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Research paper

Three-dimensional interpretation of geophysical and geotechnical investigation of landslides

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Abstract: Effective engineering design of structures requires a thorough understanding of the groundwater conditions of the substrate. In some situations, a three-dimensional survey is necessary. Landslides are examples of such cases. They are complex phenomena, and the main factors significantly influencing their behaviour over time are changes in slope geometry, inclination and water conditions. The article discusses the reconnaissance of the substrate structure in an area threatened by mass movements along a modernized section of a railway line. The analysed area is located in the marginal zone of the North Polish glacial moraine. The geological structure of the substrate consists of: glacial tills, glaciofluvial sands, lacustrine clays, and organic soils found in periodically waterlogged areas and depressions in the terrain. Colluvial deposits, mainly consisting of clayey formations, occur on the slope of the escarpment. Surface geomorphology was interpreted using LIDAR data and field observations. Two-dimensional and three-dimensional electrical resistivity tomography (ERT) was used to obtain a detailed subsurface image, which was verified by borehole drilling and laboratory analysis of soil samples for physical properties, including grain size distribution and plasticity, as well as mechanical properties of soils. This research enabled the creation of a three-dimensional substrate model, showing the spatial distribution of colluvium and areas at risk of active landslides. The results indicate that an integrated approach, combining geophysical imaging and geotechnical reconnaissance, allows for a detailed understanding of the structure and lithology of landslide areas.

Keywords: 3D geotechnical model, electrical resistivity tomography (ERT), geophysical techniques, landslides

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1. Introduction

Landslides belong to the group of geohazards that cause casualties and financial losses. The main factors that have a significant impact on their behaviour include changes in slope geometry and water conditions [1].

The classical, one-dimensional approach to landslide issues appears to be inadequate in contemporary times. Researchers now have the ability to conduct fairly accurate analyses of changes in the morphology of landslide-prone terrain based on satellite data analysis, such as InSAR [5] or laser scanning LIDAR [7]. Generally, they do not provide practical information about the internal structure of the landslide. On the other hand, inclinometer data and classic drilling and probing, as well as sampling offer detailed, but point data, with limited applicability due to the need to conduct research in a dangerous, unstable area. This process is both quite expensive and time-consuming. The solution to the limitations of conventional surveys is the use of geophysical investigations to obtain subsurface characteristics [10]. Geoelectrical methods employ lightweight equipment, are minimally invasive, cause little disturbance to the ground, and provide spatial and volumetric subsurface information. In recent years, electrical resistivity tomography (ERT) has emerged as a standard geophysical imaging technique in engineering investigations and is routinely used in studies of landslide-prone areas. The increased use of geophysical methods is due to efficient data acquisition, digital measurement recording, and improved data processing and interpretation procedures. These improvements include the automation of data analysis, interference reduction and integration of data from various geophysical methods, which allow for a more comprehensive understanding of the subsurface conditions. Two-dimensional electrical resistivity tomography is widely used in landslide studies due to its ability to model landslide geometry, identify slip surface locations, and locate areas with high water content [16]. Three-dimensional electrical resistivity tomography (ERT) is less commonly used for studying landslide systems due to the need for conducting a greater number of field surveys and longer data processing times: 2D ERT profiles, aerial imaging, and surface geomorphological data [10–22]. It is important to note that the results of geophysical surveys require complex interpretation, cannot be directly utilized, and necessitate support and calibration with supplementary geotechnical investigations [26].

The article aims to present the use of different research and visualization techniques in interpreting the geological structure of an area prone to mass movement processes. The study utilized field survey results, borehole investigations, and geophysical methods. Based on these, a three-dimensional interpretation of the landslide area, posing a threat to the modernized section of the railway line, was conducted. To define the subsurface structure and geometry of the landslide, data from airborne laser scanning LIDAR, two-dimensional electrical resistivity tomography (ERT), and geotechnical data were utilized.

2. Study area

The analysed area contains deposits from the North Polish glaciation, including glacial tills, fluvioglacial sands, and gravels, as well as lacustrine clays and silts, with a total thickness of up to 25 meters [28]. The geological structure of the studied area is significantly affected by a landslide located south of the modernized railway embankment. The location of landslides, according to the Landslide Counteracting System SOPO of the Polish Geological Institute – National Research Institute [29], is shown in Fig. 1.

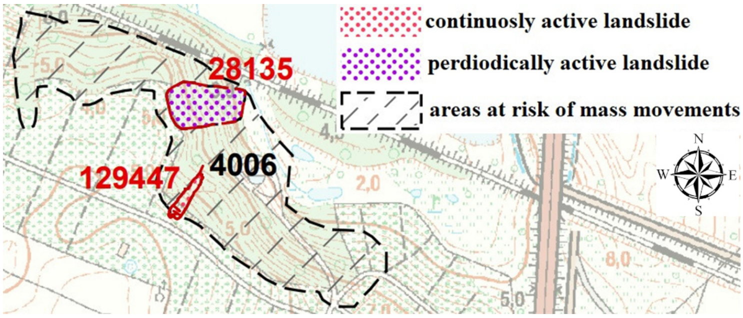

Fig. 1. Location of landslides according to the SOPO, [29]

As shown in Fig. 1, the periodically active landslide may pose a threat to the railway line, both during the modernization phase and subsequent operation. In the upper part of the moraine slope, within a small area, there is a continuously active landslide. The shaded area is characterized by a slope inclination of approximately 20 degrees, and due to this inclination and the type of soils in the substrate, it is an area susceptible to mass movements. It is located in the immediate vicinity of the modernized railway line, spanning up to 100 meters in length.

3. Geotechnical investigations

Geotechnical drillings and laboratory tests of soil samples confirmed that the substrate of the modernized railway line exhibits diverse soil conditions. Non-cohesive soils, sands with varying grain sizes of fluvioglacial origin, and cohesive soils: glacial tills and lacustrine clays were identified in the substrate. There are also present organic sediments. On the slope of the escarpment, there are colluvial deposits with a thickness reaching up to 7–9 meters. These are clayey sediments interlayered with sands, as well as silty clays associated with local mass movements of moraine hill slopes. The boundary between in-situ soil and colluvial deposits could potentially serve as the slip surface in case of slope instability.

In the substrate of the planned investment, geotechnical layers with similar physical and mechanical properties have been identified. The criteria distinguishing individual geotechnical layers include: soil type, genesis of cohesive soils, consistency, density index for coarse-grained soils and liquidity index for fine-grained soils. The results of geotechnical investigations indicated that the landslide material exhibited moisture content very close to the plasticity limit and higher clay content.

Five main lithological-genetic types of sediments have been distinguished: n – anthropogenic soils in the embankments of the existing railway line, I – non-cohesive soils; II, IV – glacial tills and lacustrine clays; III – organic soils. The characteristic values of geotechnical parameters of these layers contains Table 1.

Table 1. Geotechnical parameters values

Symbol	**Type of soil**	**Density index [%] Liquidity index I_L [-]**	**Friction angle ϕ' [°]**	**Cohesion *c'* [kPa]**	**Oedometer modulus E_{oed} [kPa]**
n	siSa, FSa, MSa, CSa, Gr, grSa	40	33.0	–	40 000
I	siSa, FSa, MSa, CSa	50	35.0	–	50 000
IIa	saclSi, sisaCl, clSi, clSa	0.60	9.5	17.6	10 000
IIb		0.30	17.5	20.0	25 000
IIc		0.20	18.0	30.3	30 000
III	Or	0.50	6.5	10.4	2 500
IV	Cl	0.10	18.5	31.7	10 000

To spatially visualize the results of geotechnical research, software enabling the creation of a 3D model of the subsoil called GEO5 Stratigraphy was utilized. The model was generated based on delineated geotechnical layers of the subsoil. The location of the research boreholes is shown on the topographic map in Fig. 2. In order to clearly present the arrangement of layers in substrate, they were shown on the geotechnical cross-sections in Fig. 3.

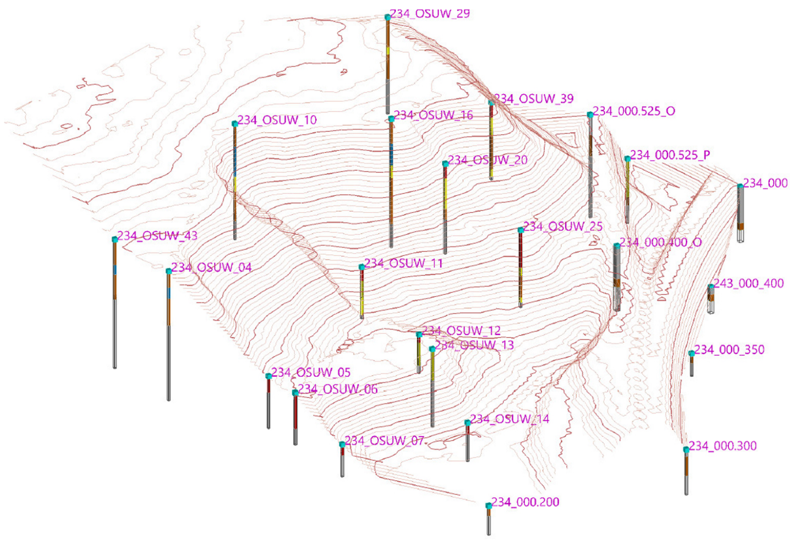

Fig. 2. Location of geotechnical boreholes

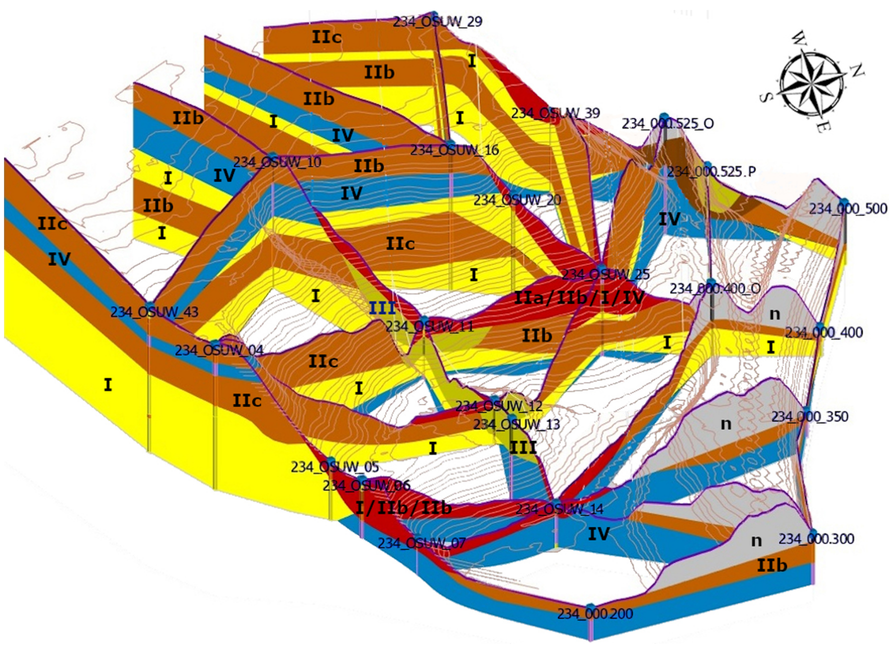

Fig. 3. Geotechnical cross-sections

4. Geophysical investigations

In the area prone to surface mass movements, electrical resistivity surveys were conducted, involving measurements of artificially induced electric field in the subsoil. The electrical resistivity tomography (ERT) method was utilized, which belongs to techniques widely applied in near-surface geology investigations [11]. It has a depth range from a few to several tens of meters, and within this range, Quaternary formations are present in the studied area. The assumptions and scope of application of the ERT method are described in works [30].

Along the line where the geotechnical researches were also conducted, electrodes were placed and connected to the measuring apparatus. The current intensity and potential difference were measured. Based on this data, apparent resistivity values were calculated [11]. It should be noted that the apparent resistivity value is a quantity related to the investigated half-space of soil through which the electric field flows and depends on the type of measurement (gradient) and the current geometry of the electrode array.

The aim of the geophysical studies using electrical resistivity tomography (ERT) was to determine the continuous distribution of soil electrical resistance along selected measurement profiles within the slope. The ERT profiles were stretched in the scarp zone in accessible places (Fig. 4).

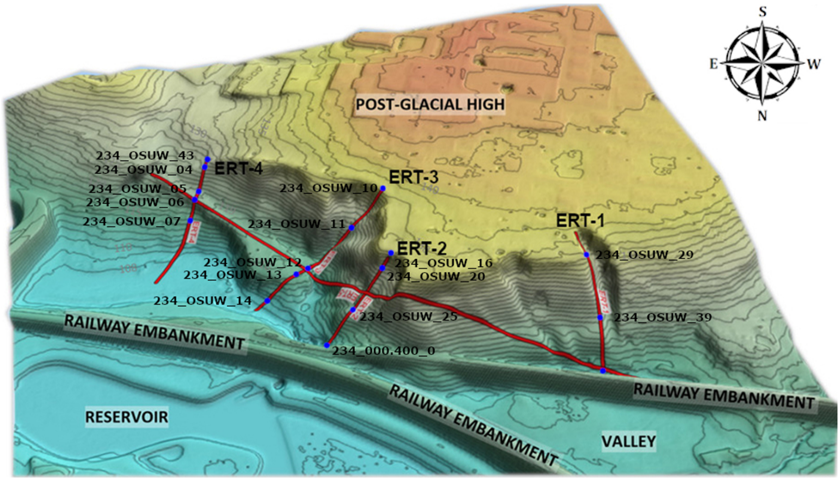

Fig. 4. Location of electrofusion profiles (ERT) in the landslide area

5. Interpretation of research results

Analysis of the obtained geophysical survey results led to the identification of five geoelectric layers, corresponding to lithological-genetic series: anthropogenic soils (n), sands and gravels (I), silty sands, silts and sandy silts, clays (II and IV) and organic soils (III).

The distribution of resistivity values was obtained through the inversion of measurement data. The inversion parameters of the ERT profile are summarized in Table 2.

Table 2. Inversion parameters used in Res2DINV program

Inversion parameter	Solution
electrical resistivity modelling method	finite elements method
finite mesh grid size	four nodes
mesh refinement	the finite element mesh is as dense as possible
number of iterations	five iterations
model refinement	introducing a virtual electrode between the actually grounded electrodes – doubling the number of finite element cells
type of inversion	L1 (robust, blocky)
inversion optimalization type	Gauss-Newton method

Table 3 contains the characteristics of field geophysical measurements and the results of ERT processing. The distance between electrodes was 2 meters, with 16 measurement levels. The exploration depth reached 14 meters below ground level. The root means square error of inversion (RMS %) indicates the quality of the measurement data and/or deviation from the 2D subsurface structure. In the analysed profiles, an error of approximately 5% or less was achieved. This means that accurate measurement data were obtained.

Table 3. Characteristics of geophysical measurements and ERT processing results

Profile	**Measurement protocol**	**Profile length [m]**	**Number of measurement points**	**Number of removed points**	**Number of electrodes**	**RMS [%]**
ERT-1	gradient 2 × 21	134	1028	21	68	0.65
ERT-2		96	622	12	49	5.35
ERT-3		146	1132	32	74	1.22
ERT-4		138	1061	18	70	1.12

It should be noted that the position of boundaries and anomalies is related to the vertical resolution of the method.

During the geological interpretation of the obtained results, several assumptions were made based on a general understanding of both the physical properties of the soils in the study area and the overall nature of electrical resistivity tests:

– based on the geotechnical boreholes, characteristic ranges of resistivity for the investigated soils were determined,
– drilling profiles were overlaid on the geoelectrical cross-sections to correlate the boundaries obtained from ERT surveys with those obtained from the lithology of the boreholes,
– geological interpretation was conducted based on the correlation between boreholes and ERT cross-sections.

Figure 5 shows electric resistivity scale for separated soil layers.

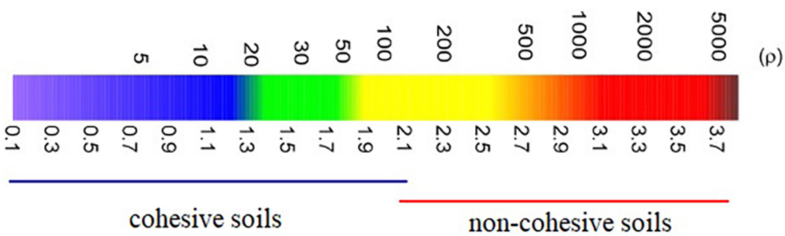

Fig. 5. Soil electric resistivity scale [Ωm]; low (10–20 Ωm), medium (20–50 Ωm), high (< 100 Ωm)

The results of geophysical surveys using the ERT method were presented in the form of 2D sections (Fig. 6 to Fig. 9) and 3D visualization (Fig. 10).

ERT-1 profile (Fig. 6) was conducted in a valley, in the western part of the area. On the slope of the hill, the distribution of electrical resistivity is layered (from the surface of the terrain): medium, low, medium, and high resistivities. There are no anomalies characteristic of displaced colluvial sediments. In the case of intense and prolonged rainfall, water may infiltrate through the roof of sediments with low resistivities (clays), creating a slip surface for the overlying sediments.

ERT-2 profile (Fig. 7) was conducted in the periodically active landslide area. The distribution of electrical resistivity is highly heterogeneous, meaning it varies both vertically and horizontally. The potential slip zone is located in the contact zone of soils with low and high resistivity, on the slope and at its base.

ERT-3 profile (Fig. 8) was conducted in the central part of the area. On the slope of the hill, the distribution of electrical resistivity is layered, similar to the ERT-1 profile. There are no anomalies characteristic of colluvial deposits.

ERT-4 profile (Fig. 9) was conducted in the eastern part of the area. There is the constantly active landslide in this area (Fig. 1). Colluvial deposits (layer I) are characterized by significantly increased electrical resistivity (above 300 Ωm). In their bottom, it was proposed slip surface, indicated in Fig. 9 red arrows.

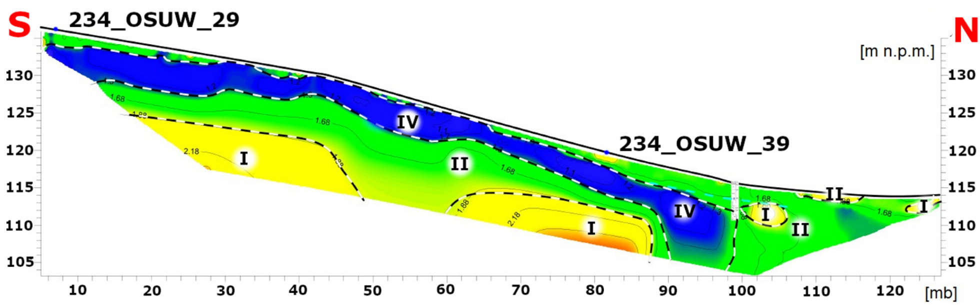

Fig. 6. ERT-1 cross-section of electrical resistance

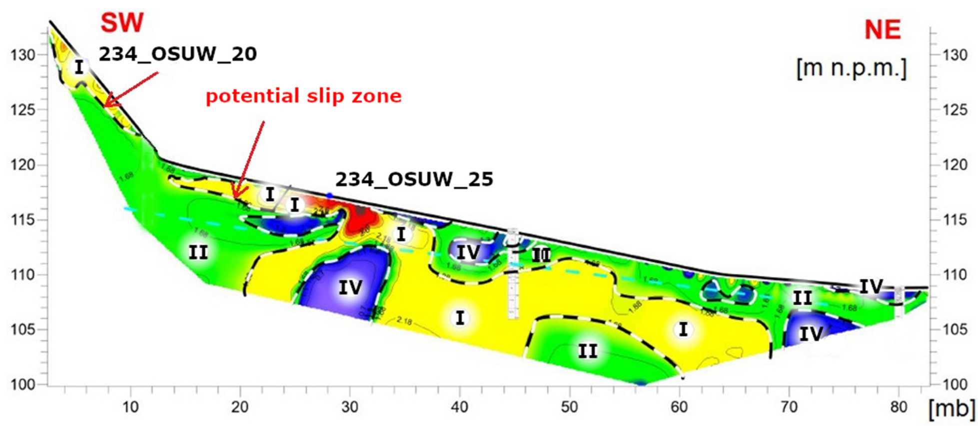

Fig. 7. ERT-2 cross-section of electrical resistance

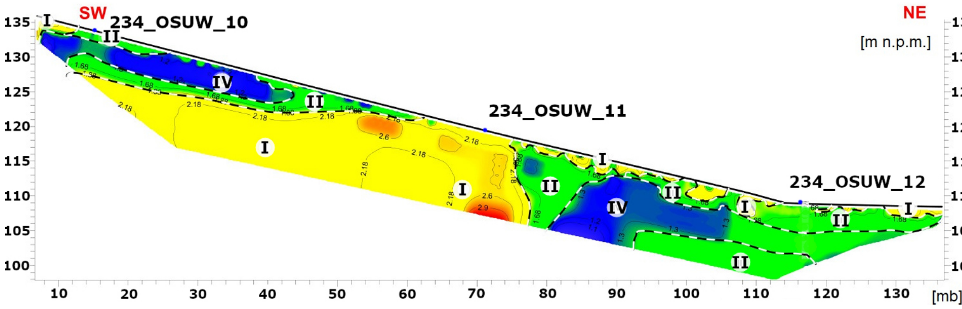

Fig. 8. ERT-3 cross-section of electrical resistance

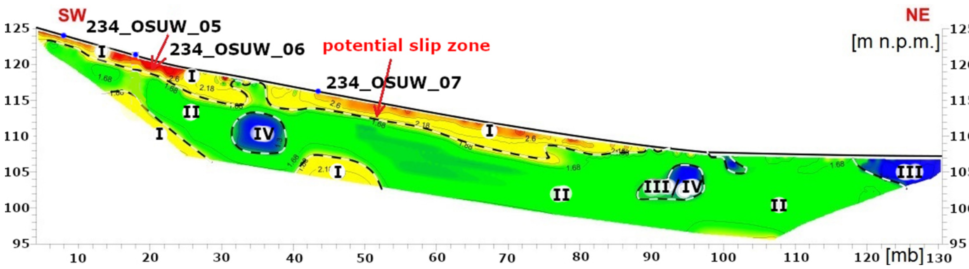

Fig. 9. ERT-4 cross-section of electrical resistance

In summary:

- Four ERT profiles were conducted along the slope, proceeding from top to bottom.
- Profiles ERT-1 and ERT-3 revealed a parallel arrangement of resistivity layers in the substrate suggesting slope stability.
- Profile ERT- 4 exhibited an anomalous zone of resistivity distribution halfway up the slope, which may indicate slope activity.
- Profile ERT-2 demonstrated significant heterogeneity in both horizontal and vertical the electrical resistivity distribution, this profile was located in the area of periodically active landslides.
- The zone with heterogeneous resistivity in profile ERT-2 was estimated to be approximately 7 to 9 meters thick, this zone likely corresponds to colluvium (Fig. 3). The base of the colluvial deposits can be roughly determined as the slip surface of the landslide.

Comparing the results of geotechnical investigations (Fig. 3) with the results of geophysical investigations, it was found that colluvial deposits are characterized by significantly increased electrical resistivity (above 300 m). In their bottom, the potential slip zone was proposed (Fig. 7, Fig. 9).

The development of all ERT cross-sections allowed for the 3D presentation of the electrical resistivity distribution of the subsoil. Distinct zones of increased resistance (>300 Ωm) can be correlated with mass movements (colluvium). Figure 10 illustrates the results of 3D interpretation of geophysical research.

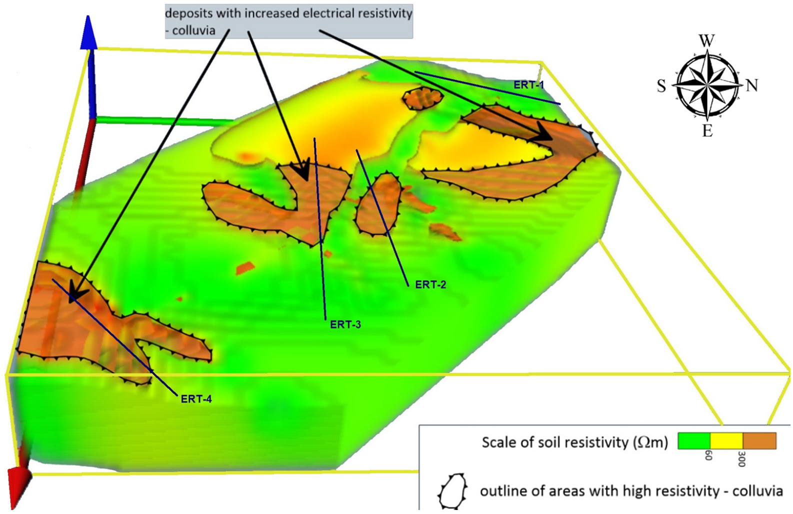

Fig. 10. 3D electrical resistivity distribution

6. Conclusions

The results of landslide studies indicate that an integrated approach based on geophysical imaging effectively provides a detailed understanding of the structure and lithology of complex landslide systems, which cannot be achieved solely through local sample collection data. Considering that geotechnical studies are point-based, vertical profiling can locate discontinuities where material may shift along the slope. Geophysical surveys allow for the identification of weakening or waterlogging zones that can affect slope stability. ERT results have identified the 3D geometry and geological structure of the landslide area, revealing several lithological formations with varying resistances. These results helped identify a potential slip zone. The combined use of geotechnical ERT method, and field surveys has resulted in a comprehensive and accurate characterization of the landslide. This is achieved by calibrating geophysical results with direct measurements of physical properties of materials obtained from the landslide and its surroundings.

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Trójwymiarowa interpretacja badań geotechnicznych i geofizycznych osuwisk

Słowa kluczowe: geotechniczny model 3D, badania geofizyczne, osuwiska, tomografia elektrooporowa (ERT)

Streszczenie:

Efektywne projektowanie obiektów inżynierskich wymaga dokładnego rozpoznania warunków wodno-gruntowych podłoża. W niektórych sytuacjach koniecznym wydaje się rozpoznanie trójwymiarowe. Do takich przypadków należą osuwiska. Są one zjawiskami złożonymi, a głównymi czynnikami, które mają znaczący wpływ na ich zachowanie się w czasie, są zmiany geometrii i nachylenia skarp oraz zmiany warunków wodnych. W artykule omówiono rozpoznanie budowy podłoża w rejonie zagrożonym ruchami masowymi, w ciągu modernizowanego odcinka linii kolejowej. Analizowany obszar znajduje się w strefie brzeżnej moreny zlodowacenia północnopolskiego. Budowa geologiczna podłoża to gliny lodowcowe i piaski wodnolodowcowe, iły zastoiskowe oraz grunty organiczne występujące na terenach okresowo podmokłych i w obniżeniach terenu. Na zboczu skarpy występują koluwia, głównie są to utwory ilaste. Geomorfologia powierzchni została zinterpretowana z danych LIDAR oraz wizji terenowej. Tomografia elektrooporowa 2D i 3D (ERT) została wykorzystana w celu uzyskania szczegółowego obrazu podpowierzchniowego, który został zweryfikowany za pomocą wierceń badawczych i analizy laboratoryjnej próbek gruntu pod kątem właściwości fizycznych, w tym granulometrii i plastyczności, oraz własności mechanicznych gruntów. Badania umożliwiły stworzenie trójwymiarowego modelu podłoża, pokazały przestrzenne rozmieszczenie koluwiów oraz obszary zagrożone aktywnymi osuwiskami. Wyniki badań wskazują, że zintegrowane podejście, polegające na równoczesnym obrazowaniu geofizycznym i rozpoznaniu geotechnicznym, pozwala na szczegółowe zrozumienie struktury i litologii obszarów osuwiskowych.

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