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USING ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) AS A TOOL IN GEOTECHNICAL INVESTIGATION OF THE SUBSTRATE OF A HIGHWAY

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Abstract
Geological and geotechnical engineering field tests, like structure drillings and dynamic (DPL, DPSH) or static probing (CPT), are considered for a fundamental source of information about soil and water environments. Since Eurocode 7 has been introduced, it has become more common to use also dilatometers (DMT) or pressure meters (PMT). Results obtained using all the mentioned tests are always of a discrete nature – information is provided in certain points in the field. However, they determine the basis for creating spatial models of geological structure and geotechnical conditions of a substratum. The range and number of investigations conducted (including drilling, probing and laboratory tests) influence precision, in which a geological structure is identified and thus, also affect probability of compatibility between spatial model and real geological conditions of a substratum. In the paper, results of non-invasive electrical resistivity tomography (ERT) method are presented, comprising 2-dimensional image of a soil medium resistance. Electrical resistance is a parameter that reflects diversification of a soil medium, considering its lithological aspect. In addition, when combined with drilling results, it can be used to accurate determination of boundaries between soil layers. Carrying out of ERT tests in the field during expressway construction contributed to identification of weak, low-strength soils like organic soils (peat, aggradated mud) and of soft consistency cohesive soils. These kinds of soil are the main cause for unacceptable deformations appearing in the new road engineering structure.

Key words: electrical resistivity tomography (ERT), expressway, field testing, geotechnical engineering, organic soils, peat.

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INTRODUCTION

Proper identification of soil and water conditions is essential before a designing process of any engineering investment can be started. Correct determination of soil parameters is a key factor for optimal designing and thus economical solutions. Therefore, it is also important to choose appropriate testing method during a pre-design phase of a project. Many researchers (Białostocki and Farbisz, 2007; Białostocki *et al.*, 2006; Bzówka *et al.*, 2012; Kowalczyk and Mieszkowski, 2011, Maślakowski, 2013) point out a need to use geophysical testing methods in identification of soil and water conditions and advantages of this approach during construction of roads and expressways. Many factors, like non-invasiveness, speed, ease of conducting tests act in favour for using these methods but the most important advantage is the possibility to obtain a spatial model of an analysed area (e.g. in electrical resistivity tomography).

Geophysical methods are used as complementary tests at the stage of soil substratum investigation and as reliability tests at building stages of an engineering object. Application of geophysical tests can significantly contribute to identification of soil substratum as it allows for a quality control of lateral or/and vertical variations of conditions in a subsoil zone. Good qualitative compatibility between electrical resistivity and geotechnical data was pointed out by Cosenza *et al.* (2006). However, the author emphasized that quantitative correlation between these parameters was not an easy task and still needed more research to be done.

Geophysical tests can be also used at the stage of using an engineering structure. They allow, for instance, to estimate settlements of a road embankment (Fortier and Bolduc, 2008). Additionally, with a use of geoelectrical methods, it is possible to monitor periodic changes of moisture content within a whole embankment applying empirical relations between electrical resistance and soil water content (Jackson *et al.*, 2002). Such monitoring is especially vital in areas of the world where embankments can be constructed of cohesive soils, because water content changes can influence stability of a whole embankment.

In the paper, a use of electrical resistivity tomography (ERT) for determination of spatial variation of organic soils was described. Tests were carried out on a site of a new road investment being constructed near Warsaw where inadmissible settlements (over 10 cm) had appeared before the road was even put into operation. The reason for these settlements was organic soils, location of which has not been identified during a soil substratum testing.

The goal of ERT tests carried out was to obtain spatial model image of soil medium resistance variation. This image was combined with geotechnical tests and thus a reliable, spatial profile of soil and water environment was found. The obtained information concerning spatial occurrence of low-strength soils (i.e. organic soils or soft consistency cohesive soils) allowed using an appropriate reinforcement technology of the soil substratum of the new road structure construction in order to prevent its further settlements.

IN SITU GEOTECHNICAL TESTING

Drillings and probing are the most common field tests in geotechnics. There are many methods and devices used to create exploratory boreholes for these tests including manual drilling kits, small size self-propelled drill rigs and heavy, multi-function units mounted on sophisticated devices adapted for drilling with casing pipes, taking cores and being able to conduct CPT-CPTu static probing, dilatometer DMT and presiometer PMT tests and others.

There are many advantages of all these devices and we can obtain a wide range of parameters to find and describe soil and water conditions in detail. However, undoubtedly the biggest disadvantage is a one-dimensional characteristics of geological medium. Measurements taken at certain points are interpolated in order to characterize spatial structure of a soil area. This fact generates dependency of a soil investigation precision at assumed distance between measurement points and on the level of soil structure complexity.

METHODOLOGY OF ELECTRICAL RESISTIVITY TOMOGRAPHY TESTS

Electrical resistivity tests are characterized by high effectiveness of surveying, because electrical resistivity is a parameter which can highly illustrate diversity of a geological medium, considering lithological and hydrological aspects (Białostocki and Farbisz, 2007; Farbisz *et al.*, 2010). Electrical impedance, acquired directly from measurements, does not define a value of resistance of an analysed area, however it reflects its diversity well. Values of resistance obtained from electrical resistivity tests cannot be used to identify explicitly soil types appearing in a substratum. For this purpose, one needs to conduct drillings, which give precise information about soil conditions. According to Białostocki (1974), drillings should be located taking into account preliminary interpretation of geophysical data. In other hand, drilling results should be taken into consideration during final interpretation of geophysical data as well.

In tests that were carried out, the electrical resistivity tomography (ERT) method was used, which, similarly to other resistivity methods, relies on effect of a direct current flow through a soil or rock medium. During electrical resistivity survey a geological medium acts as a resistor in a circuit in which electrical current is injected to the ground using two electrodes. A voltage drop, recorded using two different electrodes (potential/measurement electrodes), is proportional to electrical resistance of the medium. Electrical resistance obtained in such a measurement is called the apparent resistivity. This quantity does not define accurately electrical resistance of an analysed space, but it maps its diversity well.

In electrical resistivity tomography, measurements can be conducted along the whole length of a profile during a process that is controlled by a measuring apparatus. Before the measurements begin, all the electrodes are arranged along the entire analysed section at fixed spaces between them. In the course of measurement, a microprocessor system activates successively appropriate groups of electrodes according to a measuring arrangement chosen by an operator. In consequence, the accuracy, with which results are recorded along a measuring arrangement, depends on the assumed distance between electrodes. ERT method, in comparison to classic electrical resistivity methods, has many advantages. Among them there are:

– relatively high robustness to electrical interferences,

– possibility of detailed measurements, which allow to track electrical resistivity variations of a medium in both horizontal and vertical directions; this is connected with assumption in the interpretation of the soil medium model where a measuring space is divided into plane-parallel blocks, as opposed to plane-parallel layers of infinite size assumed in classic interpretation (Loke, 2001),

– possibility to freely choice and switch of measuring arrangement schemes out of the most common ones used in electrical resistivity tests – without any need to change locations of electrodes in an existing line of profiling.

A depth range of electrical resistivity tomography method depends on a length of spaces between electrodes used in the test and on distribution of electrical resistivity in the analysed space. As a result of measurements, a trapezoidal cross-section is obtained. Such a shape is created due to a fewer number of measurements at the beginning and at the end along with an increase of distance between electrodes involved in the measurement. Cross-sections obtained during the tests represent, with isolines, horizontal and vertical variation of electrical resistivity along a measuring line.

ERT measurements were conducted using Terrameter LS apparatus produced by the Swedish company ABEM with a spacing between electrodes equal to 3 m in two measuring arrays that is Schlumberger's and gradient. In every measuring profile, 41 electrodes were used. Schlumberger's array is a symmetrical measuring array, where measuring electrodes (MN) are placed between electric current electrodes (AB) and the following geometric relationship concerning distance between electrodes is satisfied: MN 1/3 AB. The depth of the penetration increases along with an increase of spacing between electric current electrodes AB. A basis of gradient array is to arrange electric current electrodes at both ends of a measuring profile. Measuring electrodes, on the other hand, have to be placed so that they move along the surveying line between current electrodes. When measuring electrodes are in the middle of a surveying profile, the gradi-

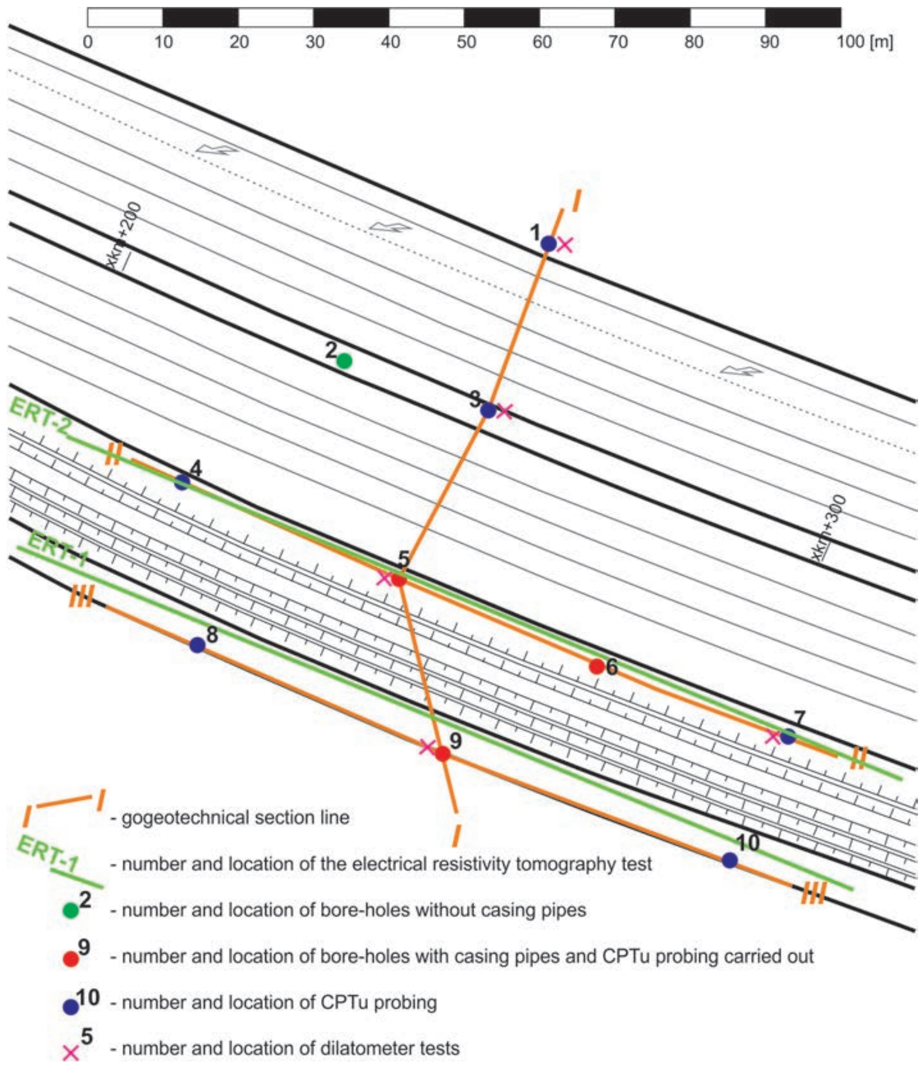

Fig. 1. Location of the test area

ent array measurements are identical to Schlumberger's ones. Moreover, during electrical resistivity tomography measurements in gradient array it is also possible to record potential difference in several pairs of measuring electrodes simultaneously while in Schlumberger's array this can be done only for a single pair of MN electrodes.

Field data obtained during electrical resistivity tomography tests were interpreted using RES2DINV software (Loke and Barker, 1996; Loke *et al.*, 2003). Processing of data involved inversion, which relies on choosing the most probable geoelectric model of a soil medium which reflects geotechnical field data. This is done in an iterative manner, by successive calculations and comparisons, assuming minimization of the fitting error.

TEST AREA DESCRIPTION

Tests were carried out on the site where a new section of an S-class road was being constructed, which consisted of 6 traffic lanes (3 for each direction). For procedural reasons the exact location cannot be given.

Test area was located in Pleistocene glacial deposits depression filled with deposits of lacustrine and swamp origin (Sarnacka, 1976). Glacial deposits consisted of sandy clays and fine sands. Among lacustrine deposits there were clays, clayey sands and aggradate mud with fine sand additions. At the stage of identification of soil and water conditions of investment substratum no regions of peat were detected. Original soil was covered with embankments of varying thickness. Hydrogeological recognition found out the existence of three water-bearing levels. The first, superficial level was located in embankments at about 1.7 – 2.0 m depth. The second water-bearing level appeared at depth of 6.0 – 6.5 m. The next level, with no importance for the investment, occurred at 10 to 20 m depth.

The first geotechnical tests in the road section (including 3 drillings and 1 probing with a light dynamic probe DPL to 3.0 m depth) were conducted with spacing equal to 250 m. As a result of these tests, information was obtained which confirmed archival data stating that from a ground level to at least 3.0 m depth, there were embankments built of medium density coarse soils.

Basing on this data, a section of road was designed and constructed. This part of road started to settle down before the road was put into commission. Displacements were so big, inadmissible, that in the ensuing situation new field tests had to

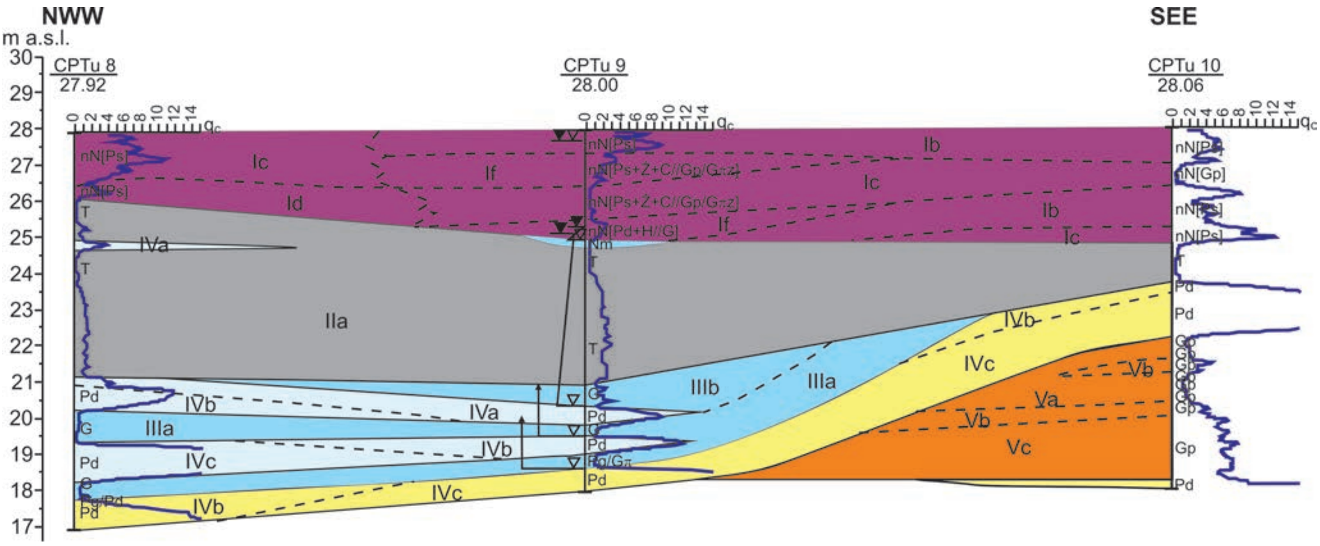

Fig. 2. Geotechnical cross-section I-I (for location see Fig. 1)

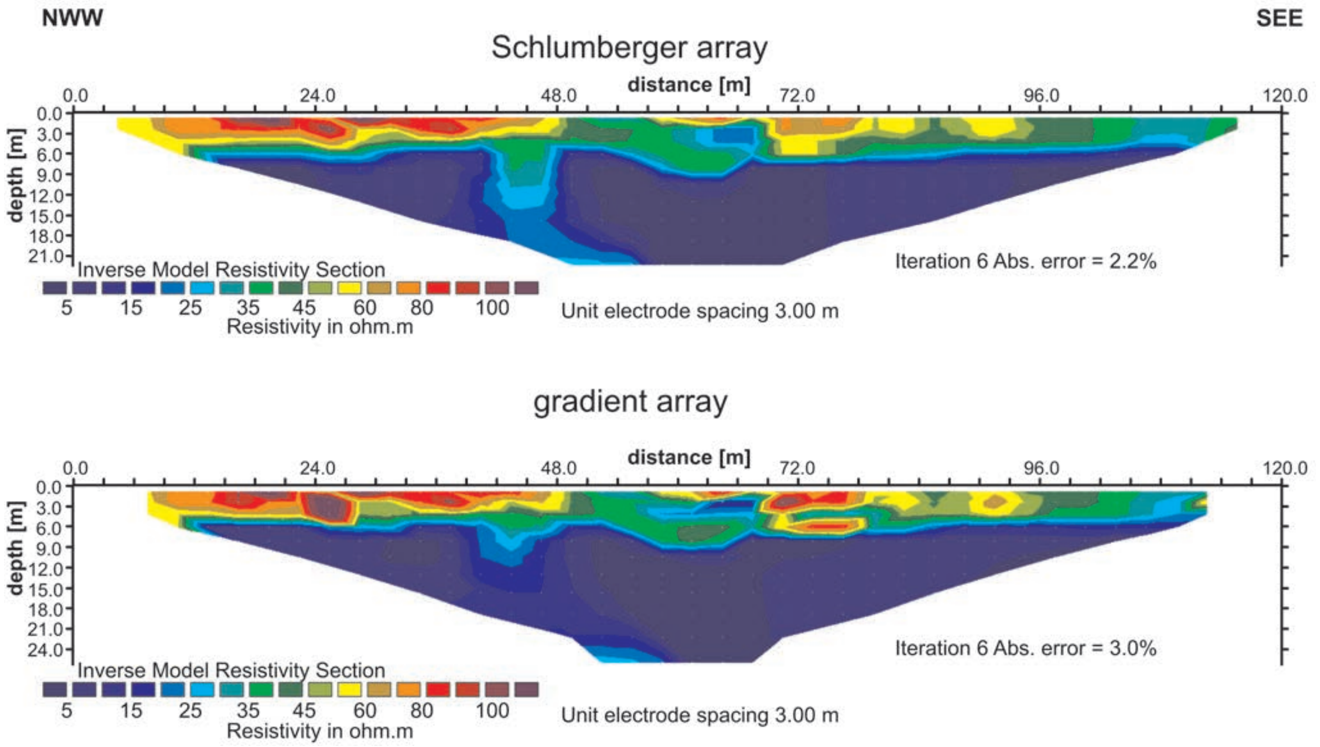

Fig. 3. ERT along the axis of the service road

be carried out to find out reasons behind this phenomenon. A series of drillings were conducted, this time deeper to 8.0 – 10.0 m below ground level, located every 20–30 m (Fig. 1). Obtained data provided that under embankment soils, organic soils were present including peat and aggradate mud of significant thickness equal to about 3.5–4.0 m, which were underlain by cohesive soils of soft and very soft consistency (Fig. 2). Identified low-strength soils consisted of organic soils (geotechnical layer 'II') built of peat (layer 'IIa'), aggradate mud and lacustrine clays of soft (layer 'IIIa') and very soft (layer 'IIIb') consistency.

TEST RESULTS

Electrical resistivity tomography tests were carried out at two 120 m long sections, parallel to each other. The first one was located at an axis of a service road, and the second one at the main road shoulder. Measurements on every segment were taken in Schlumberger's and gradient arrays with the electrode spacing equal to 3.0 m, with surveying depth of about 20.0 m.

Each of the measuring arrays used in electrical resistivity surveys have advantages and disadvantages. They were dis-

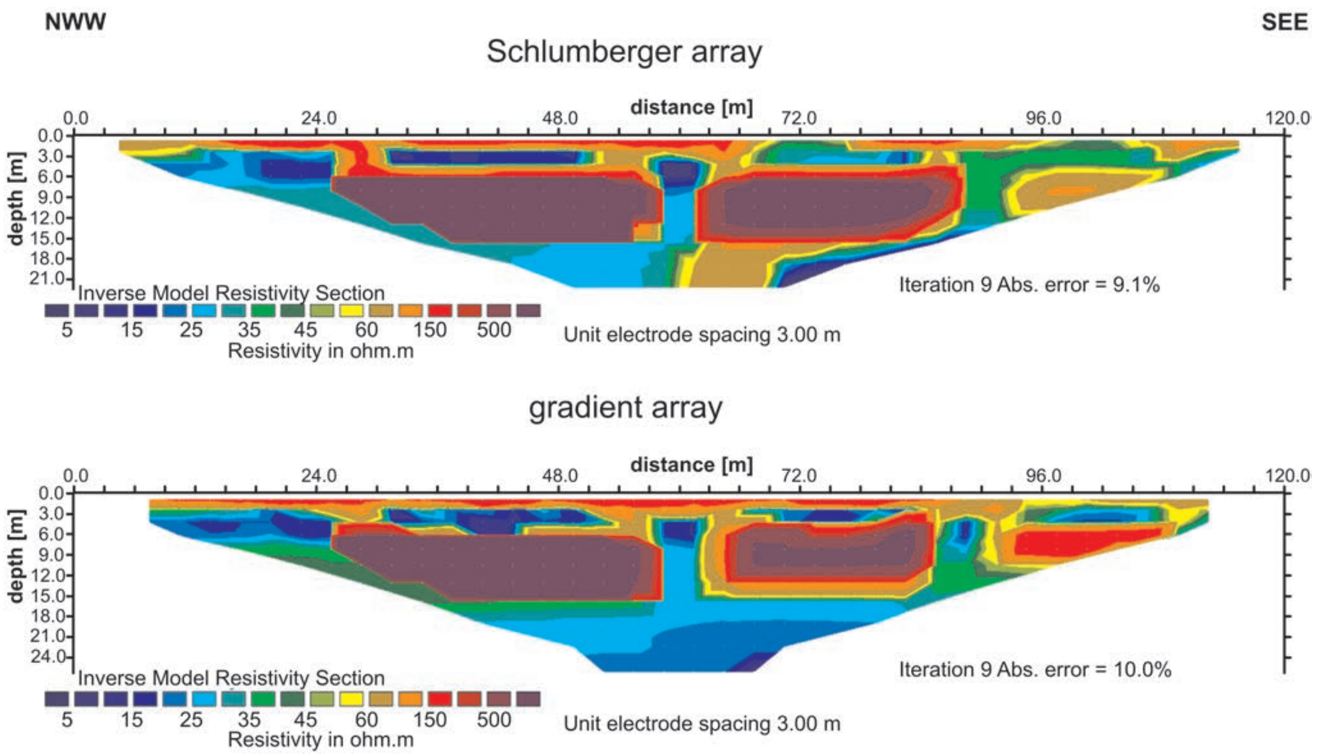

Fig. 4. ERT along the shoulder of the main road.

cussed, for example by Dahlin and Zhou (2004). The best measuring array should be chosen, in ERT tests, taking into account the surveying depth, obtained results' resolution and analysing how much time and money the test requires. The theoretical summary of both arrays used in our surveys shows that the gradient array was better for any determination of horizontal variation of a soil medium and that Schlumberger's array produced higher vertical resolution results. Because of that, gradient array was used, in general, for geologic structure mapping and Shlumberger's array was suitable for determination of vertical variation of the soil space. The surveying depths of both these methods were close to each other. Moreover, gradient distribution of electrodes was more practical as it took a lot less time for measurements.

The results of conducted electrical resistivity tomography measurements, showing horizontal and vertical variation of resistivity along the line of the section were presented for tests carried out along the axis of the service road (Fig. 3) and for tests performed on the main road shoulder (Fig. 4). Assumed configuration of electrodes for both measuring arrays yielded the surveying depth reaching over 20 m in the central part of the profile.

The imaging of resistivity section obtained as a result of measurements carried out on the service road section (Fig. 3) proved that there were three blocks of layers of much the same resistivity. The best way to find their lithological identification was to take drilling data into account. Lithology could be also estimated by analysing ranges of geological medium resistivity introduced, for example by Stenzel and Szymanko (1973). However such information should be treated only as some recommendation. The first layer, of a discontinuous nature and changeable thickness, was composed of soils, resistivity of which varied between 70 and 225 m. These were identified as embankments composed of coarse soils (fine sands, medium sands, gravels). Variation of electrical resistivity in embankments was a result, above all, of differences in water content. In general, in spaces close to ground surface, embankments resistivities were higher (about 150–225 m) and decreased with depth. The second layer, of resistivity 25–50 m, was composed of organic soils like peat and aggradated mud. This layer was covered by embankments, however between 50 and 58 m of the profile and from 102 m to the end of the section, it appeared almost at the ground level. Below, there was a layer with resistivity between 15 and 25 m, composed of cohesive soils.

Electrical resistivity distribution in Schlumberger's and gradient arrays were similar to each other for the analysed section on the main road shoulder (Fig. 4). Two regions had significant high resistivity (30–50 m and 66–78 m of the profile), ranging between 7,000 and 10,000 m. The extremely high resistivity was caused by two buried sewers filled with air. Resistivity of these sewers was so high that it made it difficult to interpret results and find soil conditions.

ERT tests yielded a fine mesh of measuring points that allowed a quasi-continuous tracking of changes of physical property images, which map a geological medium. An interpretation of electric resistivity sections was done in combination with geological data for the profile in the axis of the service road part only (Fig. 5).

CONCLUSIONS

Correct identification of soil conditions is essential for road engineering as the substratum becomes a foundation for

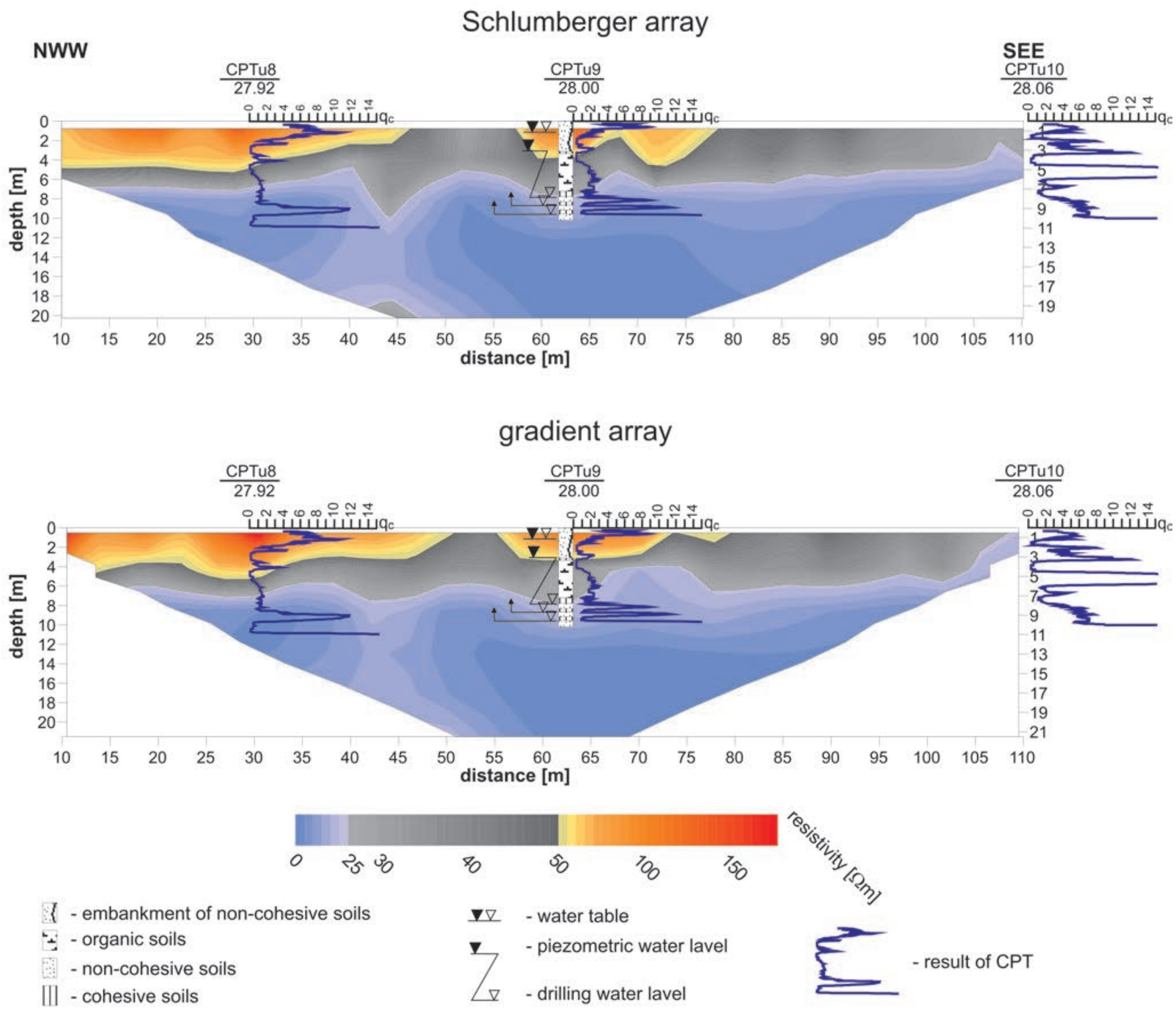

Fig. 5. Geoelectrical section after geotechnical interpretation of ERT data (cf. Fig. 3).

a pavement. Insufficient identification of a soil medium (soil types and its properties) can decrease fatigue life of a road structure, cause damage and in special cases failure or even a catastrophic construction breakdown.

It is highly advantageous whenever it is possible to use classic, geotechnical and geological engineering test methods (drillings, probing and the like) of a discrete nature (1D) along with geophysical methods (ground-penetrating radar, electrical resistivity tomography), which allow to continuously track physical properties variation in a soil medium. Such approach in measurement of substratum properties yields complementary results that give a correct evaluation of soil and water conditions.

Test results presented in the paper proved that electrical resistivity tomography is a good tool, which can be used for a non-invasive, continuous identification of organic soil zones appearing close to a ground surface. However, these tests have to be carried out in the area where there is no underground infrastructure, because such infrastructure will cause anomalies of resistivity imaging, which make it impossible to correctly and accurately analyse soil and water conditions.

An image of electrical resistivity of a soil medium obtained using ERT tests combined with geotechnical or geological engineering test data yields a reliable, spatial model of soil and water conditions variation. Such information contributes to precise and effective decision-making process concerning structural solutions preventing dangerous settlements.

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