydrogeologicznych i geologiczno-inżynierskich*, Wydawnictwa Geologiczne, Warszawa 1993.