Acta Geodyn. Geomater., Vol. 14, No. 2 (186), 221–234, 2017
DOI: 10.13168/AGG.2017.0005
journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

APPLICATION OF THE ELECTRICAL RESISTIVITY METHOD IN ASSESSING SOIL FOR THE FOUNDATION OF BRIDGE STRUCTURES: A CASE STUDY FROM THE WARSAW ENVIRONS, POLAND

Sebastian KOWALCZYK [1)] *, Piotr ZAWRZYKRAJ [1)], and Maciej MAŚLAKOWSKI [2)]

[1)] *Faculty of Geology, University of Warsaw, ul. Żwirki i Wigury 93, 02-089 Warszawa, Poland*
[2)] *Faculty of Civil Engineering, Warsaw University of Technology, ul. Armii Ludowej 16, 00-637 Warszawa, Poland*

**Corresponding author's e-mail:* s.kowalczyk@uw.edu.pl

ARTICLE INFO

Article history:
Received 21 October 2016
Accepted 13 February 2017
Available online 9 March 2017

Keywords:
Electrical resistivity imaging (ERI)
Resistivity cone penetration test (RCPT)
Engineering geological and geotechnical methods
Peat
Gyttja
Organic soils
Civil-engineering application

ABSTRACT

The paper presents an application of the geoelectrical method in organic soils occurring in the area of a designed investment. Two techniques have been applied: electrical resistivity imaging (ERI) and measurements with a resistivity cone penetration test (RCPT). ERI measurements made using Schlumberger and gradient arrays have allowed to obtain a two-dimensional image of resistivity variability in the soil medium. RCPT measurements have enabled an accurate observation of vertical changes in electrical resistivity (or conductivity) in the soil medium in selected measurement points. Electrical resistivity is a physical parameter that may reflect the variability of the geological medium with regard to lithology if the range of conductivity of water filling the pore space is narrow. When it is properly calibrated with borehole data, ERI interpretation allows to determine the boundaries between different soil layers. Adaptation of the "cumulative resistivity" method to RCPT data enabled to distinguish layers characterized by different physical properties and corresponding to boundaries of geological-engineering layers. ERI and RCPT measurements conducted during expressway construction have contributed to the recognition of soils of low bearing capacity such as organic soils (peats, gyttja and aggradate muds).

INTRODUCTION

The selection of appropriate research methods is particularly important in the recognition of areas with a complex geological structure. In such areas, the application of a multidisciplinary approach using geophysical methods is recommended by Ercoli et al. (2012) and Zini et al. (2015). The application of traditional geotechnical and geological-engineering research methods (boreholes, dynamic and static probing, etc.) supplying point data, coupled with geophysical methods (ground-penetrating radar, electrical resistivity imaging) allowing for a *quasi*-continuous record of physical changes in the soil medium, enables obtaining complementary results for the correct recognition of the soil-water conditions (Kowalczyk and Mieszkowski, 2011; Pierwoła et al., 2011; Maślakowski et al., 2014a; Kowalczyk et al., 2017).

The investigations presented in this paper have been conducted in the Raszynka River valley, which has adapted melt-out hollows and a glacial water flow for its course. The depressions were successively filled with organic sediments, becoming much shallower and currently represent peat plains. Geoelectrical methods are used in the studies of peatlands (Slater and Reeve, 2002; Comas et al., 2004; Kowalczyk and Mieszkowski, 2011; Comas et al., 2015; Walter et al., 2016) and at present more frequently for recognizing the extent of organic soils in the foundations of designed investments (Maślakowski et al., 2014a; Pasierb and Nawrocki, 2015). Electrical resistivity imaging (ERI) is often used in the recognition of complex geological conditions in investigations of the foundations of roads and motorways (Ganerød et al., 2006; Maślakowski et al., 2014a; Ngan-Tillard et al., 2010; Osinowo et al., 2011; Wisén et al., 2008; Kowalczyk et al., 2017).

The investigations presented in this paper were focused on an attempt to identify and characterize the lateral extent of organic soils occurring within a designed road investment using the electrical resistivity method. This aim was accomplished by applying electrical resistivity imaging (ERI) in different measurement arrays (Schlumberger (Dahlin and Zhou, 2004; Loke et al., 2013), gradient with multiple current-electrode combinations (Dahlin and Zhou, 2004, 2006; Loke et al., 2013)) and a resistivity cone penetration test (RCPT) (Daniel et al., 1999; Dahlin et al., 2004; Cai et al., 2016). The interpretation of geoelectrical measurements was based on geological data collected from boreholes.

Cite this article as Kowalczyk S, Zawrzykraj P, Maślakowski M: Application of the electrical resistivity method in assessing soil for the foundation of bridge structures: a case study from the Warsaw environs, Poland. Acta Geodyn. Geomater., 14, No. 2 (186), 221–234, 2017. DOI: 10.13168/AGG.2017.0005

SITE CHARACTERISTICS

The investigations were conducted in an area of a designed section of the S8 expressway (presently exploited) being the access route to Warsaw from the south (Fig. 1a). The Raszynka River valley (right tributary of Utrata River), where the measurements were made, incises into a denuded post-glacial plateau, characterized by the presence of outwash plains, kames, plateaux and local ice-dammed lakes from the Middle-Polish Glaciations (Sarnacka, 1976, 1978) (Fig. 1b-c). Lake sediments from the Eemian Interglacial occur in the basement of the Raszynka valley; they represent sediments of a landlocked basin filled with gyttja. These sediments were covered by Holocene peats, aggradate muds and fluvial sands.

The study site was restricted to an area where the MA-15 bridge construction was founded across the Raszynka valley (Fig. 1d), with a topography ranging between 96.7 and 99.7 MASL. According to archival data (Fig. 1d, black circles), the sediments of the Raszynka valley include fluvial sands and gravels, overlain by humus sands, aggradate muds and peats (Sarnacka, 1976, 1978; Wysokiński, 2004). Local peats and aggradate muds occur also in the landlocked depressions filled with clay. The thickness of aggradate muds and peats is from 0.5 to 2 m, and locally exceeds even 4.5 m (Wysokiński, 2004). The conducted geological-engineering investigations (Fig. 1d, red circles and triangles) have confirmed the presence of complex soil-water conditions occurring in direct vicinity of the designed investment. The ground of the designed bridge construction MA-15 is composed of organic soils such as peats, aggradate muds and gyttja, reaching down even to 12 m below the surface (Fig. 2).

Organic soils in the study area are represented by peats, gyttja and aggradate muds. Their base is strongly inclined towards the south-east, i.e. perpendicularly to the road axis. The ground of the MA-15 bridge construction across the Raszynka River required reinforcement along about 200 m of the designed expressway (km 2+150 ÷ 2+350) due to the thickness, geological setting, and type of organic soils occurring in the ground. At first, partial soil exchange was planned, with removal of the remaining part of organic soils from the ground by a loading embankment. Eventually, the application of controlled modulus columns (CMC) was carried out (Maślakowski et al., 2014b; Mahdavi et al., 2016). The application of this method allows for reducing ground compressibility by semi-rigid soil reinforcement columns. This choice was influenced by such factors as large thickness and type of organic soils (peats and gyttja), by the local geological setting, but also due to a fast construction, lack of excavated material and low settlement (Maślakowski et al., 2014b).

In general in the study area, groundwater stabilizes at about 88.0 MASL and is confined by the overlying peat and/or aggradate muds. Electrical conductivity of water (ECW) was estimated and the ECW variation was observed. Samples of water have an ECW range between 1.3 – 1.5 mS/cm, which is a high range of conductivity for fresh water. The presence of aggressive carbon dioxide in the groundwater sample has been indicated. Other water aggressiveness (such as acidic, magnesium, ammonium, sulphate and leaching) has been not found.

SURVEY METHOD

Two techniques using geoelectrical methods were applied to characterize the ground. Electrical resistivity is a physical property of the medium that depends on several factors, such as the mineral composition (e.g. presence of clay minerals), structural and textural features (porosity, grain cementation, compaction), water content. The amount of water in the medium and the water's conductivity has the strongest impact on the resistivity value. Although a large number of variables affect the resistivity values, such parameter may reflects very well the lithological variability of the geological medium. The theoretical basics of the geoelectrical method and its development have been described for example by Loke (2011), Loke et al. (2013), and Samouëlian et al. (2005).

Electrical resistivity imaging (ERI) known also as electrical resistivity tomography (ERT) or continuous vertical electrical sounding (CVES), described in detail by Dahlin (1996) and Loke (2011), has been used in the investigations. ERI is a method based on the flow of direct current through a soil/rock medium. The studied object is the space of the geological medium between the most distant electrodes used in the measurement. Measurements are taken along the measurement line, with electrodes distributed at the same distances with regard to each other. In each survey, the current is introduced into the soil by two electrodes (AB, also referred to as C_1C_2). Potential difference registered by the other electrodes (their number depends on the measurement array and the number of channels supported by the equipment) is proportional to the electrical resistivity of the medium. Electrical resistivity determined from such measurement is known as "apparent resistivity" and expressed by the following formula:

$$\rho_a = k \cdot \frac{\Delta V}{I}$$

where: ρ_a = apparent resistivity; k = geometric factor for the array; ΔV = potential difference, in volts; and I = current magnitude, in amperes.

The value of apparent resistivity obtained from such measurement does not strictly determine the electrical resistivity of the studied medium, but well reflects its variability. ERI measurements allow for determining both vertical and horizontal changes of electrical resistivity of the medium, with resolution that generally decrease with depth and depending on the electrodes spacing, array configuration (Loke, 2001).

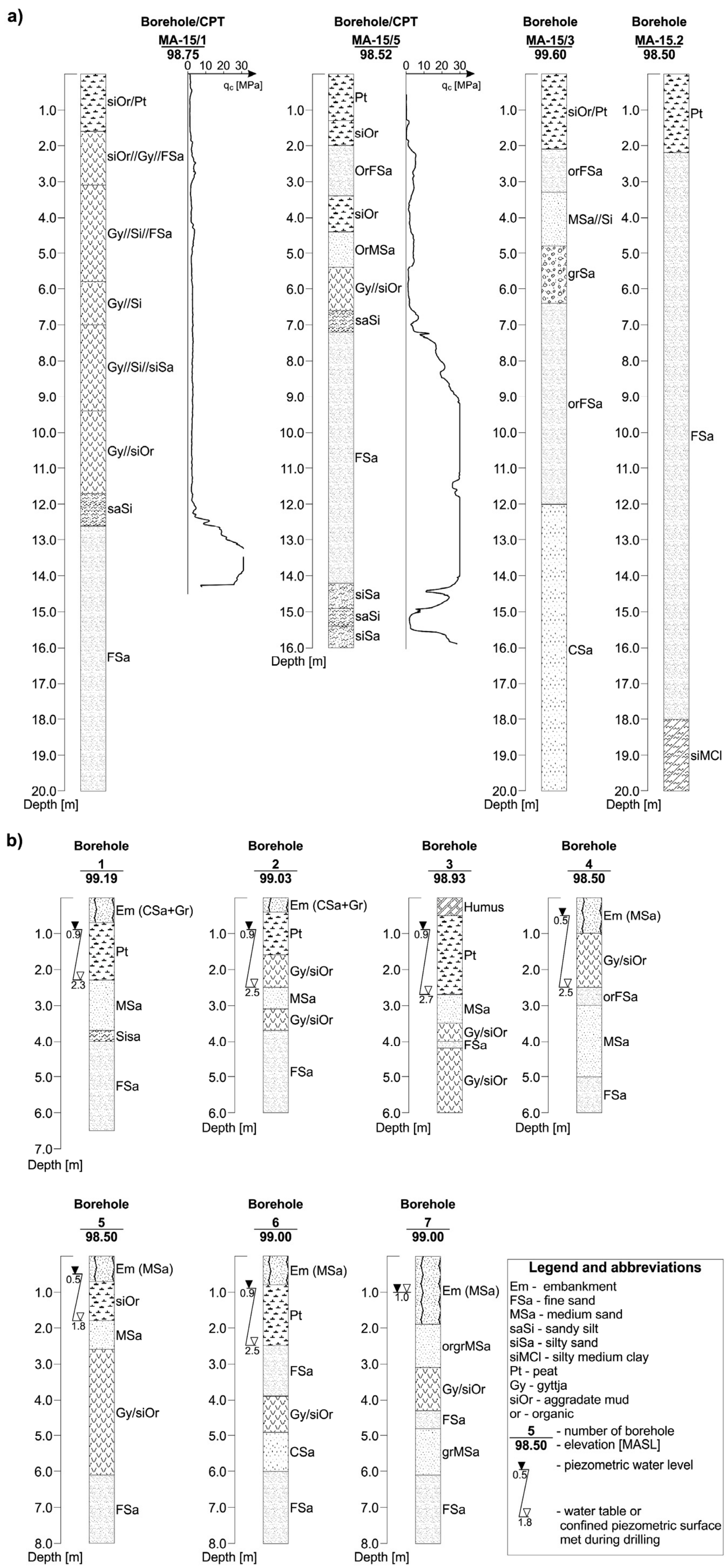

Fig. 2 Geological profiles of: a) archival boreholes and results from CPT, b) boreholes drilled during this investigation.

Table 1 Summary of ERI measurements acquisition and processing parameters.

Line	**ERI_1**		**ERI_2**
Array type	Multiple gradient	Schlumberger	Schlumberger
Profile length [m]	80	80	60
Electrode spacing [m]	1		
Number of electrodes	81	81	61
Number of measurement points	1072	1200	815
Number of points after removal of bad data points	1050	1174	806
Number of iterations	6	4	4
The RMS error [%]	2.9	2.9	2.2

ERI measurements were conducted using a Terrameter LS apparatus of the Swedish company ABEM equipped with 21 electrodes 1 m spaced, distributed along 4 cables. The measurements were made along two lines on both banks of the Raszynka River. On the northern bank of the river the survey followed the Schlumberger and gradient arrays, whereas on the southern bank only the Schlumberger array was used. The apparent resistivity data from the field investigations were processed in Res2DInv to obtain a two-dimensional (2D) model for resistivity of the geological medium subsurface (Loke, 1996–2002, 2001; Loke and Barker, 1996; Loke et al., 2003). The first step was to remove bad data points. The next step was to carry out an inversion procedure in order to obtain a model for a spatially varying distribution of resistivity. Both methods available in the program (the smooth (L2 norm) or the robust/blocky (L1 norm) inversion method) were used. The results obtained using the smoothness-constrained least-squares method with the smoothing of model resistivity values were chosen for the final interpretation. The root-mean-square (RMS) error shows the adjustment of the measured and calculated values of resistivity. The measured and calculated apparent resistivity pseudosections together with the model obtained by the inversion process are shown in Figure 3. The acquisition and processing parameters are shown in Table 1.

Measurements of soil resistivity conducted with a resistivity cone penetration test (RCPT) give high-resolution results thanks to copper ring electrodes distributed on the electrical module of the cone, spaced 3 cm (Wenner array). During soil penetration by the cone at a steady rate of 2 cm/s, the following parameters were measured in relation to the depth: cone resistance q_c, friction sleeve f_s, pore water pressure u_2 and soil resistivity ρ_a. The measured q_c is typically corrected for pore pressure effects (q_t). Based on the friction ratio R_f, which is the ratio of a unitary f_s to q_c and the measured ρ_a referred to relevant classifications, the lithology can be assessed (Schmertmann, 1975; Robertson et al., 1986; Młynarek et al., 1997; Robertson, 2010; Robertson and Cabal, 2012). The index of drainage conditions and indirectly of the type of soils occurring along the cone penetration route is the pore pressure parameter (B_q) reflected as a dimensionless index from the following formula:

$$B_q = \frac{u_2 - u_0}{q_{t-\sigma_{vo}}}$$

where: u_2 = pore pressure measured just behind the cone tip; u_0 = equilibrium pore pressure (consequently, $u_2 - u_0$ = excess pore pressure, Δu); σ_{v0} = total overburden stress.

Lithology can also be estimated from resistivity ranges of the geological medium (Stenzel and Szymanko, 1973; Palacky, 1987; Seidel and Lange, 2007; Everett, 2013). The range of resistivity values proposed by Stenzel and Szymanko (1973) has been used in this paper, because it refers to the most common resistivity values for particular soil types in Poland (Table 2).

PHYSICAL PROPERTIES OF ORGANIC SOILS

Geological-engineering properties of soils are dependent upon: grain size composition, mineral composition, porosity and moisture content. In the case of organic soils, a significant role is played by the percentage content of organic matter, mineral parts and calcium carbonate, as well as the degree of peat decomposition. Factors influencing the strength and deformability of soils are their origin and geological history. Therefore, recognition of organic soils requires determination of their origin, followed by the

Table 2 Most common resistivity values for particular soil types in Poland (Stenzel and Szymanko, 1973).

Soil type	Resistivity values most common in Poland [Ωm]	
Sands of the aeration zone	250	10000
Sands of the saturation zone	80	350
Silts and loams	35	80
Clays and clayey aggradate muds		below 30
Peat	8	50

subdivision of each genetic group with regard to the organic matter content. Physical and mechanical parameters, significant for foundation structures on organic soils, vary not only with regard to the organic matter content but also to the properties reflecting depositional conditions and later postdepositional processes (Myślińska, 1999, 2003).

A detailed review of the engineering properties of peat, including physical and mechanical parameters and also the permeability has been presented by Hobbs (1986). Peats are soils with high compressibility. Studies of these soils from different parts of Poland indicate that peats are characterized by the compression modulus in the range of 0.1-3.5 MPa, most commonly 0.5-0.9 MPa (Myślińska, 2001). The compression modulus for peats from Wisconsin (USA) and north-eastern China, referred to by Yang and Liu (2016), are in the range of 0.8-1.1 MPa and 1.0-5.0 MPa, respectively, and usually attain values at 1.0-3.0 MPa. In comparison to peats, the compressibility of gyttja is much higher, and the compression modulus for different parts of Poland are in the range of 0.1-2.5 MPa, usually at 0.2-0.7 MPa (Myślińska, 2001). The mechanical parameters of organic soils may increase with time. Older sediments, in effect of early diagenetic changes, may reveal larger stiffness, exceeding 5 MPa (Pietrzykowski, 2011). However, these soils in foundation structures are treated as soils of low bearing capacity and require reinforcement or replacement (Ulusay et al., 2010; Lechowicz and Szymański, 2002a and b; Madaschi and Gajo, 2015).

As mentioned above, the foundation of the study area includes Eemian gyttja, and Holocene peats and aggradate muds. Basic determinations of the physical properties have been conducted for these soils. The collected peat samples had an amorphous structure. The values of organic matter content (9.1 to 28.9 %) indicate that some soils (samples) should be classified as aggradate muds. The studied samples of these soils had $CaCO_3$ content from 5.5 to 10.0 % and natural moisture content from 62 to 145 %. Samples of carbonate gyttja were characterized by organic matter content from 6.4 to 11.9 %, $CaCO_3$ from 43.3 to 75.2 % and natural moisture content from 80 to 121 %. Moisture content of gyttja increased with the organic matter content. This relationship is not linear, because the moisture content value is influenced by other components of gyttja.

RESULTS AND DISCUSSION

Borehole logs (Fig. 2) indicate that the study area is characterized by complex soil conditions. The soil layers are discontinuous, origin variable and include organic soils with considerable thicknesses (e.g. 11.7 m – Borehole MA-15/1). Organic soils represent particularly unfavourable foundation for construction objects. They are characterized by high compressibility and usually low bearing capacity. Their specific properties include low bulk density, soil skeleton containing both mineral and organic particles, significant contribution of pores filled with water and fine organic particles, and in the case of carbonate sediments (gyttja, lake chalk), a specific reaction between phytoclasts, calcium carbonate and water (Dobak and Wyrwicki, 2000), influencing water permeability. Therefore recognition of the range of organic soils is crucial. It can be aided by geophysical prospection (Kowalczyk and Mieszkowski, 2011; Maślakowski et al., 2014a). Due to the assets of ERI, this method was included by Instruction No. 58 (General Director for National Roads and Motorways, 2015) to standard geological-engineering investigations in the recognition of foundation structure for dual carriageways. The measurements presented in this paper have been carried out in 2014, thus prior to Instruction No. 58.

Resistivity images obtained from measurements with gradient (Fig. 3c) and Schlumberger arrays (Fig. 3f) along the measurement line on the northern Raszynka River bank seem to be different. However, correlation of these images with geological data from boreholes and adaptation of resistivity ranges for particular types of soils occurring in the ground has resulted in coinciding information from both ERI measurements, although characterized by different resolution.

Generally, as revealed by measurements along line ERI_1, organic soils on saturated sands occur below the surface. The Schlumberger array measurements allowed to obtain a deeper prospection. Such measurements indicate that a layer of cohesive soils occurs below the saturated sands (Fig. 3f). This interpretation confirms previous studies of Wysokiński (2004), according to which the top of ice-dammed soils developed as soft silty medium clay (siMCl) appears at the depth of 17.7-18.5 m (Fig. 2a – Borehole MA-15.2). The basal part of the saturated sands most probably contains a significant contribution of the silt fraction, which influences lower resistivity values.

When comparing the properties of measurement arrays (Zonge et al., 2005), it becomes evident that the gradient array is characterized by a much higher lateral resolution than the Schlumberger array. The Schlumberger array is applied to determine the vertical variation whereas the gradient array is suitable rather for mapping of geologic structures. This is confirmed by measurements made using these arrays along line ERI_1 (Fig. 3c and 3f). In the image from the gradient array, a 1 m thick layer with resistivity between 20 and 40 Ωm is visible directly below the surface. This layer is correlated with peat. In the WNW part of the profile, this layer overlies a layer with resistivity at 80 to 150 Ωm, corresponding to saturated sands. Next, between the 22 and 44 m of the measurement line, the peat layer lies on soils identified as organic sands or sands interbedded with organic soils, such as gyttja and aggradate muds. This layer is characterized by resistivity at 60-80 Ωm. A further part of the measurement line shows the presence of a layer with resistivity at 40-60 Ωm, corresponding to gyttja or aggradate muds. In the ESE part of the measurement line occurs a lens of saturated sand within the organic soils. Based on measurements with the gradient array, it can be concluded that along this line, organic soils occur to the depth of about 5 m, and a layer of saturated sands is present below. Measurements made with the Schlumberger array along line ERI_1 show a more generalized image of the occurrence of organic soils, in which lenses of saturated sand do not occur. These measurements confirm that in the ESE part of the measurement line, the thickness of organic soils is higher and there are premises on the presence of a layer of cohesive soils underlying the layer of saturated sands.

On the southern bank of the Raszynka River, measurements were made only with the Schlumberger array. In the image of resistivity distribution (Fig. 3i), a layer of organic soils is visible directly below the surface. Up to 40 m of the measurement line, this layer if characterized by resistivity values at 25-40 Ωm and corresponds to peats. Between 40 and 60 m of the measurement line, resistivity ranges between 40-60 Ωm and the layer is identified at gyttja and/or aggradate muds. Saturated sands with resistivity at 80-100 Ωm occur below the layer identified as peats in the WNW part of the measurement line, whereas in the central part, the geological medium is characterized by resistivity in an interval of 60-80 Ωm; it is referred to sands interbedded with organic soils. The gyttja and aggradate mud layer in the ESE part of the measurement line reaches a much larger thickness (over 6 m). Geological information obtained from measurements along line ERI_2 corresponds to the data from the boreholes (MA-15/5 and MA-15/1 – Fig. 2a).

Summarising, the investigations by electrical resistivity imaging coupled with borehole data have allowed for the assessment of the distribution of organic soils located directly below the surface along the measurement lines. However, the method does not supply unambiguous results for the distribution of organic soils occurring below low-resistivity soils (Kowalczyk et al., 2015).

Surveys with application of resistivity cone in a soil medium supply detailed data on its structure (Antoniuk and Mościcki, Daniel et al., 1999; 1994; Antoniuk and Mościcki, 2001; Dahlin et al., 2004; Yoon et al., 2011; Kowalczyk et al., 2015), the relation between electrical resistivity and the clay content (Zawrzykraj, 2005; Long et al., 2012), the relationships between electrical resistivity and soil behavior type index I_c, relative density (Cai et al., 2016), or detect contaminated soil layers (Antoniuk and Mościcki, 2001; Fukue et al., 2001; Mondelli et al., 2007; Kim et al., 2009). Moreover, the results of such measurements are extremely valuable in the interpretation of standard, surface geoelectrical surveys, restricting the natural ambiguity of these methods (Antoniuk and Mościcki, 1994; Dahlin et al., 2004; Kowalczyk et al., 2015).

RCPT surveys allowed to assess the vertical variability of the soil medium in selected measurement points (Fig. 4, location in Fig. 1). The vertical variability of strength and physical parameters can be estimated based on the registered parameters. For example, ρ values registered during cone penetration and the calculated R_f allow for an accurate identification of the subsurface zone of the geological medium. Resistivity variability obtained in the investigations corresponds with the variability in q_c, u_2, and R_f. This interdependence was already observed by Dahlin et al. (2004).

Organic soils are characterized by the values of R_f above 3 %, low values of q_t (usually below 1 MPa, although gyttja in RCPT_3 between 6 and 11 m attains q_t values between 1 and 2 MPa), and ρ values between 30-50 Ωm. It should be pointed out that ρ values increase with higher sand content in organic soils and the resistivity of organic silty clay (or siCl) is lower than 30 Ωm due to the high content of clay minerals in this soil. Electrical resistivity of gyttja in vertical section undergoes insignificant fluctuations, whereas peats show a high variability in vertical section. Electrical resistivity for gyttja in RCPT_2 is at 40-50 Ωm, and in RCPT_3 at 30-40 Ωm. These values correspond to the results obtained by Pietrzykowski (2008) using an resistivity cone on Eemian gyttja in Warsaw, in which ρ variability was in the range of 24-40 Ωm.

Low variability of electrical resistivity in vertical section would indicate low variability of physical properties and mineralogical-lithological composition for gyttja, and high variability of these features in peat layers. However, laboratory tests indicate the variability of particular factors from several percent (organic matter content) to several tens of percent ($CaCO_3$ content or moisture content). It should be mentioned that the CPT and CPTU surveys conducted by Pietrzykowski (2011) on gyttja of the same age occurring within the Żoliborz subglacial tunnel valley in Warsaw reveal high uniformity and low dispersion of results in vertical profile, whereas laboratory tests have indicated a variability of particular soil components.

Electrical resistivity measured in RCPT or a different resistivity cone may be used for precise determination of the depth of the boundaries between layers characterized by different physical properties, and usually corresponding to boundaries of geological-engineering layers. In this case the "cumulative resistivity" method, described by Herman (2001) can be applied. This method employs a plot of the sum of the apparent resistivities ($\Sigma\rho_a$) versus depth. Change of the angle of the curve on the cumulative resistivity vs. depth graph points to the presence of a boundary between two layers (Fig. 5). Application of this method in RCPT measurements may allow for distinguishing even very thin layers if there is significant contrast of physical properties at their boundary. Accordingly, RCPT_3 sounding at the depth of 4 m has revealed a 0.2 m thick layer of

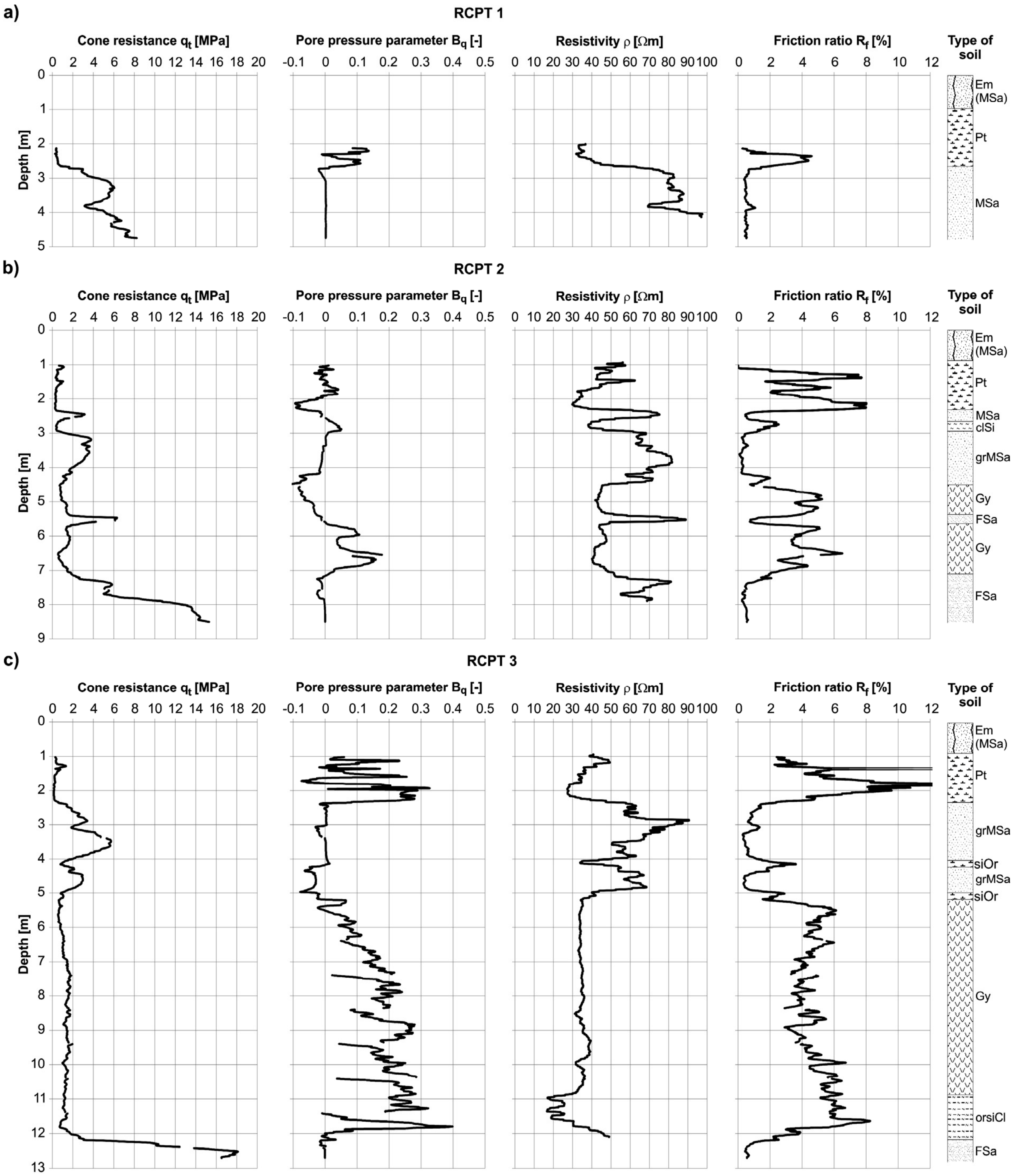

Fig. 4 Results of resistivity cone penetration test with geological interpretation for a) RCPT_1 b) RCPT_2 c) RCPT_3 (for location see Fig. 1).

aggradate muds (siOr) in a sand layer. In turn, at the depth of 5 m, an interbed of aggradate muds between sands and gyttia of a similar thickness is not registered on the cumulative resistivity vs. depth graph due to a low contrast of resistivity between the aggradate muds and gyttja (Fig. 5c).

Moreover, the ERI method allows to determine the boundaries between physical layers, which correspond to geological-engineering layers. Therefore, the total transverse resistance (T) can be calculated from the following formula:

$$T = \sum_{i=1}^{m} \rho_i \cdot h_i$$

where: ρ_i and h_i is the resistivity and thickness of the i^{th} layer, respectively

Transverse resistance indicates the ability of the i^{th}-layer to carry the flow of an electric current when the current is flowing vertically (perpendicularly) through the layers. Transverse resistance has been commonly applied in hydrogeological studies because this parameter correlates well with the saturated zone

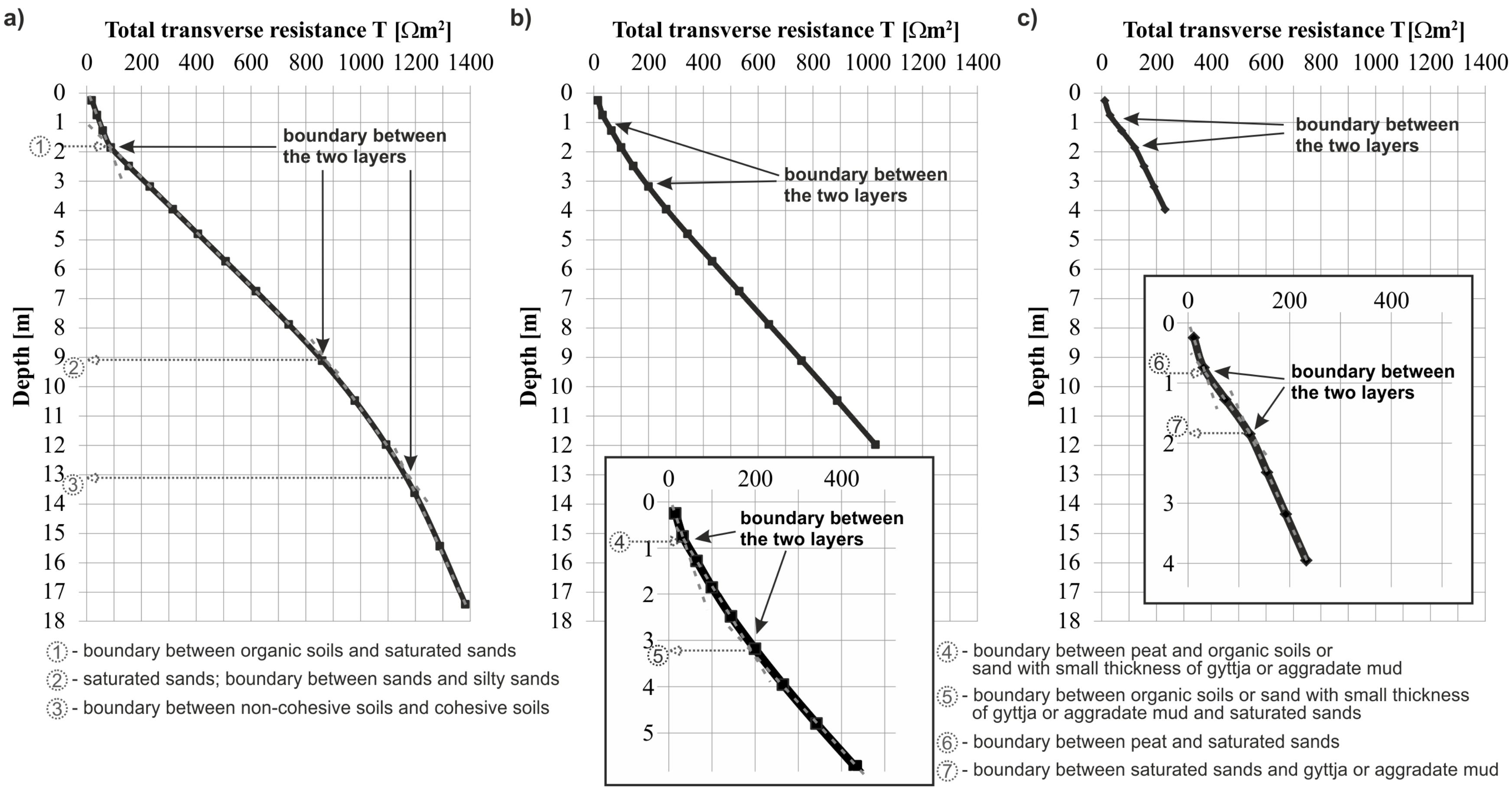

Fig. 6 Determination of boundaries between physical layers, which correspond to the engineering geological layers based on the relationship of total transverse resistance vs. depth. Analysis based on data from electrical resistivity imaging measurements a) 40m of cross-section I-I in a Schlumberger array b) 40m of cross-section I-I in a gradient array c) 70m of cross-section I-I in a gradient array.

of the aquifer (e.g. Salem, 1999; Singh and Singh, 2016). Total transverse resistance vs. depth is presented on the graph and change of the angle of the curve on the graph will allow to determine the depths of boundaries between layers characterized by different physical properties (Fig. 6). Obviously, due to measurement resolution, the layers distinguished by ERI will be much less accurate than those recognized by RCPT.

Interpretation of measurements from resistivity imaging results in some ambiguity, which increases with a more complex geological structure. The way to reduce this ambiguity of interpretation is integration with additional geophysical datasets and geological data to tie the ERI sections. The integration of resistivity from RCPT projected on the inverse model resistivity section for ERI_2 is shown in Figure 7a. This integration provides information at different scales and different accuracy. Nevertheless, a high concordance may be observed for the subsurface zone, to the first boundary between layers characterized by highly different physical properties. Boundaries between layers with different physical properties interpreted from ERI and lithological logs interpreted from RCPT have been correlated with projected boreholes and shown in Figure 7b. The boundaries interpreted from ERI are concordant with the data from boreholes and RCPT interpretation. Based on the compiled data, the boundary which is most significant for the foundation of the bridge construction was determined between the packet of organic soils and the underlying fluvial sands.

CONCLUSIONS

The conducted surveys have allowed to confirm the effectiveness of electrical resistivity imaging to determine the distribution of organic soils occurring directly below the surface. Application of the ERI method helps to assess the range of organic soils, providing that variability exists in the physical properties of organic and surrounding soils. The resolution of the obtained distribution of resistivity images is influenced by the applied array measurements. The image of resistivity obtained from the measurements with a gradient array is characterized by a much higher lateral resolution and a shallower depth of prospection than the Schlumberger array (Fig. 3).

Surveys using the geoelectrical method have allowed to characterize the spatial variability of the foundation structure for a bridge. Information on the variability of the soil foundation obtained from ERI surveys can be correlated with point data from boreholes. RCPT soundings enable an accurate determination of vertical variability in the soil medium. Application of the "cumulative resistivity" method to RCPT allows for determining the boundaries between layers having different physical properties, usually corresponding to boundaries of geological-engineering layers. The results of RCPT measurements have turned out to be very useful in the interpretation of ERI measurements and the geological engineering model. The presented analyses indicate that RCPT should be commonly used in the recognition of the ground characterized by complex soil conditions.

In the study area, the resistivity of organic soils is in the range of 20-60 Ωm. In RCPT measurements, ρ was in the range of 30-50 Ωm, whereas in ERI changed in the range of 20 to 60 Ωm. Interbeds of sand and gyttja have averaged resistivity values for these soils in the range of 60 to 80 Ωm. Based on the presented data it was possible to determine the most significant boundary for the foundation of the bridge construction between the packet of organic soils and the underlying fluvial sands.

ACKNOWLEDGEMENTS

The Terrameter LS apparatus, produced by the Swedish company ABEM, was purchased as part of the Regional Operational Program project entitled: "Modernization and equipment of the laboratories of the Faculty of Geology, University of Warsaw, to conduct research essential for Mazovia in the field of environment geoengineering - STAGE I, No. RPMA.01.01.00-14-011/10".

The authors express their thanks to the two anonymous Reviewers for their valuable comments and suggestions which contributed to improve the quality of the manuscript.

REFERENCES

Antoniuk, J. and Mościcki, J.: 1994, A method of penetrometer-based electrical resistivity logging - examples of applications. Przegląd Geologiczny, 42, No. 10, 857–862, (in Polish with English summary).

Antoniuk, J. and Mościcki, W.J.: 2001, Application of geoelectric methods into studying and protecting of geological environment influenced by human activity (vicinity of municipal and industrial waste dumps, settling reservoirs etc.. Geophysics in environmental engineering and protection for needs of local self-government, Dębe near Warsaw, S. 9–31, Marzec 2001, (in Polish with English summary).

Cai, G., Chu, Y., Liu, S. and Puppala, A.J.: 2016, Evaluation of subsurface spatial variability in site characterization based on RCPTU data. Bulletin of Engineering Geology and the Environment, 75, No. 1, 401–412. DOI: 10.1007/s10064-015-0727-8

Comas, X., Slater, L. and Reeve, A.: 2004, Geophysical evidence for peat basin morphology and stratigraphic controls on vegetation observed in a Northern Peatland. Journal of Hydrology, 295, 173–184. DOI: 10.1016/j.hydrol.2004.03.008

Comas, X., Terry, N., Slater, L., Warren, M., Kolka, R., Kristiyono, A., Sudiana, N., Nurjaman, D. and Darusman, T.: 2015, Imaging tropical peatlands in Indonesia using ground-penetrating radar (GPR) and electrical resistivity imaging (ERI): implications for carbon stock estimates and peat soil characterization. Biogeosciences, 12, 2995–3007. DOI: 10.5194/bg-12-2995-2015

Dahlin, T.: 1996, 2D resistivity surveying for environmental and engineering applications. First Break, 14, 275–283. DOI: 10.3997/1365-2397.1996014

Dahlin, T. and Zhou, B.: 2004, A numerical comparison o 2D resistivity imaging with ten electrode arrays.

Geophysical Prospecting, 52, No. 5, 379–398. DOI: 10.1111/1365-2478.2004.00423.x
Dahlin, T., Garin, H. and Palm, M.: 2004, Combined resistivity imaging and RCPT for geotechnical pre-investigation. Proc. Nordic Geotechnical Meeting (14th NGM), Ystad Sweden, C81-C88.
Dahlin, T. and Zhou, B.: 2006, Multiple-gradient array measurements for multichannel 2D resistivity imaging. Near Surface Geophysics, 4, No. 2, 113–123. DOI: 10.3997/1873-0604.2005037
Daniel, C.R., Giacheti, H.L., Howie, J.A. and Campanella, R.G.: 1999, Resistivity piezocone (RCPTU) data interpretation and potential applications. Proc. XI Pan-American Conference on Geotechnical Engineering, Igusau Falls, Brazil 1–8.
Dobak, P. and Wyrwicki, R.: 2000, Impermeable properties of lacustrine chalk. Przegląd Geologiczny, 48, No. 5, 412–415, (in Polish with English summary).
Ercoli, M., Pauselli, C., Forte, E., Di Matteo, L., Mazzocca, M., Frigeri, A. and Federico, C.: 2012, A multidisciplinary geological and geophysical approach to define structural and hydrogeological implications of the Molinaccio spring (Spello, Italy). Journal of Applied Geophysics, 77, 72–82. DOI: 10.1016/j.jappgeo.2011.11.011
Everett, M.E.: 2013, Near-Surface Applied Geophysics. Cambridge University Press, New York, 441 pp.
Fukue, M., Minato, T., Matsumoto, M., Horibe, H. and Taya, N.: 2001, Use of a resistivity cone for detecting contaminated soil layers. Engineering Geology, 60, 361–369. DOI: 10.1016/Soo13-7952(00)00116-2
Ganerød, G.V., Rønning, J.S., Dalsegg, E., Elvebakk, H., Holmøy, K., Nilsen, B. and Braathen, A.: 2006, Comparison of geophysical methods for sub-surface mapping of faults and fracture zones in a section of the Viggja road tunnel, Norway. Bulletin of Engineering Geology and the Environment, 65, 231–243. DOI: 10.1007/s10064-006-0041-6
General Director for National Roads and Motorways: 2015, Zarządzenie, nr 58, Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 23 listopada 2015 r. w sprawie dokumentacji do realizacji inwestycji, (in Polish).
Herman, R.: 2001, An introduction to electrical resistivity in geophysics. American Journal of Physics, 69 (9), 943–952, DOI: 10.1119/1.1378013
Hobbs, N.B.: 1986, Mire morphology and the properties and behaviour of some foreign peats. Quarterly Journal of Engineering Geology and Hydrogeology, 19, 7–80. DOI: 10.1144/GSL.QJEG.1986.019.01.02
Kim, Y., Oh, M. and Park, J.: 2009, Analysis of resistivity data obtained from cone penetrometer in contaminated soil layers. Environmental Geology, 58, 1309–1317. DOI: 10.1007/s00254-008-1634-0
Kowalczyk, S. and Mieszkowski, R.: 2011, Determination of a bottom layer of organic soil using geophysical methods at two sites on the Polish Lowland. Biuletyn Państwowego Instytutu Geologicznego, 446, 191–198, (in Polish with English summary).
Kowalczyk, S., Zawrzykraj, P. and Mieszkowski, R.: 2015, Application of electrical resistivity tomography in assessing complex soil conditions. Geological Quarterly, 59, No. 2, 367–372. DOI: 10.7306/gq.1172
Kowalczyk, S., Cabalski, K. and Radzikowski, M.: 2017, Application of geophysical methods in the evaluation of anthropogenic transformation of the ground: A Case study of the Warsaw environs, Poland. Engineering Geology, 216, 42–55. DOI: 10.1016/j.enggeo.2016.11.008
Lechowicz, Z. and Szymański, A.: 2002a, Deformation and stability of embankment constructed on organic subsoil. Part I. Testing methods. Wydawnictwo SGGW, Warszawa, (in Polish with English summary).
Lechowicz, Z. and Szymański, A.: 2002b, Deformation and stability of embankment constructed on organic subsoil. Part II. Calculation methods). Wydawnictwo SGGW, Warszawa, (in Polish with English summary).
Loke, M.H.: 1996–2002, Tutorial: 2-D and 3-D electrical imaging surveys. Geotomo Software.
Loke, M.H.: 2001, Electrical imaging surveys for environmental and engineering studies. A Practical Guide to 2-D and 3-D Surveys: RES2DINV Manual, Geotomo Software, Malaysia.
Loke, M.H. and Barker, R.D.: 1996, Rapid least squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting, 44, 131–152. DOI: 10.1071/j.1365-2478.1996.tb00142.x
Loke, M.H., Acworth, I. and Dahlin, T.: 2003, A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. Exploration Geophysics, 34, 182–187.
Loke, M.H.: 2011, Electrical resistivity surveys and data interpretation. In: Gupta, H. (ed.), Solid Earth Geophysics Encyclopaedia (2nd Edition) "Electrical and Electromagnetic", Springer-Verlag, 276-283.
Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O. and Wilkinson, P.B.: 2013, Recent developments in the direct-current geoelectrical imaging method. Journal of Applied Geophysics, 95, 135–156. DOI: 10.1016/j.japppgeo.2013.02.017
Long, M., Donohue, S., L'Heureux, J.S., Solberg, I.L., Rønning, J.S., Limacher, R. and Lecomte, I.: 2012, Relationship between electrical resistivity and basic geotechnical parameters for marine clays. Canadian Geotechnical Journal, 49, No. 10, 1158–1168. DOI: 10.1139/t2012-080
Madaschi, A. and Gajo, A.: 2015, One-dimensional response of peaty soils subjected to a wide range of oedometric conditions. Géotechnique, 65, No. 4, 274–286. DOI: 10.1680/geot.14.P.144
Mahdavi, H., Fatahi, B., Khabbaz, H., Vincent, P. and Kelly, R.: 2016, Comparison of coupled flow-deformation and drained analyses for road embankments on CMC improved ground. Procedia Engineering, 143, 462–469. DOI: 10.1016/j.proeng.2016.06.058
Maślakowski, M., Kowalczyk, S., Mieszkowski, R. and Józefiak, K.: 2014a, Using Electrical Resistivity Tomography (ERT) as a tool in geotechnical investigation of the substrate of a highway. Studia Quaternaria, 31, 83–89. DOI: 10.2478/squa-2014-0008
Maślakowski, M., Michalczyk, R., Józefiak, K. and Superczyńska, M.: 2014b, The use of Controlled Modulus Columns (CMC) to improve the subsoil characteristics -expressway S8 case study. Czasopismo Logistyka 6/2014 - DVD No. 3, 7130–7137, (in Polish with English summary).
Młynarek, Z., Tschuschke, W. and Wierzbicki, J.: 1997, Soil classification by means of CPTU). Proc. of XI Polish Conference on Soils Mechanics and Foundation Engineering, Gdańsk, 119–126, (in Polish).
Mondelli, G., Giacheti, H.L., Boscov, M.E.G., Elis, V.R. and Hamada, J.: 2007, Geoenvironmental site investigation using different techniques in a municipal solid waste disposal site in Brazil. Environmental Geology, 52 (5), 871–887. DOI: 10.1007/s00254-006-0529-1
Myślińska, E.: 1999, Physical properties of peats and evaluation of methods of their determination. Przegląd Geologiczny, 47, No. 7, 676–682, (in Polish with English summary).

Myślińska, E.: 2001, Organic soils and laboratory methods for their testing. Wydawnictwo Naukowe PWN, Warszawa, (in Polish).

Myślińska, E.: 2003, Classification of organic soils for engineering geology. Geological Quarterly, 47, No. 1, 39–42.

Ngan-Tillard, D., Venmans, A., Slob, E. and Mulder, A.: 2010, Total engineering geology approach applied to motorway construction and widening in the Netherlands: Part II: Pilot site in tidal deposits. Engineering Geology, 114, 171–180. DOI: 10.1016/j.enggeo.2010.04.015

Osinowo, O.O., Akanji, A.O. and Akinmosin, A.: 2011, Integrated geophysical and geotechnical investigation of the failed portion of a road in Basement Complex terrain, southwestern Nigeria, RMZ. Materials and Geoenvironment, 58, 143–162.

Palacky, G.J.: 1987, Clay mapping using electromagnetic methods. First Break, 5, 295–306. DOI: 10.3997/1365-2397.1987015

Pasierb, B. and Nawrocki, W.: 2015, A study of bedrock geological structure of the ARENA object in Kraków-Czyżyny using geophysical methods to detect the presence of organic soil. Przegląd Geologiczny, 63, No. 5, 289–294, (in Polish with English summary).

Pierwoła, J., Badera, J. and Mirkowski, Z.: 2011, Identification of geotechnical conditions in areas of former shallow mining activity using geoelectrical methods. In: Idziak, A.F. and Dubiel R. (Eds.): Geophysics in Mining and Environmental Protection, Springer Berlin Heidelberg, 91–100. DOI: 10.1007/978-3-642-19097-1_9

Pietrzykowski, P.: 2008, Electrical methods in geological and engineering investigations of interglacial calcareous and organic sediments from Warsaw. Geologija, 50 (Supplement), S95–S100. DOI: 10.2478/v10056-008-0032-3

Pietrzykowski, P.: 2011, Eemian gyttja and lacustrine chalk from Warsaw as an example of ”hard” organic soils. Biuletyn Państwowego Instytutu Geologicznego, 446, No. 2, 385–396, (in Polish with English summary).

Robertson, P.K.: 2010, Soil behaviour type from the CPT: an update. 2nd International Symposium on Cone Penetration Testing, CPT'10, Huntington Beach, CA, USA.

Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J.: 1986, Use of piezometer cone data. Use of In Situ Tests in Geotechnical Engineering. Proceedings of In Situ '86, Blacksburg, Specialty Publication, 1263–1280.

Robertson, P.K. and Cabal K.L.: 2012, Guide to Cone Penetration Testing for Geotechnical Engineering. Gregg Drilling and Testing, Inc, Signal Hill, California, US., 5th Edition.

Salem, H.S.: 1999, Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements. Hydrology and Earth System Sciences, 3, 421–427.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A. and Richard, G.: 2005, Electrical resistivity survey in soil science: a review. Soil and Tillage Research, 83, 173–193. DOI: 10.1016/j.still.2004.10.004

Sarnacka, Z: 1976, Detailed geological map of Poland 1:50,000. Sheet Raszyn (559). Wydawnictwa Geologiczne, Warszawa, (in Polish).

Sarnacka, Z.: 1978, Explanation to detailed geological map of Poland 1:50, 000. Sheet Raszyn (559). Wydawnictwa Geologiczne, Warszawa, (in Polish).

Schmertmann, J.H.: 1975, Measurement of in situ shear strength. Proc., Specialty Conference on In Situ Measurement of Soil Properties: ASCE. 2. ASCE, USA, 57–138.

Seidel, K. and Lange, G.: 2007, Direct Current Resistivity Methods. In Knödel K., Lange G., Voigt H.-J. (Eds.), Environmental Geology. Springer-Verlag Berlin Heidelberg, 205–237. DOI: 10.1007/978-3-540-74671-3_8

Singh, S. and Singh, V.S.: 2016, Estimation of hydraulic characteristics from electrical resistivity data in coastal aquifers of southern India. Journal of the Geological Society of India, 88, No. 1, 77–86. DOI: 10.1007/s12594-016-0460-3

Slater, L.D. and Reeve, A.: 2002, Investigating peatland stratigraphy and hydrogeology using integrated electrical geophysics. Geophysics, 67, 365–378. DOI: 10.1190/1.1468597

Stenzel P. and Szymanko J.: 1973, Geophysical methods in hydrological and geological-engineering investigations. Wydawnictwa Geologiczne, Warszawa, (in Polish).

Ulusay, R., Tuncay, E. and Hasancebi, N.: 2010, Geo-engineering properties and settlement of peaty soils at an industrial site (Turkey). Bulletin of Engineering Geology and the Environment, 69, No. 3, 397–410. DOI: 10.1007/s10064-010-0290-2

Walter, J., Hamann, G., Lück, E., Klingenfuss, C. and Zeitz, J.: 2016, Stratigraphy and soil properties of fens: Geophysical case studies from northeastern Germany. Catena, 142, 112–125. DOI: 10.1016/j.catena.2016.02.028

Wisén, R., Christiansen, A., Dahlin, T. and Auken, E.: 2008, Experience from two resistivity inversion techniques applied in three cases of geotechnical site investigation. Journal of Geotechnical and Geoenvironmental Engineering, 134, 1730–1742. DOI: 10.1061/(ASCE)1090-0241(2008)134:12(1730)

Wysokiński, L. (team leader): 2004, Geological and engineering documentation as part of a study of the construction project of construction of the expressway on the section Salomea - Wolica linking with the national road No. 7. Instytut Techniki Budowlanej (Building Research Institute), (unpublished, in Polish).

Yang, M. and Liu, K.: 2016, Deformation behaviors of peat with influence of organic matter. SpringerPlus, 5, 1–18. DOI: 10.1186/s40064-016-2232-3

Yoon, H.K., Jung, S.H. and Lee, J.S.: 2011, Characterisation of subsurface spatial variability using a cone resistivity penetrometer. Soil Dynamics and Earthquake Engineering, 31, No. 7, 1064–1071. DOI: 10.1016/j.soildyn.2011.03.012

Zawrzykraj, P.: 2005, Practicability of new geoelectrical equipment for the lithological characteristic of varved clays from Plecewice near Sochaczew (central Poland). Przegląd Geologiczny, 53, No. 8, 677–681, (in Polish with English summary).

Zini, L., Calligaris, C., Forte, E., Petronio, L., Zavagno, E., Boccali, C. and Cucchi, F.: 2015, A multidisciplinary approach in sinkhole analysis: The Quinis village case study (NE-Italy). Engineering Geology, 197, 132–144. DOI: 10.1016/j.enggeo.2015.07.004

Zonge, K., Wynn, J. and Urquhart, S.: 2005, Resistivity, induced polarization, and complex resistivity. In: Butler, D.K., (Ed.) Near-surface geophysics. Investigation in geophysics. No. 13, Society of Exploration Geophysicists, 265–300.

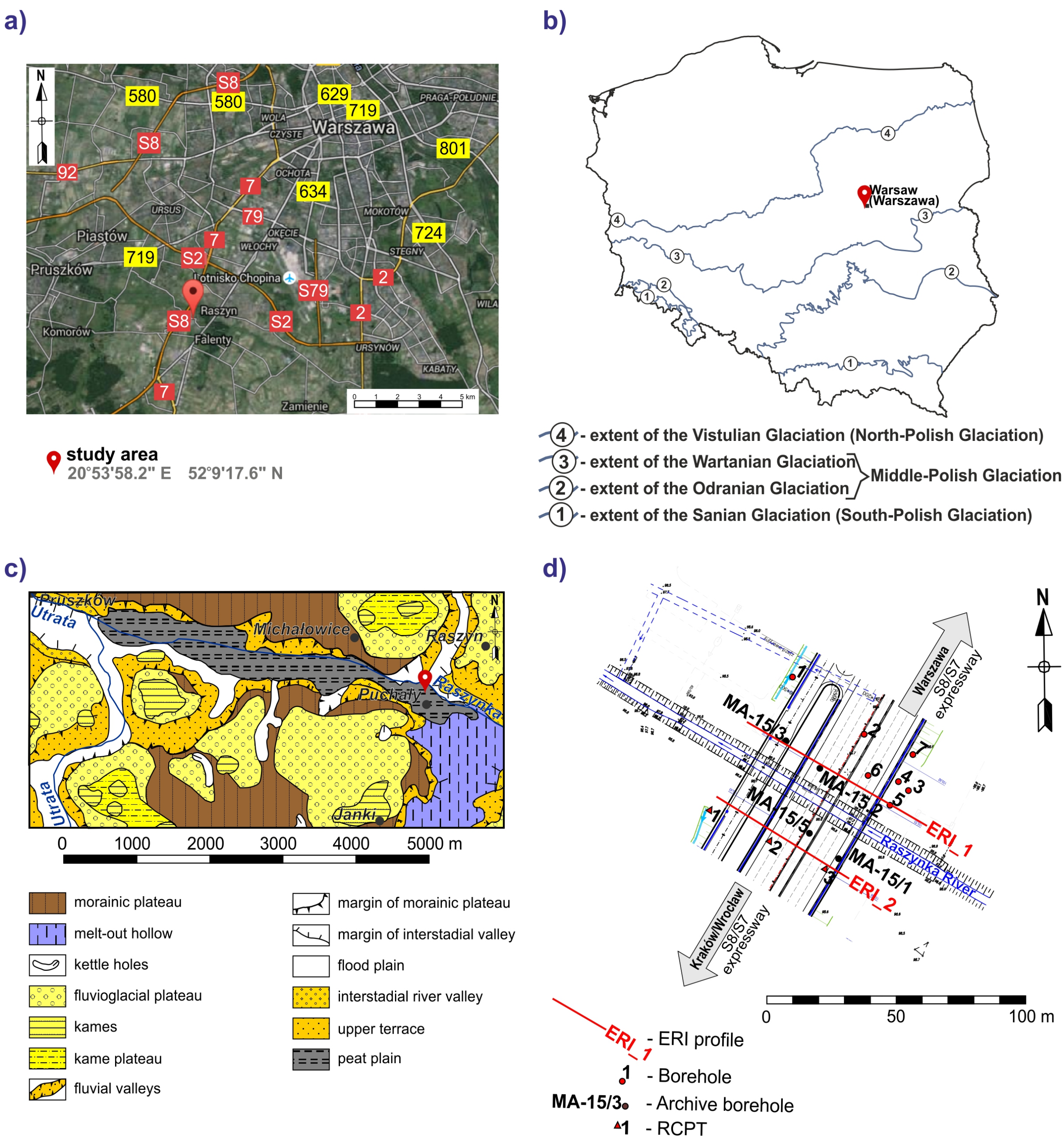

Fig. 1 Study area a) satellite image with study area marked (www.maps.google.com; adopted), b) position of the study area on the map of Poland, c) fragment of geomorphological map (after Sarnacka, 1976), d) location of the survey.

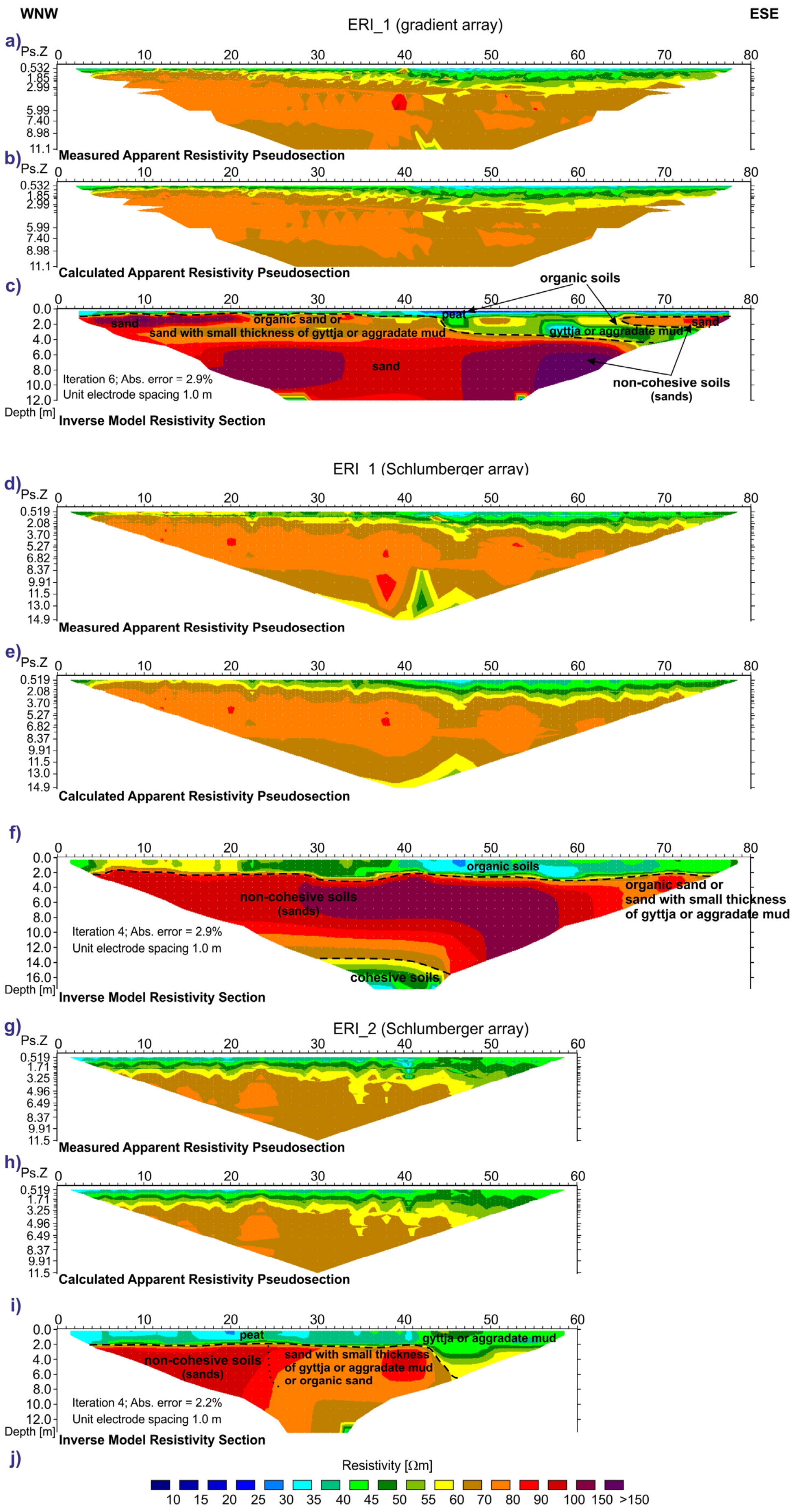

Fig. 3 Results of ERI survey. Measured [a), d), g)] and calculated [b), e), h)] apparent resistivity pseudosections and inverse model resistivity sections with interpretation [c), f), i)] of cross-section I-I in a gradient array, in a Schlumberger array and cross-section II-II in a Schlumberger array, respectively; j) resistivity scale (for location see Fig. 1).

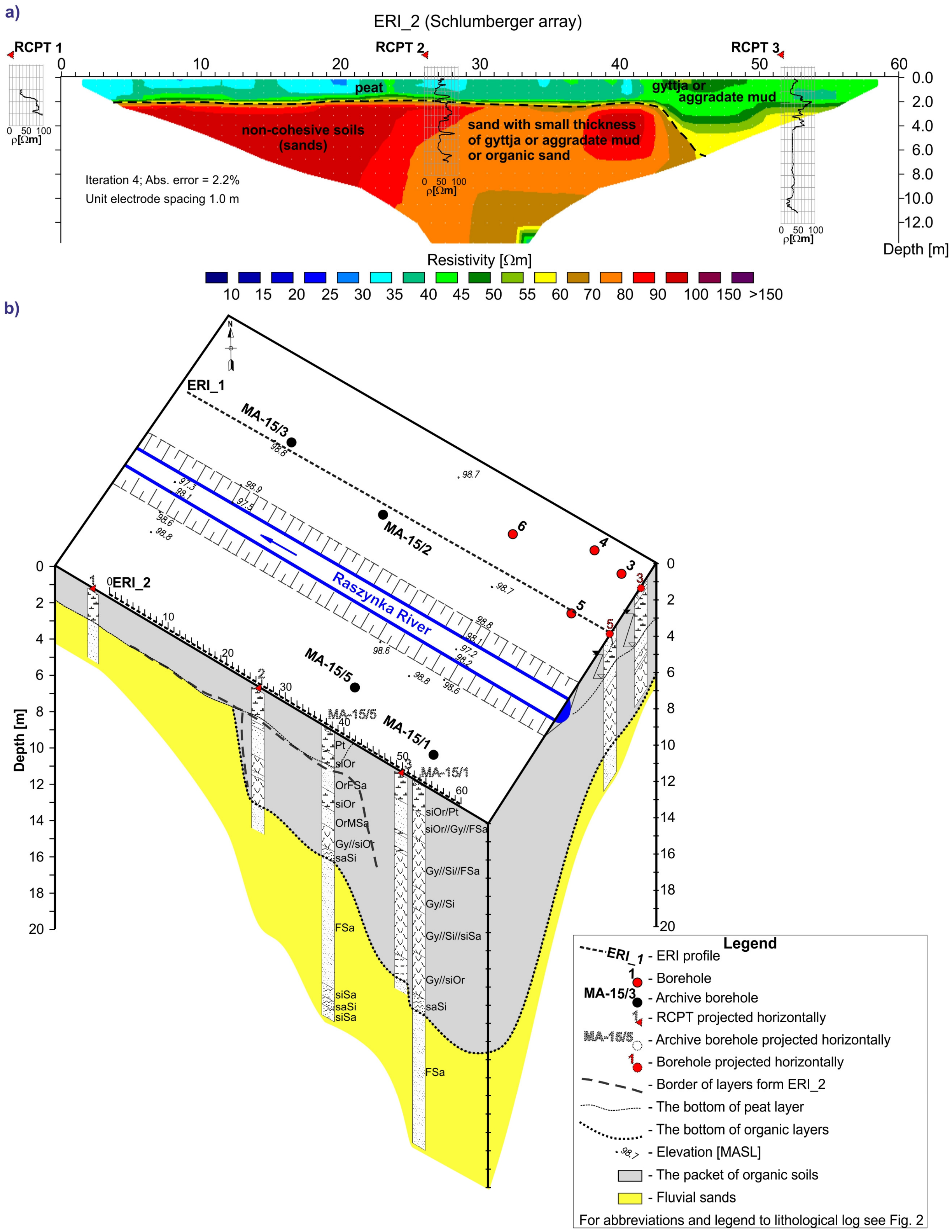

Fig. 7 Interpretation of obtained data. a) Resistivity from RCPT projected on an inverse model resistivity section for ERI_2. b) Block diagram showing the generalized geological model.