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Application of electrical resistivity tomography in assessing complex soil conditions

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Appropriate assessment of spatial variation of soil and hydrogeological conditions is a crucial issue in recognizing foundation soil. The best methods to achieve this goal are those that supply continuous rather than scattered data on soil medium variation. Electrical resistivity was measured with the resistivity cone penetration test (RCPT) and electrical resistivity tomography (ERT) with electrodes spaced at 1 and 3 m in order to discriminate peat layers beneath low-resistivity clays. Soil conditions determined by drillings and ERT were not concordant, therefore resistivity modelling of the medium was conducted based on geological units determined by drillings and values of apparent resistivity obtained from RCPT. The strata thickness and electrode spacing is shown to have an influence on resistivity imaging in complex soil conditions.

Key words: electrical resistivity tomography (ERT), resistivity cone penetration test (RCPT), peat.

INTRODUCTION

Numerous reports (Białostocki et al., 2006; Białostocki and Farbisz, 2007; Soupios et al., 2007; Kowalczyk and Mieszkowski, 2011; Bzówka et al., 2012) point to the necessity of application and to advantages of geophysical surveys in recognizing soil and hydrogeological conditions. Electrical resistivity is one of the leading geophysical methods applied for assessing the quality of foundation soil in civil engineering (e.g., Cosenza et al., 2006; Soupios et al., 2007; Sudha et al., 2009; Syed and Siddiqui, 2012) and for determining the depth to the groundwater table (e.g., Owen et al., 2005; Kirsch, 2009; Saad et al., 2012).

Application of resistivity surveys, particularly electrical resistivity tomography (ERT), allows for an estimated projection of the soil and hydrogeological conditions in the subsurface using imaging of apparent resistivity obtained from the survey, both with regard to its magnitude and the geometry of the geological units. A detailed, although scattered identification of the soil and hydrogeological conditions is obtained from drillings which act as benchmarks and are essential for a correct recognition of the geological structure, particularly in complex soil conditions. According to Białostocki (1974), the drillings should be localized based on initial interpretation of geophysical data. Moreover, drilling data should be taken into account in the final stage of geophysical interpretations.

Electrical resistivity surveys are characterized by high effectiveness of their prospection, because electrical resistivity is a parameter that perfectly reflects the lithological and hydrogeological variation of the geological medium (Białostocki and Farbisz, 2007; Farbisz et al., 2010). Apparent resistivity obtained directly from the measurements does not define the resistivity values in the studied geological medium but may be used to image its variation.

The paper presents an attempt of identifying and characterizing the position of two peat horizons occurring within sandy deposits under a low-resistivity clay layer. The attempt was achieved by applying electrical resistivity tomography in the field with variable electrode spacing and a resistivity model of the medium, developed on the basis of drilling and RCPT sounding data.

SITE CHARACTERISTICS

The present survey was conducted near Zwierzyniec, ca. 4 km to the north-east of Radzymin and ca. 30 km to the north-east of Warszawa (central Poland; Fig. 1). The study area is located within a vast geomorphological unit known as the Radzymin terrace. Its formation is linked with the Vistulian Glaciation, during which a marginal lake developed in the Warsaw Basin. The lake resulting from the damming of water flow by the Scandinavian ice sheet was subsequently filled with ice-dammed deposits. After the retreat of the ice sheet, the flat top of the ice-dammed deposits was covered by a thin layer of alluvial sands, which were later subject to eolian processes (Baraniecka and Konecka-Betley, 1987).

The geological succession in the study area begins (from the top) with fine sands of eolian origin. They are underlain by horizontal varved clays with thin intercalations of silty sands. Deeper occur sandy and organic deposits representing the Eemian Interglacial. Fine and medium sands with gravel and pebbles at their base are separated from the organic deposits

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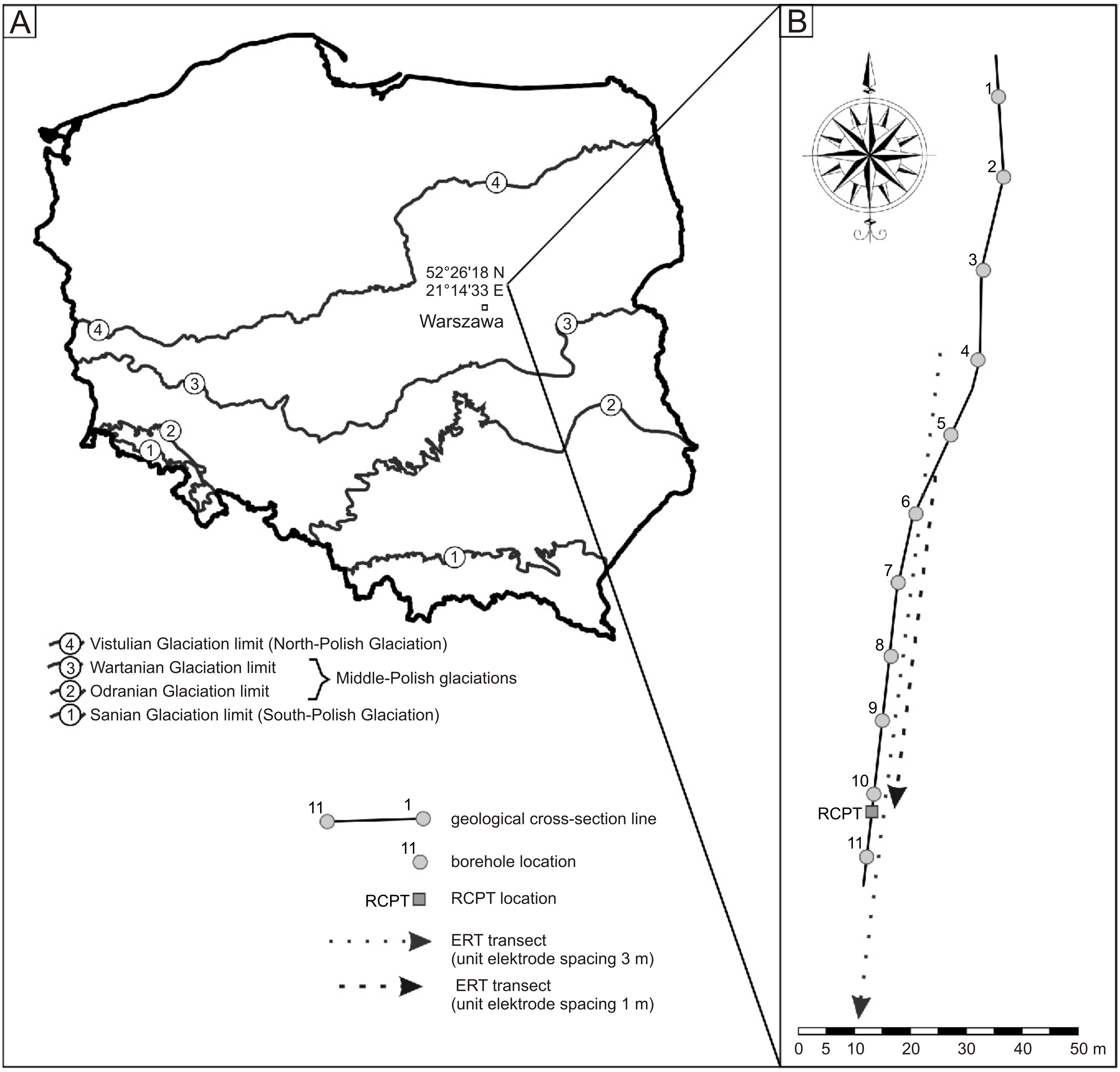

Fig. 1. Study area

A – position of the study area on the map of Poland, **B** – location sketch of the survey

by ice-dammed clays. The organic series is composed of two peat horizons and gyttja occurring in the basal parts of the lower peat horizon. The peat horizons are separated by fine sands of alluvial origin. Below the organic deposits there are medium sands of fluvioglacial origin, underlain by glacial deposits of the Middle-Polish glaciations, represented by tills and silts (Fig. 2).

METHODS

Electrical resistivity methods involve the measurement of the subsurface changes of the electrical current, manifested as the increase or decrease of electric potential between two electrodes. This relationship is reflected by electrical resistivity, which may be linked with lithological variation of the soil or rocks. Electrical resistivity tomography (ERT) is a method allowing calculation of subsurface electrical resistivity based on a large number of measurements with application of numerous electrodes installed along a profile. ERT data were collected using the *ABEM* system in a Schlumberger array. The data was collected along two profiles with 1 and 3 m electrode spacing, and with lengths of 120 and 60 m, respectively. The data collected in this survey were interpreted using *RES2DINV* software (Loke and Barker, 1996; Loke et al., 2003) to provide an inverse model that approximates the actual subsurface structure. Data processing and the inversion process included selection of the most accurate geoelectrical model for the medium that would reflect data collected in the field. The procedure comprises successive, multiple calculations and subsequent comparisons (iterations), assuming a minimal matching error. High precision of ERT measurements, which allows tracing lateral and vertical variations of electrical resistivity in the medium,

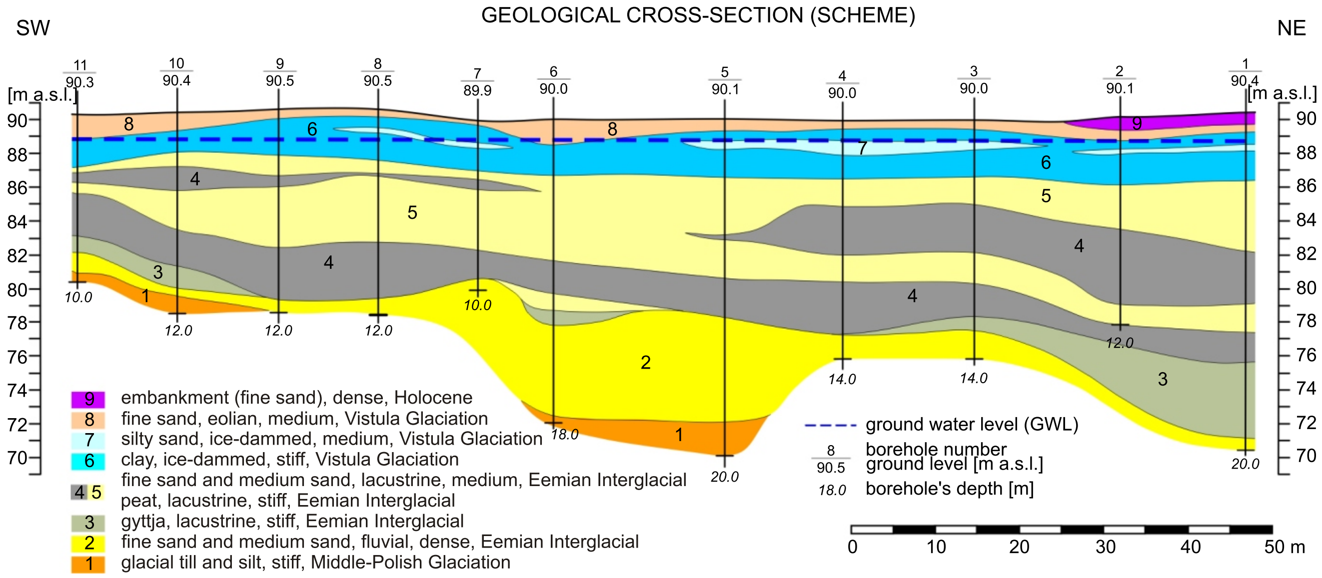

Fig. 2. Geological cross-section

results from the assumption that interpretation of the medium model is based on the subdivision of the measurement space into flat, parallel blocks and not into flat and parallel, infinite horizons (Loke, 2001).

ERT surveys supply a dense network of measurement points allowing for a quasi continuous record of variations in the image of physical properties characterizing the geological medium. Interpretation of the obtained model in ERT surveys was generally based on drillings, RCPT sounding, as well as resistivity range of the geological medium presented by Stenzel and Szymanko (1973).

Soil resistivity surveys conducted with application of the resistivity cone penetration test (RCPT) supply high resolution results due to the fact that the copper ring electrodes are spaced at 3 cm on an electrical module of the cone (Wenner array). When the cone penetrates the soil at a constant velocity of 2 cm/s, the following cone parameters are measured as a function of depth: cone resistance q_c, sleeve friction f_s and soil resistivity ${}_a$. Based on the friction ratio R_f, which is sleeve friction versus cone resistance, and the measured soil resistivity in relation to specific classification, it is possible to interpret the lithology of the medium.

RESULTS AND DISCUSSION

Correct application and interpretation of geophysical data in assessing soil and hydrogeological conditions requires not only the knowledge and understanding of the physical laws, on which the particular methods are based, but also geological data. Beside general data on the study area, detailed information comprising borehole data and laboratory analyses is also important.

According to the conducted drillings, the study area is characterized by complex soil conditions with regard to engineering-geological classification: the soil horizons are discontinuous, genetically diverse and include organic deposits (Fig. 2). From the ground surface, beneath a thin bed of sands and embankments, there is a continuous clay horizon with a variable thickness between 1.6–2.7 m and with lenses of fine and clayey sand. Deeper occur saturated sands with two peat horizons. The first peat horizon is discontinuous and variably thick between 0.3–4.4 m. The second peat horizon, 1.6–3.0 m thick, is separated from the first horizon by saturated sand, 0.6–4.0 m thick. Below the second peat layer, gyttja occurs locally on saturated sands. The lowest strata drilled were silts (with the top at 9.3–10.9 m below ground level) and tills (with the top at 17.5–18.0 m below ground level). The groundwater table in the study area was stabilized at ca. 1.3 m below the ground surface.

ERT survey aimed at discriminating peat horizons beneath the low-resistivity clays. So far, there are very few reports on the application of electrical resistivity surveys in depicting peat horizons below cohesive soils. However, such surveys are often used in studies of peatlands (Salter and Reeve, 2002; Comas et al., 2004; Nolan et al., 2008). Resistivity data was collected to characterize the peat thickness and structure and to image the hydrogeological framework beneath the organic soil. ERT surveys were made in two profiles along the same line, with electrodes spaced at 3 and 1 m, respectively. Generally, in the ERT method, the spacing between the particular electrodes is selected according to the desired resolution. Application of larger spacing results in deeper penetration of the geological medium but lower resolution of the obtained results. In the conducted survey, application of different spacing between the electrodes was aimed at checking the influence of spacing on the characteristics of complex soil conditions, particularly on the discrimination and description of the peat horizons.

The ERT survey allowed to obtain cross-sections imaging the distribution of resistivity in the basement, using 2D inversion (Fig. 3). These images show generalized models of the variation of physical parameters, which depend mainly on two factors: horizontal and vertical variation of the electrical properties of the particular soils, as well as thickness of particular horizons in the geological medium. The base of the sands and embankments occurring beneath the surface, as well as the top and base of the clays, characterized by the lowest values of resistivity in the area can be distinguished in electrical resistivity cross-sections. The ERT survey discriminated the presence of peat horizons in the subsurface. However, due to the fact that peats in the study area occur as rather thin, discontinuous horizons within the sands, their geometry is not easily determinable, because the resistivity of peats and sands occurring directly beneath the clays and between the sands has been generalized. Due to insignificant variation with regard to electrical properties,

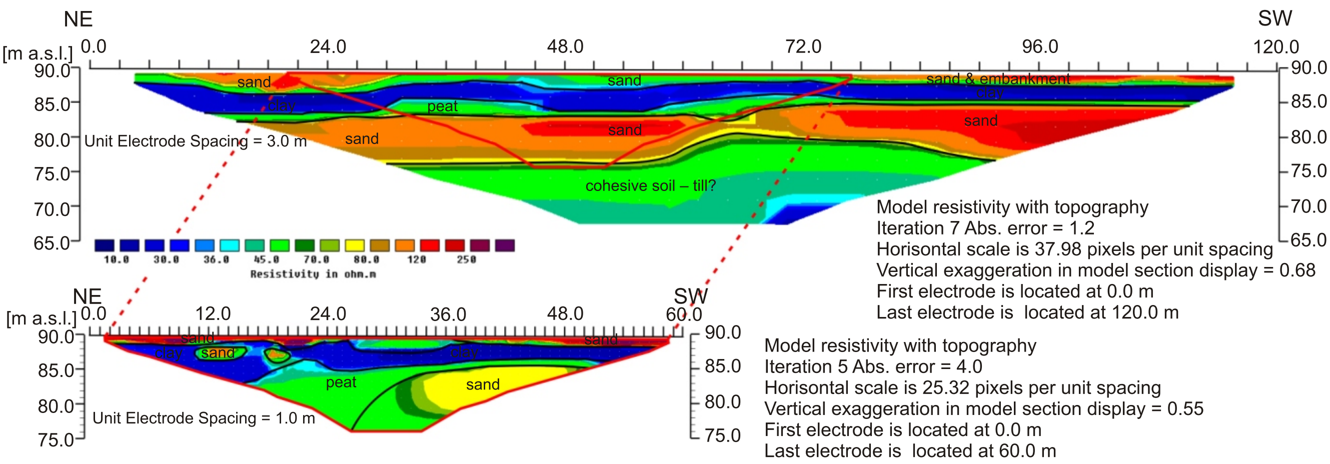

Fig. 3. Results of ERT survey made in a Schlumberger array at electrode spacing of 1 and 3 m

the organic deposits, i.e. peats and gyttja, have also been generalized on the obtained image (Fig. 3). Combination of ERT data and information supplied by drillings and RCPT sounding allows geological identification of the distinguished units.

Due to lack of full concordance between the geological situation recognized by drillings on the one hand and by ERT on the other, a model of resistivity variation based on geological units determined by drillings was prepared. The geological situation described above and shown in the geological cross-section (Fig. 2) was modelled with *RES2DMOD* software (Loke, 2002), which is a free 2D forward modelling program that calculates the apparent resistivity pseudosection for a user-defined 2D subsurface model. Values of apparent resistivity for particular soil horizons were accepted from RCPT sounding conducted in the vicinity of the drilling (Fig. 4). The determined range of horizons with similar electrical properties is concordant with the lithological units drilled in the nearby borehole, as well as horizons evaluated through the R_f friction ratio. Resistivity values accepted after RCPT are as follows: 10 m for clays; 40 m for the first peat horizon, 45 m for the second peat horizon; 50 m for gyttja; 85 m for saturated fine sands; and 120 m for saturated medium sands. The following values of resistivity were accepted for the remaining soils on the geological cross-section: 60 m for tills; 70 m for clayey sands and silts; 300 m for sands in the aeration zone; and 500 m for embankments.

2D resistivity model was prepared using *RES2DMOD* software which corresponds to the structure of the sub-surface part of the geological object obtained by a Schlumberger array for electrode spacing at 1 m (Fig. 5) and 2 m (Fig. 6). For these two cases, models of apparent resistivity were calculated with the help of *RES2DMOD* software and the obtained values were saved in *RES2DINV* format. These activities were aimed at preparing data to calculate actual resistivity by inversion (Figs. 5 and 6 – Inverse Model Resistivity Section) of the apparent resistivity data (Measured Apparent Resistivity Pseudosection).

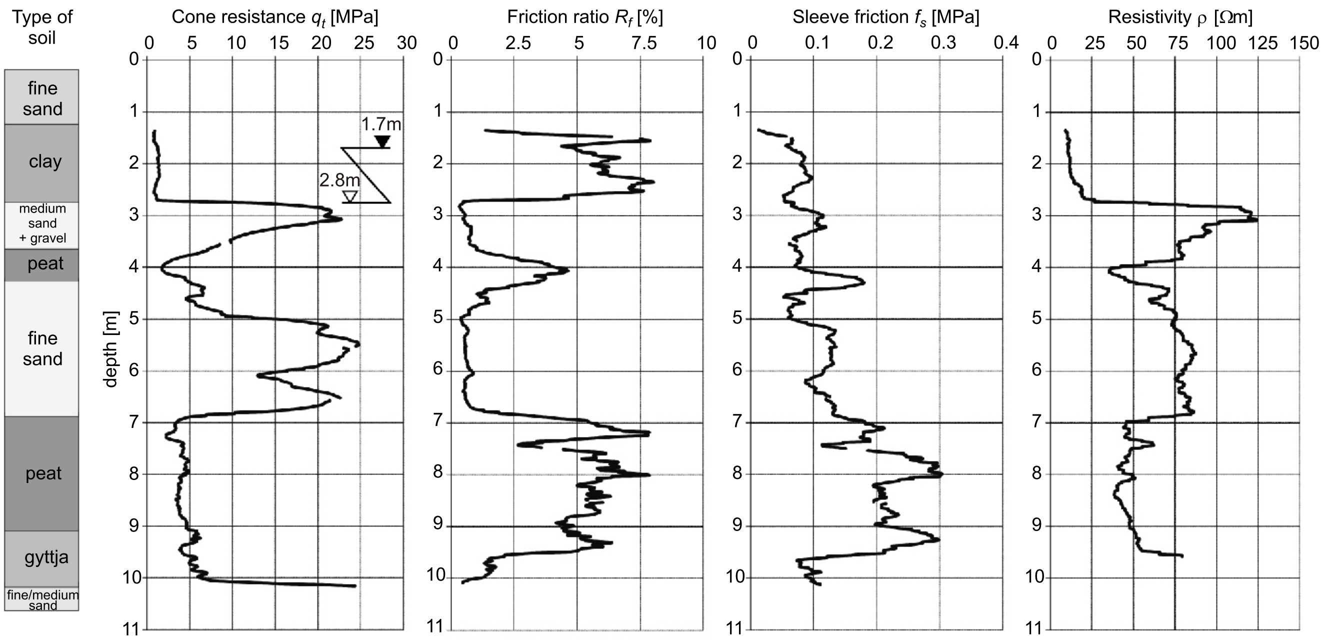

Fig. 4. Resistivity cone penetration test (RCPT) results

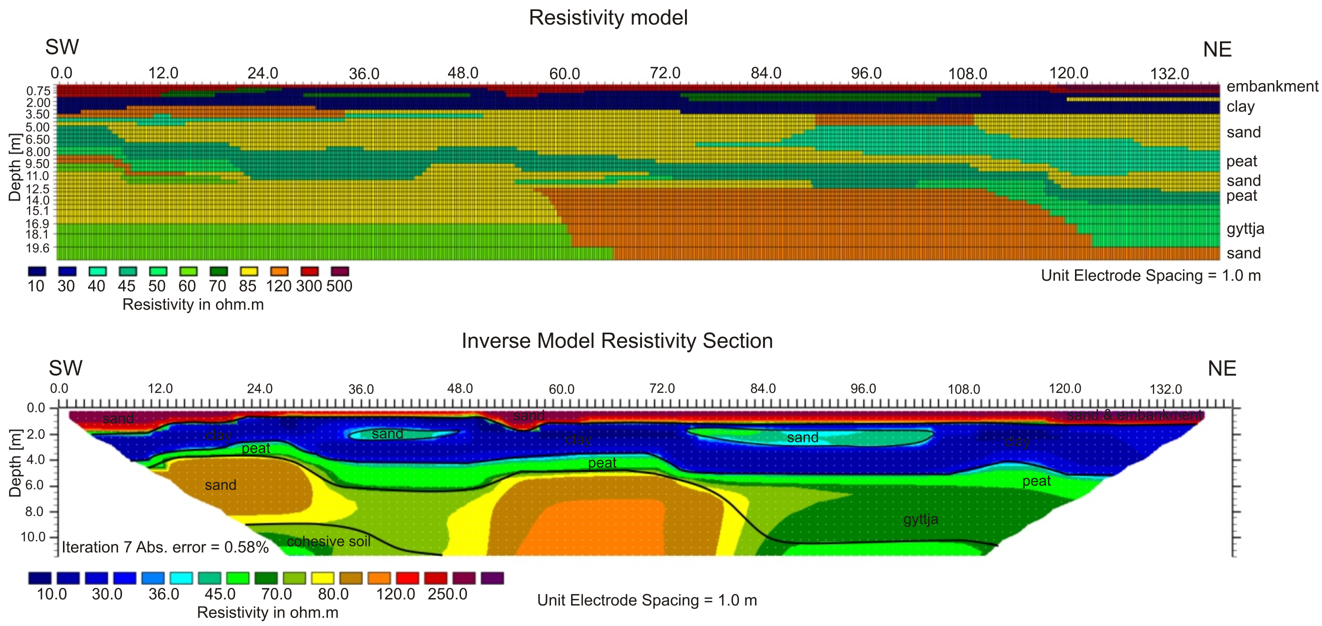

Fig. 5. Results of modelling made in a Schlumberger array at electrode spacing of 1 m

RES2DINV software allowed to obtain an inverse model resistivity section, which is the image of actual resistivity, and a calculated apparent resistivity pseudosection, which shows theoretical data that would have been registered in the field in the case when the obtained resistivity model would have corresponded with the actual resistivity imaging in the studied medium. The similarities between the apparent resistivity imaging introduced as input data to *RES2DINV* software and the calculated imaging indicate the correctness of the obtained model of resistivity imaging and is shown as the absolute error values (Abs. error).

The model shows that electrode spacing in ERT surveys had significant influence on the image resolution of the resistivity variation. In the model prepared for 1 m electrode spacing, the geometry of particular resistivity units can be determined in larger detail in comparison to the model prepared for 2 m spacing; in turn, the depth of the prospection increases with increase of electrode spacing.

Analysis of geoelectrical cross-sections obtained during modelling confirms the conclusions drawn from geoelectrical field surveys, i.e. resistivity for the discontinuous, thin peat horizons has been generalized with that for sands occurring within and above the organic deposits.

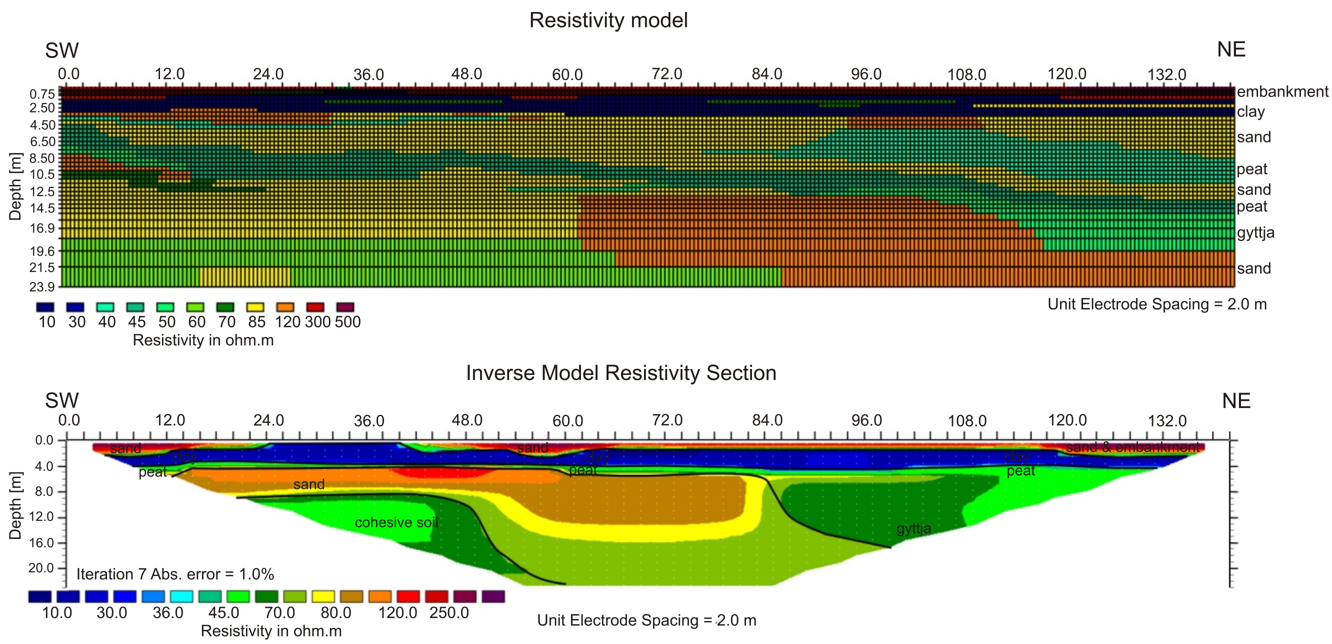

Fig. 6. Results of modelling made in a Schlumberger array at electrode spacing of 2 m

CONCLUSIONS

The ERT survey aimed at discriminating peat horizons lying beneath low-resistivity clays. The conducted analyses have accomplished this aim, but the detailed geometry of the peat layer could not be determined due to the fact that the resistivity of peats was generalized with the resistivity of sands, within which the peats occur.

ERT surveys do not supply satisfactory results in areas with complex soil conditions when the thickness of the particular horizons is small and/or the resistivity variation for particular horizons is low.

At present, the basic surveys determining the *in situ* shear strength of soils are CPT and DMT. The applied devices are frequently equipped with seismic (SCPT, SDMT) or electrical modules (RCPT). Soil resistivity continuously registered with penetration of cone in the soil should be taken into account in interpreting ERT or vertical resistivity surveys.

Models of apparent resistivity imaging in the surveyed medium are proposed to be made when interpreting electrical resistivity cross-sections for complex soil conditions. The thickness and number of distinguished units in the model should be based on knowledge gained from geological drillings, while the values of apparent resistivity for particular units should be accepted after RCPT surveys conducted in the vicinity of the borehole.

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