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ARTICLE

USING SURFACE GEOPHYSICAL METHODS TO DETECT VOIDS IN THE NEAR-SURFACE ZONE

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Abstract: This study investigates the properties of rock formations using seismic down/up-hole measurements and electrical resistivity methods to identify structural anomalies such as voids. Surveys were conducted in four test wells in southern Poland and the analysis emphasizes the practical applications of mentioned geophysical techniques in subsurface imaging. The seismic method measured wave propagation, while electrical resistivity assessed rock resistance variability, aiding subsurface zoning. The methodology involved designing resistivity maps as depth cuts, based on seismic results. Presented velocity profiles identified weak zones, and was establishing critical geomechanical boundaries in depth, which was a basis for further resistivity geometry projecting. Resistivity measurements were conducted radially around wells, highlighting resistivity anomalies that signify risks related to subsurface void migration and changes in geomechanical properties. The analysis confirmed a general trend of increasing seismic velocity with depth, with significant deviations suggesting differences in rock quality. The resistivity method at the selected depth-cuts, mapped zones with high resistance, which was a direct indicator of the presence of changes in the rock mass. These findings are crucial for planning safe earthworks, soil stabilization, and environmental monitoring, particularly in subsidence-prone areas. Future research may enhance anomaly detection and monitor changes in rock mass properties over time. Combining seismic velocity profiling and resistivity measurements proves effective in identifying subsurface structures, which is vital for risk mitigation in engineering and environmental projects.

Keywords: uphole measurements, resistivity measurements, voids detection, subsurface mapping, shallow surveying

1. Introduction

Studies employing uphole measurements and electrical resistivity methods aim to determine the physical and mechanical properties of the rock and detect potential structural anomalies, such as voids or changes in geological composition. Velocity profiling enables the measurement of seismic wave propagation speed in rocks, allowing for the assessment of their geomechanical condition, while the electrical resistivity method examines the variability of the rock electrical resistance, which is helpful in identifying different zones in the subsurface. In such studies, understanding the geological setup is crucial for engineering, mining, or environmental protection projects, allowing for risk minimization related to underground voids or terrain deformations [1–5]. The article presents the results of velocity and electrical resistivity measurements analyses, conducted in four test boreholes located in southern Poland. The studies were carried out to examine changes in the mechanical properties of the rock with a focus on detecting potential anomalies, such as voids or structural disturbances.

2. Methodology of conducting velocity profiling and electrical resistivity method

2.1. Description of the down/uphole method

The borehole velocity measurement is one of the most accurate techniques for determining the physical and mechanical properties of rocks. The measurement is based on using an impact source that generates P seismic waves. These waves propagate through the geological layers and are received at various depths by an appropriate system of receivers which are then recorded by a seismograph. The receiving probe typically consists of a receiver made up of three geophone coils oriented in space along the (z, x, y) axes or several to a dozen hydrophones. The probe is placed in the borehole at known depths, while the wave is simultaneously triggered at the surface, where “d” is the distance from the borehole’s axis to the source, “r” is the distance between the source and the triplet of sensors, and “z” is the depth (Fig. 1).

The standard data processing methodology consists of the following phases:

- picking the first arrivals of the seismic wave;
- determining the wave arrival times (*t*);
- calculating the velocity values for individual depth intervals [1–5].

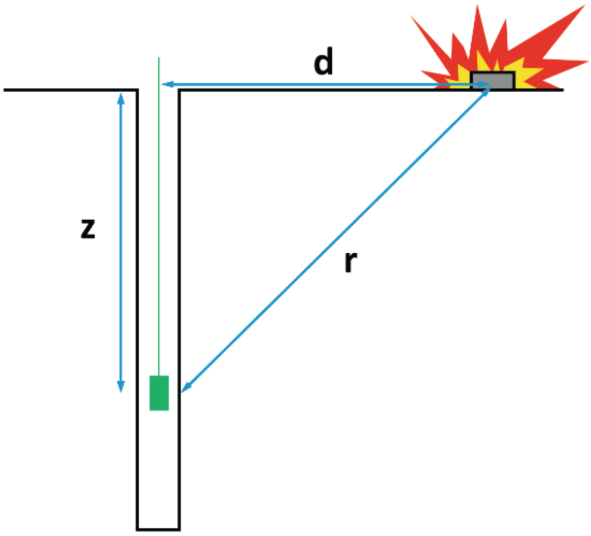

Fig. 1. Schema of down/up-hole measurements

Based on the obtained hodographs, the interval velocity is calculated, defined by the following relation:

$$V\,int = \frac{(Z_2 - Z_1)}{(T_2 - T_1)} \tag{1}$$

where:
Z – depth,
T – wave arrival time [1–5].

During the tests, a point-loading probe was used, with a natural frequency of the built-in sensors equal to 10 Hz. The source of vibrations during the tests was a seismic hammer weighing 5 kg.

2.2. Description of the electrical resistivity method

The electrical resistivity method is a geophysical technique used to investigate the structure of subsurface, utilizing the variation in the electrical properties of rocks (e.g., the ability to conduct electric current and the capacity to polarize the rock environment) [1–3, 6, 7]. Geoelectrical methods are applied to understand the geological structure for engineering, hydrogeological, mining, and environmental protection purposes [2, 6–10].

In the electrical resistivity method, the change in the electric field induced artificially in the ground by applying current electrodes is observed. A key element of this technique is measuring the potential difference across a pair of potential electrodes located within the influence range of the electric field between the current electrodes. Ultimately, this method determines the apparent resistivity values of the rocks within the generated field's reach [1, 8]. Electrical resistivity surveys belong to a subgroup of electrical methods characterized by effectively registering disturbances in the rock mass in areas with significant electrical resistivity contrasts [5]. When applying the electrical resistivity method during field surveys, the apparent resistivity of the rock substrate is measured by deploying four electrodes on the ground's surface, forming a measurement configuration [4, 9]. A known current is generated from a power source connected to two current electrodes (A and B). The potential difference is measured across the other two electrodes, known as measurement or potential electrodes (M and N). The depth range of the electrical resistivity method depends on the distance between the electrodes A and B, as well as the lithology of the area. The choice of the depth range for the setup is determined by the specific, often complex geological structure, which frequently serves as the basis for conducting field tests [3–9]. The investigation of the zone around boreholes above mining excavations was carried out using a modified electrical resistivity sounding method [4, 7, 11]. One of the current electrodes was placed at the bottom of the borehole, while the other was positioned at a distance according to the methodological recommendations for Wenner-type measurement configurations [7–10]. The measurement of the potential difference was conducted using a regular radial measurement setup (with a potential change interval of 3 m). This allowed for determining the distribution of resistivity in the rock mass around the borehole selected for seismically established depth-cut.

2.2. Measurement geometry – resistivity method

Studies were conducted in a radial arrangement with a minimum of 8 profiles, each approximately 18 m long, rotated every 45 degrees relative to the well. In cases where significant changes in resistivity were observed, the profiles were densified. One of the current electrodes was permanently placed in the well, while the other was positioned at an appropriate distance to ensure adequate depth of electrical resistivity investigation – usually maintaining a ratio of 3 times the depth of the resistivity cut. On each of the radial profiles, measurements of the potential change in the electric field were taken at intervals of 3 m. Measurements were carried out on the available measurement surface. The measurement data in the area of well W2 were limited due to the inability to maintain the measurement geometry caused by terrain obstacles.

3. Results

3.1. Results of measurements in well

The interpretation of seismic data involved identifying the first arrivals of longitudinal waves and calculating the interval velocity values for the entire well. The mentioned velocity distributions characterize the rock mass in two ways: by identifying the longitudinal wave velocity and by observing changes in the characteristics of velocity distributions (e.g., decreases). This allowed for the detection of discontinuities and profiling was performed in wells W1, W2, W3 and W4.

The results are presented as velocity distributions within the depth range of the investigated wells. A key feature of the obtained results is the general increase in velocity with depth. A distinguishing feature of the distributions is the variable characteristic of velocity values with depth.

It should be noted that, apart from well W1 (Fig. 2), the velocity values associated with the presence of sandstones in the range of 1 100 m/s to 1 200 m/s. This indicates that the medium is highly fractured. Well W1 represents an exception to this trend, as the rock medium in it has values of approximately 1 400–1 500 m/s, indicating it is fractured, but no displacements occur. Profiling in well W2 (Fig. 3) was concluded at a depth of 26 meters due to the heaving and clogging of the well with sand and water. In well W3 (Fig. 4), part of the recorded data from the near-bottom zone did not contain useful signals, a similar situation was observed in well W4 (Fig. 5).

It is particularly noteworthy that the mentioned distortions in the seismic signal are noticeable above the level of a probable void caused by the disturbance of rocks. This may be related to the so-called migration of the void towards the surface. On each of the profiles, locations marked with red squares indicate values greater than 700 m/s and greater than 1200 m/s. These served to design studies using the electrical resistivity technique. It was determined that the boundary of 700 m/s marks the transition from a highly altered near-surface zone to a naturally formed unconsolidated material. This boundary, on average across the four wells, occurs at about 7 m. The boundary of 1 200 m/s signals the transition to the proper rock medium, occurring on average at 19.5 m for all wells.

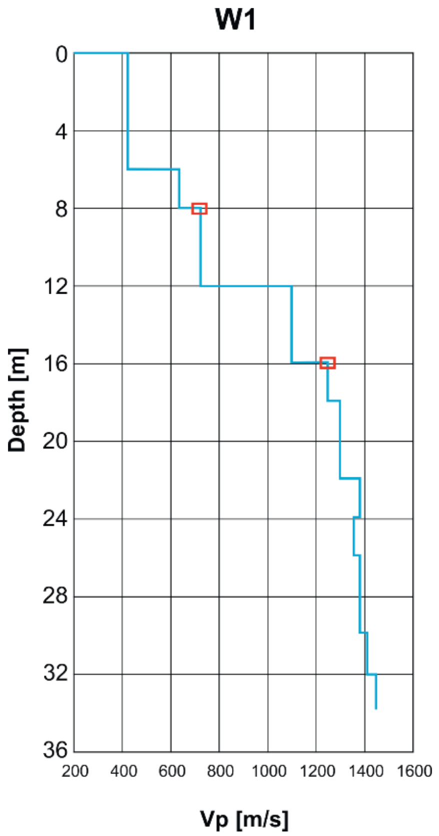

Fig. 2. Results of up/down – hole measurements in Well W1

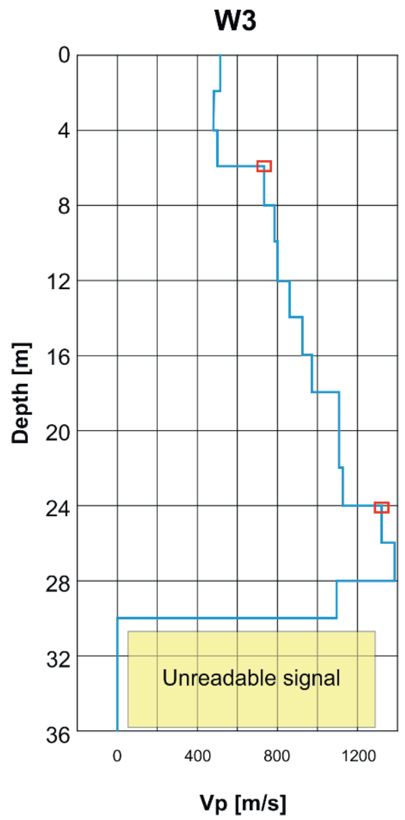

Fig. 4. Results of up/down – hole measurements in Well W3

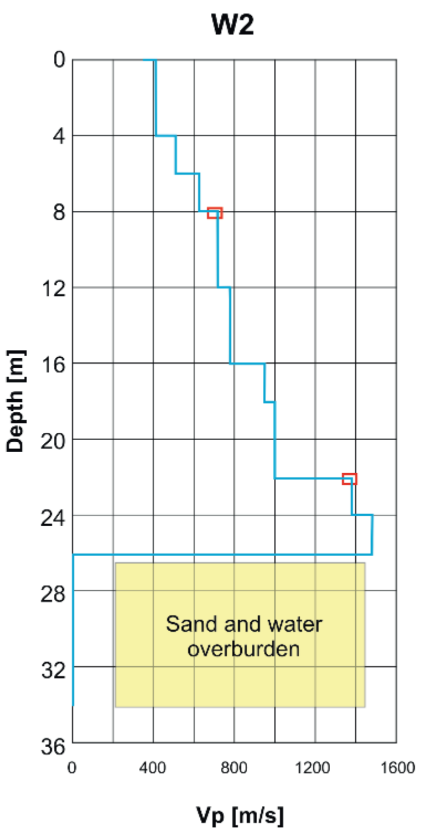

Fig. 3. Results of up/down – hole measurements in Well W2

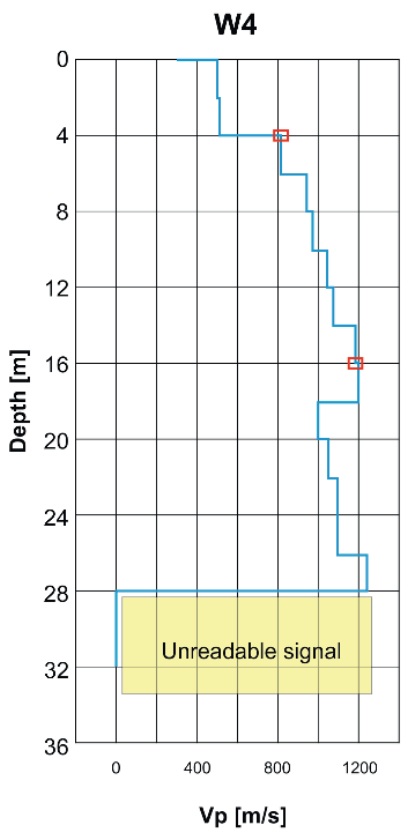

Fig. 5. Results of up/down – hole measurements in Well W4

3.2. Method of investigating the zone around the borehole using the electrical resistivity method

The depths of the electrical resistivity depth-cuts were designed based on the results of seismic velocity profiles, which indicated that the first approximately 6 m of cover consists of weakly bearing material. Therefore, its activation occurs immediately after the continuity of the deeper layers is interrupted. Moreover, this material is poorly consolidated and highly susceptible to changes in the saturation of rainfall. The quantitative interpretation of velocity profiles allowed for the identification of two characteristic geomechanical boundaries within the studied medium. These boundaries are associated with changes in geomechanical parameters, which were investigated through electrical resistivity methods.

Initially, the imaging surface was designed at the level of the bottom of the well, with subsequent depth-cuts assigned to significant changes – velocity boundaries in the wells- assigned by red marks on velocity profiles. The nearest cut to the surface was placed at approximately 10 meters below the surface level (b.s.l.), determined by the increase in velocity values above 700 m/s. The deeper electrical resistivity cut was set at a level of 20 m b.s.l., based on the averaged level where the velocity increased above 1200 m/s.

The work began sequentially in the following wells: W1, W2, W3 and W4. The data obtained at the bottom of the wells (test measurements were conducted for wells W1 and W2) exhibited weak electrical resistivity differentiation, oscillating around <= 20 Ohm·m. The main reason for this phenomenon is likely the presence of mine water with high mineralization, masking the presence of potential voids and causing low variability in the resistivity image. Ultimately, conducting cuts at the bottom of wells W1, W2, and W4 proved to be pointless.

Considering this fact, it became strategic for the investigation of the subsurface to perform measurements at the mentioned levels of 10 and 20 m b.s.l. The level of approximately 20 m b.s.l. corresponds to the upper layer of rocks and appears to be a critical depth due to observed changes in the bedrock. This level is characterized by velocities of 1200 m/s or greater (proper bedrock). On average, this velocity transition occurs at around 19.5 m (depth-cut on 20 m below the surface). The second cut at about 10 m b.s.l. was designed to be representative of the voids breaking through the weakly cohesive material above the bedrock.

This discussed level was also chosen considering the velocity profiles, as the rocks at an average depth of around 7 m b.s.l. exhibits velocities oscillating around 700 m/s or greater, marking the boundary between the heavily altered near-surface zone and more consolidated sediments, so the value of 10 m b.s.l. below the surface was adopted.

In the case of well W3, an attempt was made to conduct an electrical resistivity measurement at a level of 35 m b.s.l. (depth of electrode placement), and test measurements were performed, revealing variability in resistivity measurements. This suggests that the near-bottom zone around this well is not filled with mine water to the extent observed in wells W1, W2 and W4. Considering this result, a full intended measurement geometry was established, resulting in an electrical resistivity map.

Ultimately, for wells W1, W2 and W4 (Figs. 6–9), two depth cuts were obtained, while for well W3, three cuts were made (Figs. 10–12). It should be emphasized that the obtained resistivity maps represent an averaged resistivity value of ±1.5 m concerning the depth position of the cut.

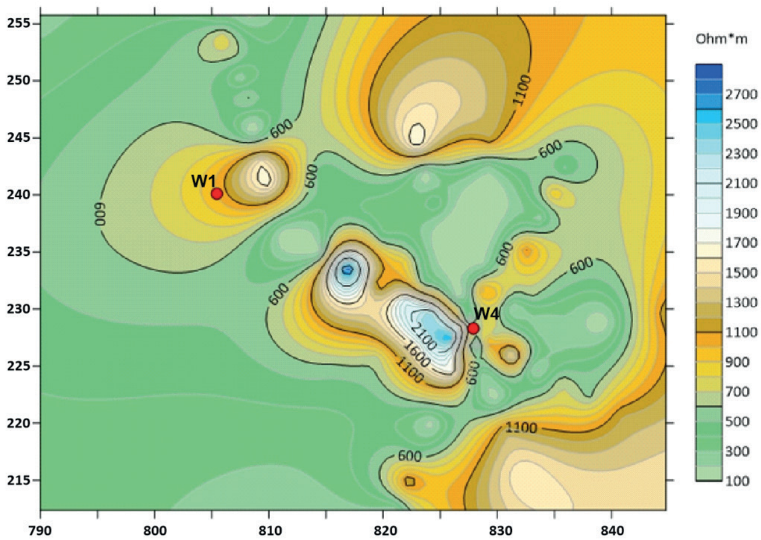

Fig. 6. Resistivity map in the Zone of Wells W1 and W4, Cut – 10 m b.s.l.

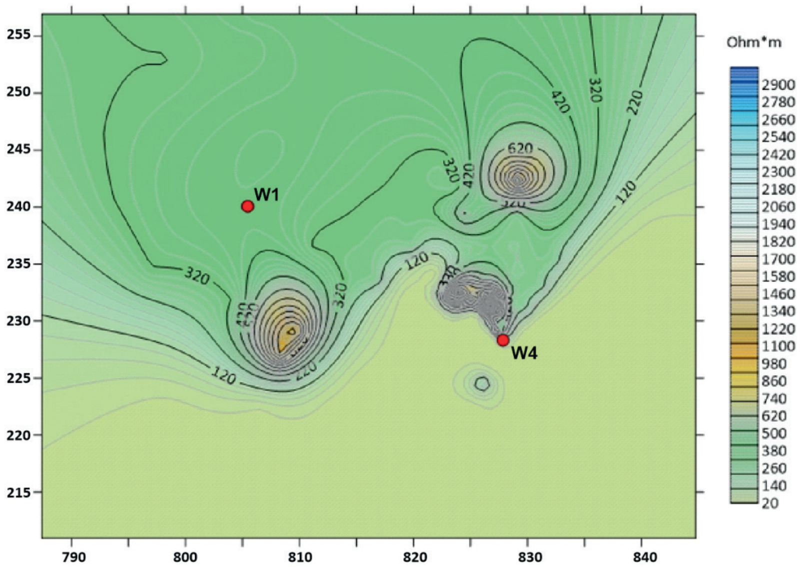

Fig. 7. Resistivity map in the Zone of Wells W1 and W4, depth – 20 m b.s.l.

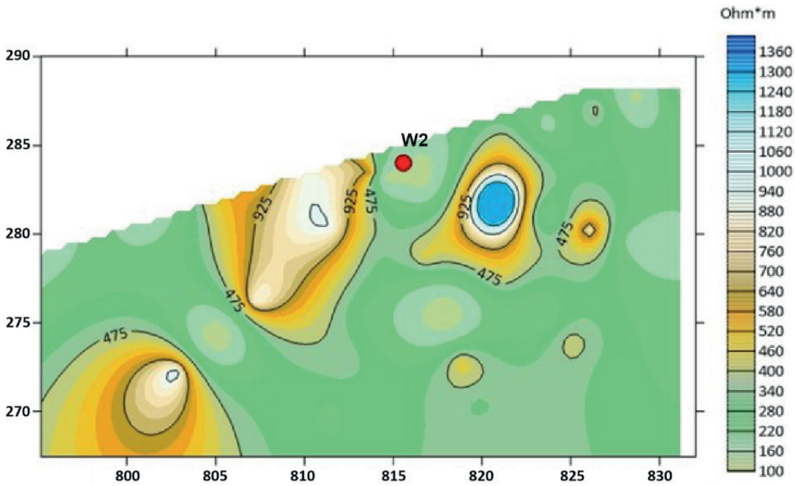

Fig. 8. Resistivity map in the Zone of Well W2, depth – 10 m b.s.l.

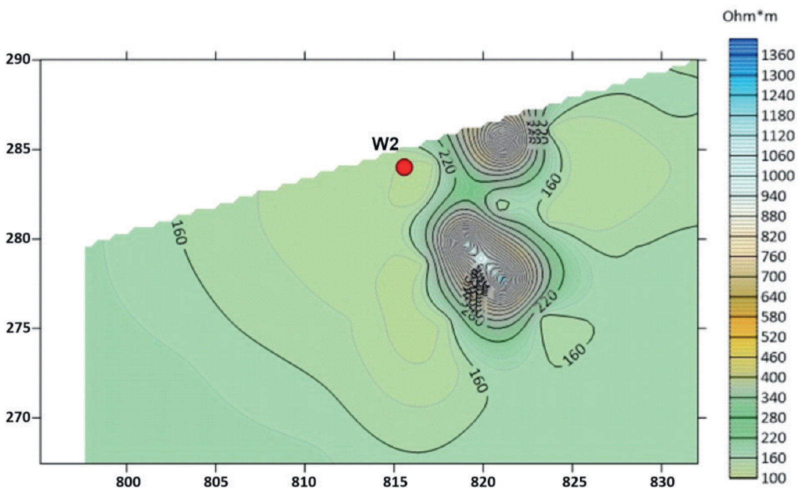

Fig. 9. Resistivity map in the Zone of Well W2, depth – 20 m b.s.l.

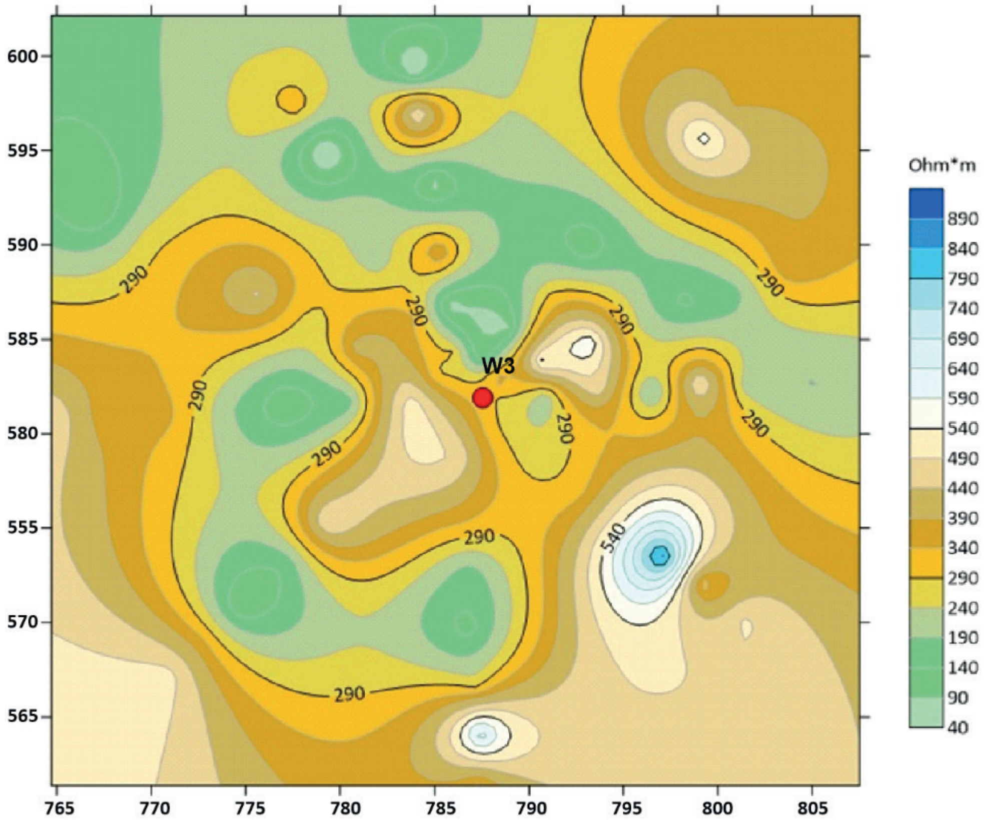

Fig. 10. Resistivity map in the Zone of Well W3, depth – 10 m b.s.l.

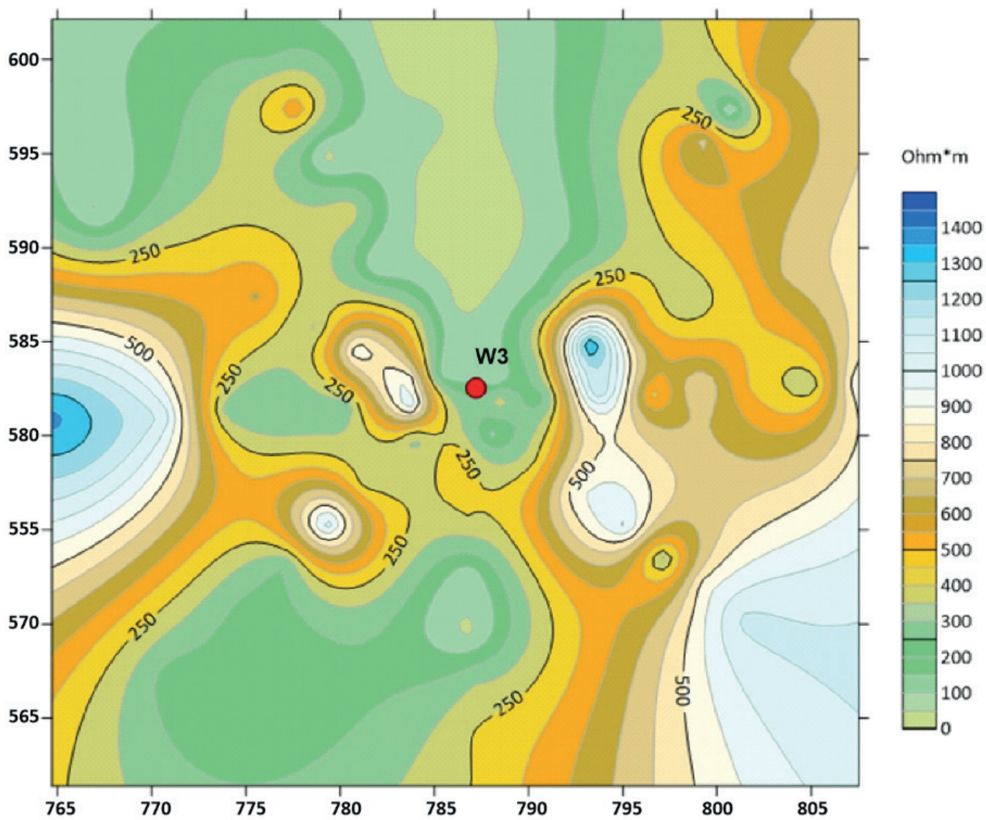

Fig. 11. Resistivity map in the Zone of Well W3, depth – 20 m b.s.l.

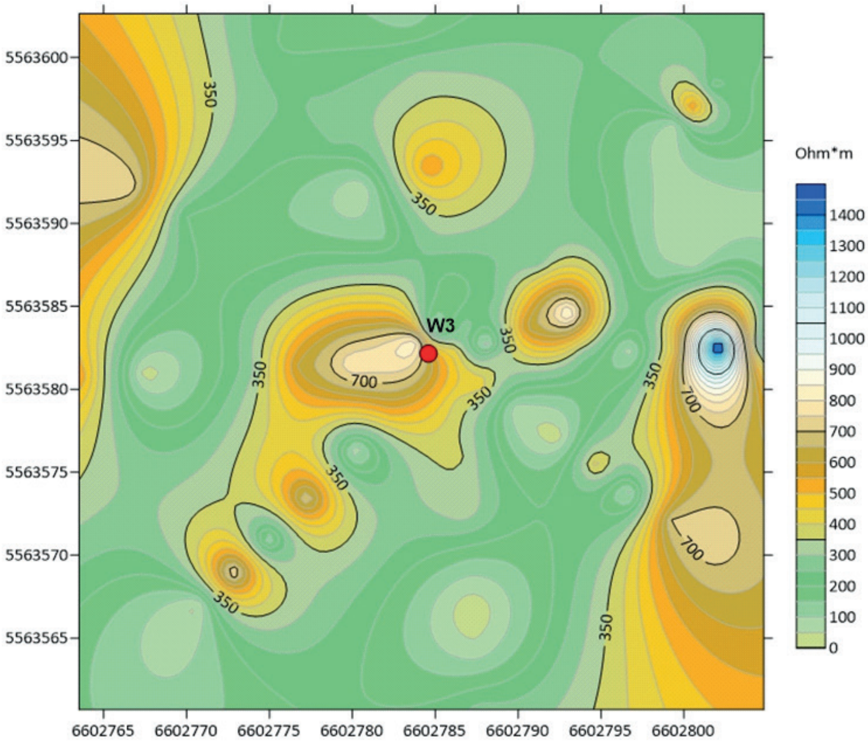

Fig. 12. Resistivity map in the Zone of Well W3, depth – 35 m b.s.l.

4. Discussion

Based on the results of the conducted studies, the investigation at the level of 20 m b.s.l. reveals a rather monotonous distribution of resistivity. High-resistivity anomalies were detected against a background value of around 300 Ohmm. In the case of the map for well W3 (Fig. 12) at the level of 35 m b.s.l., a series of anomalies arranged in a single azimuth is visible. On the same map (Fig. 12), high-resistivity anomalies also appear at the edges of the map's extent. However, the dominant background value is around 200 Ohmm. At the level of 10 m b.s.l. (Figs. 6, 8 and 10), all wells exhibit the most diverse electrical resistivity. Here a series of anomalies occur and the image is strongly differentiated. Anomalies with the highest resistivity values can be considered the most suspicious for the migration of voids toward the surface. It is also possible that the size of the detected anomaly should be taken into account for a more accurate assessment of the risk of layer continuity disruption.

5. Conclusions

This paper presents the results of geophysical studies conducted using seismic and resistivity measurements in several wells. The main objective was to identify structural anomalies such as voids.

The analysis of seismic velocity confirmed a general trend of increasing velocity with depth. However, significant deviations were observed, which may suggest differences in rock quality and the presence of potential anomalies. Resistivity measurements identified anomalous zones, indicating the potential location of voids or changes in the composition of the rock mass.

The results of the studies may have important implications for engineering and environmental projects. Detecting voids and fracture zones is crucial for planning various safe earthworks, soil stabilization, and identifying underground structures. Furthermore, conducting such studies is essential for environmental monitoring, especially in areas prone to land subsidence or water infiltration.

Future studies may focus on the application of advanced geophysical methods to improve the detection of smaller anomalies and to conduct longitudinal studies to monitor changes in the properties of the rock mass over time.

In summary, the combined use of seismic and resistivity measurements can prove effective in identifying critical subsurface structures, serving as a valuable tool for mitigating risks in engineering and environmental projects.

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Conflicts of Interest: The author of this paper declare no conflicts of interest.

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