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Research paper

The use of non-invasive ERT method to diagnose karst in roadengineering in the Lublin Upland (Poland)

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Abstract: Appropriate design in linear construction depends on many factors, including detailed geological conditions. One of the biggest problems are unrecognized erosion forms, in particular karst ones, which have a huge impact on the design and subsequent operation of roads. For this purpose, in addition to conventional methods such as drilling or geotechnical probing, which are point-based, non-invasive spatial geophysical methods are used. This article presents an example of the use of geoelectrical surveys, Electrical Resistivity Tomography (ERT) for the recognition of karst zones for linear investments. The article describes ERT investigations, which to some extent allows to identify dangerous karst phenomena occurring in the Lublin Upland (Poland), which are of great importance at the design stage of roads and in their further safe operation. Non-invasive geophysical research has been verified and confirmed by traditional geotechnical research, which confirms the effectiveness of their use. The Electrical Resistivity Tomography was used as a method providing a broader spectrum of knowledge on the spatial arrangement of soil layers in the subgrade of the planned road investments. It also enabled a more accurate, more detailed interpretation of geotechnical studies. The described geophysical investigations opens wide possibilities for their application to researchers. In the future, non-invasive methods have a chance to become as reliable as geotechnical methods, but this requires a lot of research to improve the effectiveness and accuracy of the interpretation of the obtained results.

Keywords: carbonate rocks, ERT (Electrical Resistivity Tomography), karst, Lublin Upland, Poland

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1. Introduction

Proper design in linear construction depends on detailed geological conditions. One of the biggest problems are unrecognized erosional forms, in particular karst ones, which have a huge impact on the design and subsequent operation of roads. For this purpose, in addition to conventional methods such as drillings or geotechnical probing, which are point investigations, geophysical non-invasive methods are used.

Geophysical methods have been very popular for several years in the course of recognizing ground and water conditions. The assumptions of those methods are extensively described in the works of [1–5] and others. Although they are still considered innovative methods, they have already been permanently included as mandatory in the new guidelines of the General Directorate of National Roads and Motorways [6]. Of course, they are verified by detailed geotechnical surveys, however, as they are considered as spatial surveys, they allow for a broader look below the surface of the terrain and catching possible threats, which include various types of erosion depressions filled with weak soils or even voids created as a result of karst processes.

Karst phenomena are described in many publications [7–13]. Non-invasive methods of studying this phenomenon include: (1) ground penetrating radar (GPR) which is a high-resolution, mobile geophysical method based on the emission of electromagnetic waves with frequencies in the range of short to ultra-short radio waves and the registration of waves reflected from layers characterized by changes in dielectric properties [7, 9, 14, 15]; (2) seismic (MASW and refraction) which uses the elastic properties of the soil (rock) medium, which consists in the fact that seismic waves caused by vibrations propagate deep into the earth and encountering the boundaries of geological layers with different acoustic impedance on their way, which results in the formation of secondary seismic waves recorded on the surface [13, 16, 17]; (3) Electrical Resistivity Tomography (ERT), which is the most accurate method that uses the phenomenon of different electrical conductivity of the ground depending on its composition and structure [14, 18, 19].

The article describes Electrical Resistivity Tomography (ERT) research allowing to some extent to recognize dangerous karst phenomena occurring in the Lublin Upland, which is very important at the stage of road design and in their further operation. Non-invasive geophysical research has been confirmed by geotechnical research, which confirms the effectiveness of their use.

2. The karst phenomenon

The phenomenon of karst is one of many very unfavourable phenomena in road engineering, related to carbonation – carbonization, described by the formula (2.1) consists in the dissolution of carbonate and salt-gypsum rocks by surface and underground waters. Potassium-magnesium salts are dissolved in pure water, carbonate rocks in water containing CO_2, and this reaction is two-sided and depends on the amount of CO_2.

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \tag{2.1}$$

We distinguish two types of karst: surface and underground, which can occur simultaneously depending on the intensity of climatic conditions and the content of water and carbon dioxide:

– surface karst occurs on outcrops of carbonate rocks. Forms such as: mogotes, avens and karrens, fissures, cracks, sinkholes, flat-bottomed valleys the so-called polje etc. (some of those forms are shown in Fig. 1)

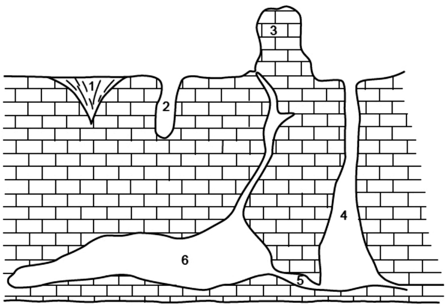

Fig. 1. Karst forms: 1 – sinkhole, 2 – aven, 3 – mogote, 4 – chimney, 5 – corridor, 6 – cave [20, 21]

– underground karst depends on the depth of groundwater occurrence, it most often develops along tectonic fracture lines and faults. The more fractured the carbonate rocks, the more caves are formed. Forms such as: karst chimneys as an extension of avens, caves and chambers are created (Fig. 1).

The development of karst forms in a heterogeneous rock massif is divided into five zones (Fig. 2): I – constant aeration (vertical chimneys), II – caves and horizontal channels, III – uniform dissolution, IV – ascending waters, V – deep karst [21, 22].

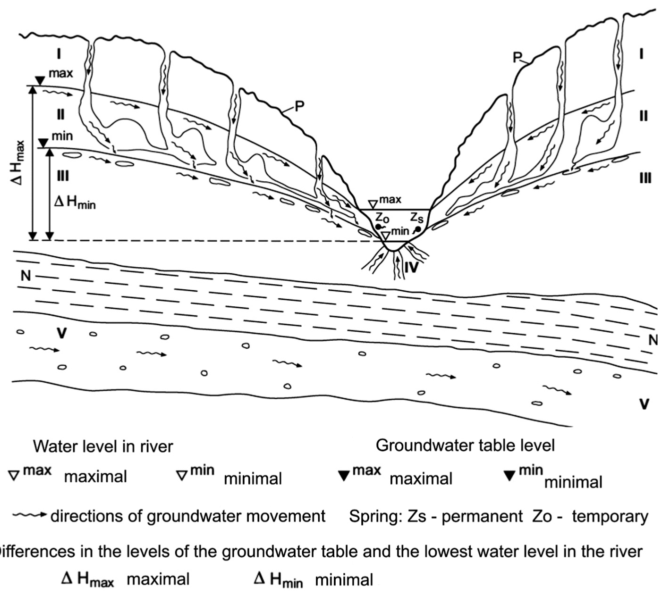

Fig. 2. Scheme of karst developed in a completely heterogeneous rock massif, where: P – terrain surface – naked karst; N – waterproof layer, separating the upper homogeneous layer with the shallow karst occurring in it from the lower heterogeneous layer with the deep karst. Shallow karst zone: I – zone of vertical chimneys, II – zone of caves and horizontal channels, III – zone of uniform dissolution, IV – zone of ascending waters, V – level of deep karst [21, 22]

The geological-engineering assessment of the karst consists in forecasting and estimating its approximate development. Karst activity can sometimes be determined by the amount of dissolved substance over a certain period of time and relates as a percentage to the total amount of dissolved soils/rocks in a given area [21]. Karst areas are considered to be unsuitable for foundation, especially for heavy structures. A very heterogeneous subsoil is shown in Fig. 3: a varied rock/soil roof, the possibility of a significant difference in subsidence pose a risk of construction disasters. Geological-engineering assessment of such substrates requires recognition by drilling and specialized geophysical research [21].

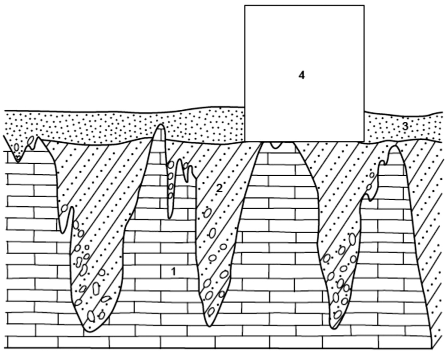

Fig. 3. Formation of the karst in the form of karst organs according to [23]: 1 – karst organs in limestones, 2 – deep erosive indentations filled with waste clays, 3 – cover sands, 4 – construction [21, 23]

3. Characteristics of the investigated area

The research area is located in Świdnica poviat located in the south-eastern part of the Świdnica Plateau, which is part of the macroregion of the Lublin Upland, belonging to the sub-province of the Lublin-Lviv Upland, and the western part of the Dorohuckie Depression, belonging to the Volyn Polesie macroregion, in the sub-province of Polesie. The approximate location of the study area is shown in Fig. 4.

The Świdnica Plateau is a flat denudation plain built mainly of carbonate rocks of the Upper Cretaceous and Quaternary sediments lying on them [25, 26]. The morphology of the terrain is in the form of levelings cut by river valleys filled with silts and peats. The plain, with few hills on the western part of the section, is built of a strongly cracked complex of rocks interbedded with marls and marlaceous limestones [27]. The whole complex is covered with Quaternary sediments, mainly silty and silty-sandy, loess-like. Near the river valleys there are numerous drainless depressions filled with muds and peats. The Dorohuckie depression is shaped in the form of a flat plain built of limestone-marl Cretaceous rocks covered with Pleistocene dune sands. The morphology of the analyzed area is poorly diversified, enriched only with peat-filled depressions formed in karst processes [26, 28].

The study area is characterized by a relatively flat, even terrain with small height differences. Initially, the research area is located at an altitude of approx. 200–210 m above sea level, it slopes gently to a height of 180 m above sea level (Fig. 5). The analysis of the digital terrain model (DTM) and the geological map also indicates zones where karst (cavities within carbonate rocks) is possible.

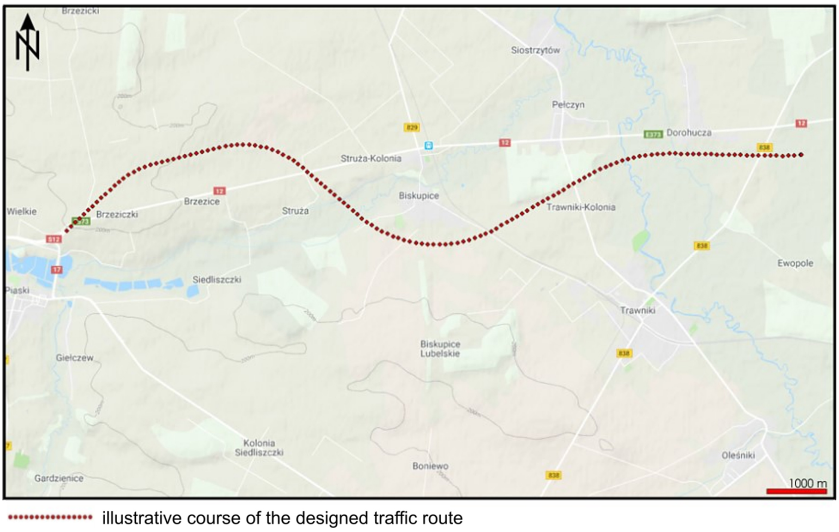

Fig. 4. Illustrative location of the research area – planned road route [24] which was fully covered with ERT investigations

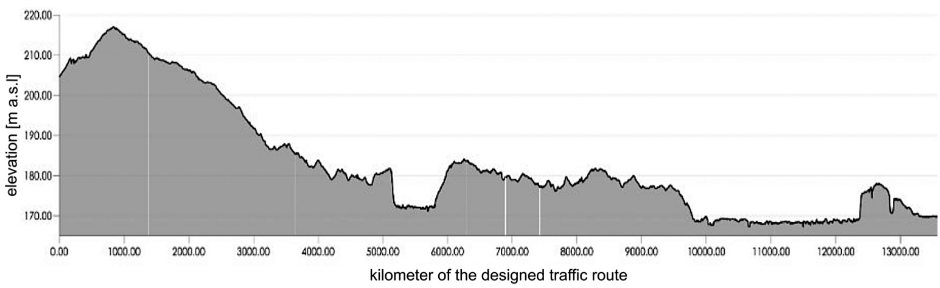

Fig. 5. Terrain morphology along the planned route along which ERT investigations were performed. The profile was developed on the basis of DTM

4. Geological structure of the study area

The oldest, documented deposits in the study area are Lower Devonian deposits [27, 29]. Their presence was found in the Trawniki 1 borehole made north of Fajsławice town (the so-called Fajsławice structure).

In the impact zone of the investment, there will be mainly Quaternary sediments (forming covers of small thickness) and Cretaceous formations in the form of marls, opoka rocks and writing chalk. The Quaternary does not occur in a large part of the area.

The characteristic geological cross-sections from the study area are presented in Fig. 6 [27,29].

The Maastrichtian sediments are 360–450 m thick and include writing chalk, marls and opoka rocks. The latter are exposed over a large part of the sheet area. The thickness of the marls is variable. Opoka rocks occur in the upper part of the Upper Maastrichtian sediments.

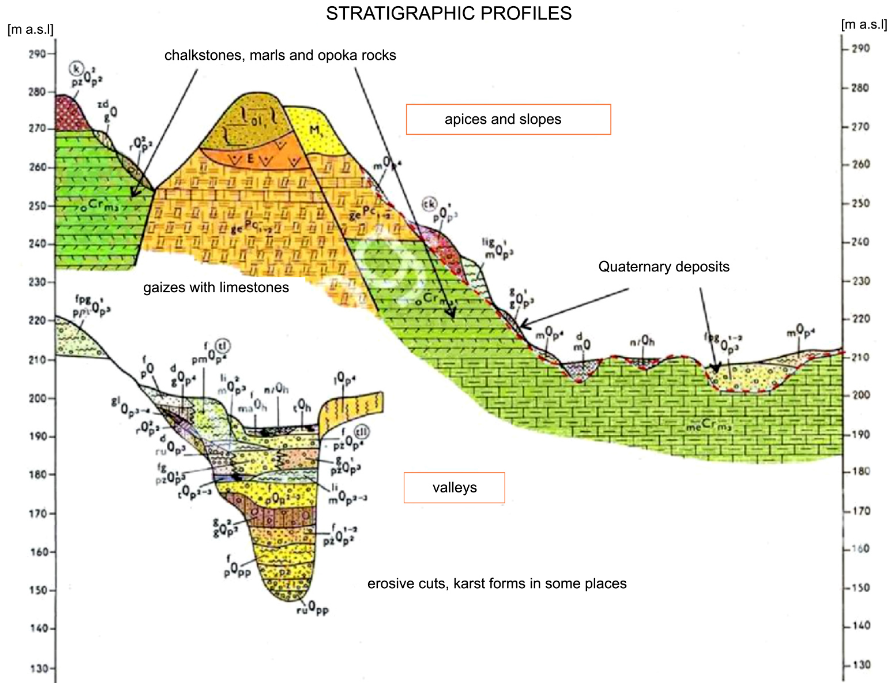

Fig. 6. Scheme of the geological structure that occurs in the analyzed area (prepared on the basis of the Detailed Geological Map of Poland, Piaski sheet) [29]

Their thickness is varied and ranges from several meters in the area of Trawniki to about 100 m in the south of the Piaski sheet [29].

The Paleogene is represented by Paleocene, Eocene and Lower Oligocene deposits. The Paleocene deposits are represented by gaize with limestone interbeds, which are exposed in patches on the surface on the western side of the Giełczwia valley, and the Eocene sediments are silica earth (decalcified gaize) about 8 m thick (they are not exposed on the surface). Oligocene age sediments (sands with glauconite and clays), occur in the form of isolated, small patches on inselberg. The thickness of the Lower Oligocene sediments reaches several meters [29]. The Miocene sediments are shallow-sea white, fine- and medium-grained quartz sands.

In the area of the Piaski sheet, the Quaternary sediment cover reaches the greatest thickness in river valleys (in the well in the Giełczwia valley it is 100 m). In non-valley areas, the thickness of the Quaternary cover often does not exceed 2 m.

Among the Pleistocene sediments, the deposits of the South Polish glaciations are very poorly preserved. They were mostly removed during the Mazovian interglacial. The deposits of the Central Polish glaciations are better preserved. These include: boulder clays, sands with gravels of glacial and fluvioglacial origin, silty sands and river-periglacial sands and sands with gravels, lake silts.

During the Northern Polish glaciations, the area of the sheet was in a periglacial climate, where intense accumulation of river sediments (sands, muds, sands with gravel) and aeolian sediments (loess) took place. Several loess patches occur within the catchment area of the Giełczew River. Loess-like sediments (sandy loams and silty sands) cover larger areas.

Holocene deposits occur mainly in the region of river valleys. These are silts and sandy silts with peat interbeds, peaty silts and peats. Holocene deposits in total do not exceed 5 m in thickness. Silts and sandy silts fill the valleys of major rivers and their tributaries. Peaty silts were identified in the central part of the Giełczew valley, in the Sierotka and Marianka valleys. The areas of peat occurrence are located in the Giełczew valley and in the Marianka valley below Fajsławice town. These sediments will also fill the Wieprz river valley, as well as forms of depressions with no outflow [29].

Among the above-mentioned divisions, there may be various karst forms, the location of which will be estimated on the basis of geophysical research and shown on exemplary geophysical and geotechnical cross-sections.

5. Electrical Resistivity Tomography (ERT): basics and methodology of work

The Electrical Resistivity Tomography method consists in measuring the parameters of an artificially induced electric field in a specific rock mass or existing natural currents and electric fields caused by natural processes occurring in the Earth's crust (Fig. 7) [30].

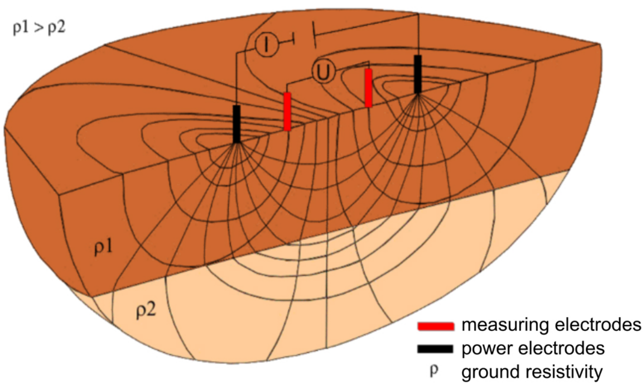

Fig. 7. Schematic example of a geoelectric survey [30]

The basic tested parameter is the resistivity of geological formations. The unit of specific (real) resistivity is an ohmmeter [Ωm]. This parameter is very diverse, its value can vary from 1 Ωm in saline sediments to tens of thousands of Ωm in rocks such as granites.

Unlike parameters such as density or magnetic susceptibility, resistivity is a complex parameter, depending on many factors and processes, such as temperature, water content and its quality, chemical compounds, porosity and permeability, lithology and mineral composition.

In Quaternary deposits, in areas where groundwater shows low mineralization, the electrical resistivity of sediments such as clays, tills, sands (i.e. the basic deposits that can be found on the studied section of the route) differ significantly, therefore the geological classification of electrical resistivity data is not a problem. The following classification criteria are generally accepted:

– clay sediments (clays, compact silty tills) – resistivity below 25 Ωm;
– cohesive sediments (silts, silty tills, tills, sandy tills, loamy sands) – resistivity in the range of 25–70 Ωm;
– non-cohesive sediments (fine sands, medium sands, coarse sands, gravels) – resistivity above 70–1000 Ωm. At the same time, dry sands can have resistivities of up to several thousand Ωm.

The classification of the above-mentioned sediments will depend mainly on flooding and the content of clay fractions in the soil, i.e. loamy sands will have lower resistivity values than fine sands. For organic deposits, such as peats, silts and gyttjas, typical resistivities have values of several Ωm to 40 Ωm. For older sediments, which will be represented mainly by chalkstone, as well as marls, opoka rocks, resistivities will be characterized by lower values (from up to 40–50 Ωm).

As can be seen from the above characteristics, the resistivity ranges of some soils or rocks overlap, which causes some difficulties in distinguishing them.

In the studied area, in the impact zone of the investment, i.e. up to a depth of 30 m, according to archival data, there should be both Quaternary sediments and older substrate deposits (Cretaceous).

Knowing the characteristic ranges of soil resistivity that occur in the studied area and correlating the results of geophysical surveys with boreholes that are located nearby, it will be possible to translate the obtained results (resistivity value distribution) into lithology of Quaternary and older deposits with high probability.

The ERT method is one of the most versatile geophysical methods in the study of shallow geology (up to 30–50 m below sea level), in particular for the study of Quaternary and sub-Quaternary deposits. Thanks to its unique features, such as a wide range of depth range (depending on the methodology of work – from a few to several hundred meters), detail and accuracy of mapping (imaging) of the geological medium, as well as a wider range of applicability than in other methods, ERT permanently entered the canon of geophysical methods.

The Electrical Resistivity Tomography method is based on the phenomenon of direct electric current flowing through the rock medium, and the subject of recognition is the space of the geological medium located below the potential electrodes (Fig. 8).

The Swedish equipment of the ABEM company – the Terrameter LS electrical resistivity tomograph – was used to perform the measurements (Fig. 10, 11).

The tests were conducted with a 5 and 2 meter electrode spacing for the route and with a 2 meter spacing for objects (Fig. 8). The division into sections on which tests were performed with 5 and 2 meter electrode spacing was designed in Geophysical Research Program (PBGf) [32]. The depth of recognition was not less than 15–20 m below sea level

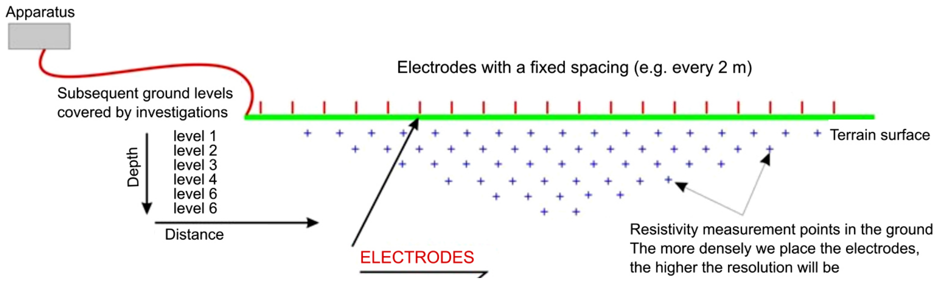

Fig. 8. Simplified measurement scheme of the Electrical Resistivity Tomography method [31]

for profiles made in the body of the designed road and 30 m for DOI. The depth of ground exploration for the main route was approx. 15 m, for DOI approx. 30 m.

In areas where, based on the analysis of archival data, karst was expected to occur, a 2 meter measurement step was also used. Field measurements were carried out using the roll-along method – transferring subsequent cables to the front of the profile (Fig. 9). Moving the cable from the first position to the last one gives you the opportunity to make longer, continuous profiles.

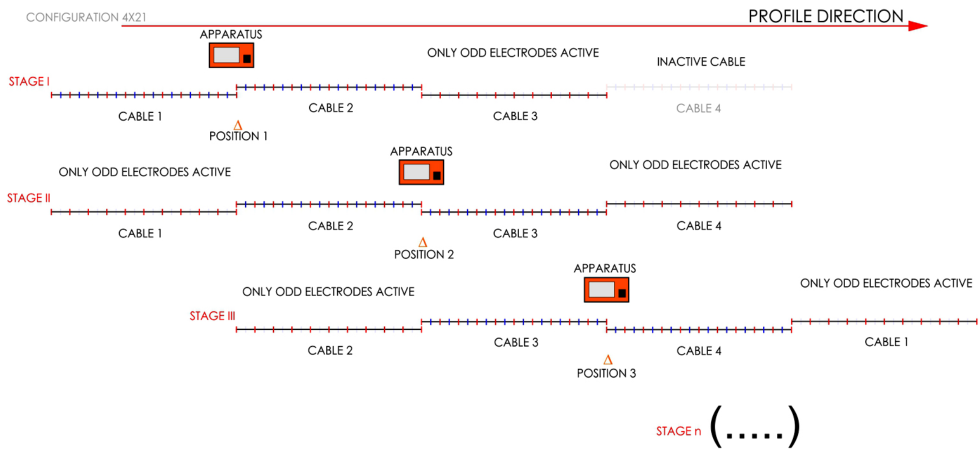

Fig. 9. Diagram of the measuring system for Terrameter LS apparatus: roll-along method, 4×21 configuration ([33], based on [34])

A gradient measurement system was used in the study, which allows for a relatively large number of measurement points with a short acquisition time. The results obtained from field measurements along with the location of individual electrodes were imported to the Res2Dinv program, where they were processed (inverted). As a result of the process presented above, an image was obtained showing the distribution of resistivity close to the real one (these are interpreted resistivities) at a given depth, including the morphology of the terrain.

Fig. 10. A set of electrodes prepared for tomography examination in real conditions [15]

Fig. 11. View of the tomograph – Terrameter LS of the Swedish company ABEM [15]

6. Results

The conducted investigations made it possible to determine the distribution of resistivity values by inversion of measurement data (and the depth scale corresponds to the actual depth in the soil medium). The electro-resistivity cross-section, as the final result of data processing, is the subject of geological interpretation.

The results were used to refine the model of geological structure. Data from the Detailed Geological Map of Poland and data from geological-engineering boreholes were used to correlate the obtained geological boundaries. Geoelectric cross-sections along the road body are compared in relation to the mileage of the route axis and the gradeline of the route axis (Fig. 12).

In the geological interpretation of the obtained results of the processed measurement data, several assumptions were made, resulting from the general knowledge of both the physical properties of the soils in the research area and the general knowledge of the nature of electrical resistivity investigations. The interpretation was based on the adopted assumptions, described in the methodology of work. The distribution of resistivity values has been generalized, dividing the medium mainly due to whether the resistivities will be classified as cohesive or non-cohesive soils. A resistivity of 60–65 Ωm was assumed as the limit. At the same time, in the documentary area, in many places in the near-surface zones it was noticeable that clay sediments had increased resistivity values.

Distributions of resistivity values on geoelectric cross-sections were drawn using a logarithmic scale (Fig. 10, 11). This procedure was performed mainly due to the fact that such a distribution gives a better visualization of the data (especially when the data on the geoelectrical cross-section have different resistivity values – from a few to several thousand Ωm). All values are convertible according to the 10× formula: the value 1 corresponds to 10 Ωm, the value 2–100 Ωm, the value 2.3–200 Ωm.

Analyzing the test results contained in the geoelectrical cross-sections, it can be seen that it is possible to distinguish non-cohesive layers: sandy (high resistivity values – above 70–100 Ωm, warm colors), cohesive: clay (till) – various types of clays (tills), from sandy loams, through clays (tills) to silty and compact clays (tills) (resistivity in the range of 30–70 Ωm – colors in shades of green), as well as low-resistivity layers (resistivity in the range of several to

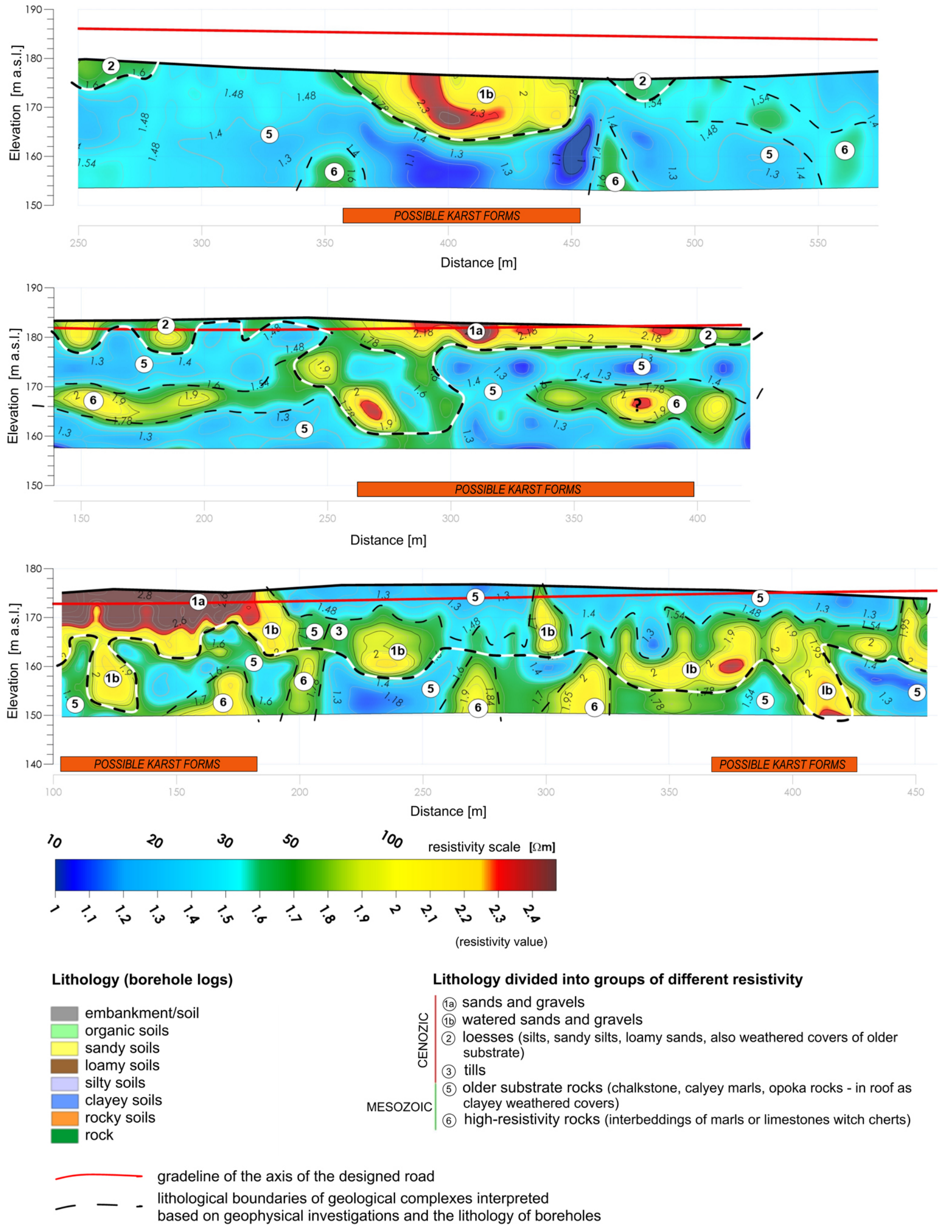

Fig. 12. Fragments of electrical resistivity cross-sections with an example of recognized karst. Layers 5 and 6 – mantle rocks (weathered cover) and carbonate rocks, interspersed with sands and gravels, and watered sands and gravels – layers 1a and 1b [32]

30 Ωm), which form thicker beds in a large area where research was carried out, which may be associated with glaciolacustrine deposits, silts and clays (resistivities below 25 Ωm).

On the geoelectrical cross-sections, interpretation was made by drawing the course of boundaries for layers differentiated by resistivity, in relation to the geological structure resulting from the Detailed Geological Map of Poland and geological-engineering boreholes. The descriptions of individual divisions on the cross-sections refer to the sediments that are located in a given place on the Detailed Geological Map of Poland. The course of the boundaries has been generalized, but it gives an idea of the geoelectrical model of the ground medium. Particular attention was paid to identifying places that may potentially be zones of weak soils and potential places of karst occurrence.

The obtained results of the geophysical surveys were used to make geotechnical/geological-engineering cross-sections (Fig. 13), where the boundaries of the divisions of various karst forms were clearly indicated, which should definitely facilitate the design of the road foundation.

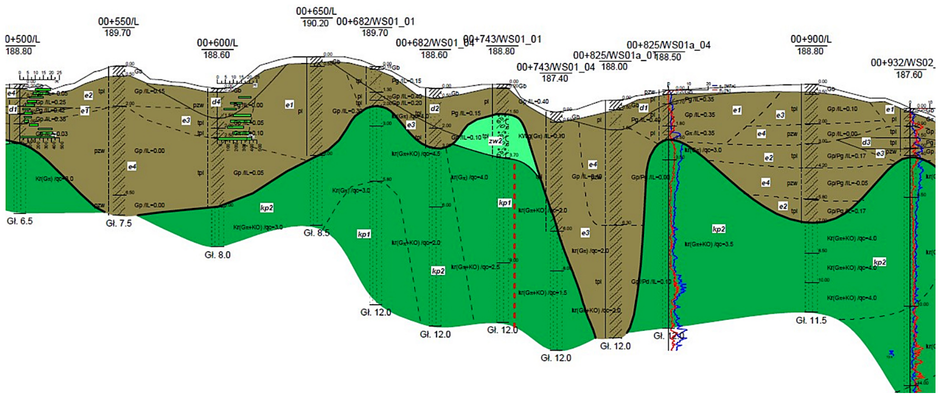

Fig. 13. An example of a geotechnical cross-section taking into account the ERT measurements, where karst depressions and sinkholes can be observed (brown colour) within the carbonate rock (green colour) [35]

7. Summary

The method of Electrical Resistivity Tomography (ERT) presented in this article is used as a method that provides a broader spectrum of knowledge about the spatial arrangement of soil layers in the subgrade of the planned road investments. This enables a more accurate, more detailed interpretation of geotechnical surveys.

Thanks to the ERT method, it is easier to indicate the zone of possible occurrence of karst or erosional cuts in carbonate rocks, possible karst voids or cuts filled with Quaternary sediments, mainly in the form of sandy or clay weathered waste. Based on this we can select the area of ongoing geodynamic processes, which should be classified as complex ground conditions.

Nevertheless, the interpretation of ERT results is unfortunately still ambiguous and needs to be confirmed by detailed research using invasive geological research, such as drilling or probing.

Apart from recognizing the fairly precise boundaries of individual divisions, we do not receive any detailed information, such as the exact composition of the soil or its condition, hence indicating the places where real dysfunctions occur is not easy.

Geophysical research opens up a wide range of applications for researchers. In the future, non-invasive methods have a chance to become as reliable as geotechnical methods, but this requires a lot of research to improve the effectiveness and accuracy of the interpretation of the obtained results.

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Zastosowanie nieinwazyjnych badań ERT do rozpoznania krasu w drogownictwie na obszarze Wyżyny Lubelskiej

Słowa kluczowe: ERT (Electrical Resistivity Tomography), kras, Polska, skały węglanowe, tomografia elektrooporowa, Wyżyna Lubelska

Streszczenie:

Odpowiednie projektowanie w budownictwie liniowym zależy od wielu czynników, w tym szczegółowo rozpoznanych warunków geologicznych. Jednym z największych problemów stanowią nierozpoznane formy erozyjne w szczególności krasowe mające ogromny wpływ na projektowanie i późniejszą eksploatację dróg. W tym celu poza metodami konwencjonalnymi takimi jak wiercenia czy sondowania geotechniczne które są punktowe, wykorzystuje się metody geofizyczne przestrzenne – nieinwazyjne. W niniejszym artykule przedstawiono przykład zastosowania badań geoelektrycznych dla rozpoznania stref krasu dla projektów liniowych. Metody geofizyczne od lat cieszą się dużą popularnością w trakcie rozpoznawania warunków gruntowo-wodnych. Mimo, iż w dalszym ciągu uchodzą za metody nowatorskie to już na stałe zostały wpisane jako obowiązkowe podczas rozpoznawania warunków geologicznych czy geotechnicznych. Są oczywiście weryfikowane przez szczegółowe badania geotechniczne, nie mniej jako badania uważane za przestrzenne pozwalają na szersze spojrzenie pod powierzchnię terenu i wyłapania ewentualnych zagrożeń do których należą różnego rodzaju zagłębienia erozyjne wypełnione słabonośnymi gruntami czy nawet pustki powstałe na skutek procesów krasowych. Do najdokładniejszych metod geofizycznych należy tomografia elektrooporowa (Electrical Resistivity Tomography, ERT) wykorzystująca zjawisko różnego przewodnictwa prądu elektrycznego gruntu w zależności od jego składu i struktury. W artykule zostały opisane badania ERT pozwalające w pewnym stopniu rozpoznać niebezpieczne zjawiska krasowe zachodzące na Wyżynie Lubelskiej, które mają bardzo duże znaczenie na etapie projektowania dróg oraz w ich dalszej bezpiecznej eksploatacji. Nieinwazyjne badania geofizyczne zostały zweryfikowane i potwierdzone tradycyjnymi badaniami geotechnicznymi co potwierdza skuteczność ich stosowania. Przedstawiona metoda tomografii elektrooporowej (ERT) została wykorzystywana jako metoda dająca szersze spektrum wiedzy na temat przestrzennego ułożenia warstw gruntowych w podłożu projektowanych inwestycji drogowych. Umożliwiła również dokładniejszą, bardziej szczegółową interpretację badań geotechnicznych. Dzięki metodzie ERT ułatwione zostało wskazanie strefy możliwego występowania krasu lub rozcięć erozyjnych – w skałach węglanowych, możliwych pustek krasowych lub rozcięć wypełnionych osadami czwartorzędowymi, głównie w postaci piaszczystych lub gliniastych zwietrzelin. Na ich podstawie wytypowano obszary trwających procesów geodynamicznych, które zakwalifikowano do skomplikowanych warunków gruntowych. Przedstawiona interpretacja wyników badań ERT niestety w dalszym ciągu nie jest jednoznaczna i wymaga potwierdzenia badaniami szczegółowymi za pomocą inwazyjnych badań geologicznych, takich jak wiercenia lub sondowania.Poza rozpoznaniem w miarę dokładnych granic poszczególnych wydzieleń nie otrzymano żadnych informacji szczegółowych, takich jak dokładny skład gruntu czy też jego stan, stąd też wskazanie miejsc występowania realnych dysfunkcji nie było proste.Opisane badania geofizyczne otwierają przed badaczami szerokie możliwości ich zastosowania. W przyszłości metody nieinwazyjne mają szansę stać się równie wiarygodne jak metody geotechniczne, lecz wymaga to przeprowadzenia wielu badań poprawiających skuteczność i trafność interpretacji uzyskiwanych wyników.

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