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Original article

Looking for subsurface features: the role of geophysical research in the revitalization of the Palace and Park Complex in Rzuchów, Poland

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ABSTRACT

This article discusses the significance of geophysical research in the context of historical renewal, emphasizing its contributions to risk assessment, sustainable redevelopment, and non-uniqueness in geophysical interpretation. The geophysical studies were conducted in the surroundings of the Palace of Rzuchów, timing to locate the modern infrastructure, historical objects, and other environmental elements that can either threaten the renewal process or add value to the historical heritage. We used three geophysical methods to study the palace surroundings: frequency domain electromagnetics, magnetometry, and electrical resistivity tomography. The findings revealed significant anomalies corresponding to buried modern infrastructure and historical artifacts, offering critical insights for preserving cultural heritage while planning sustainable redevelopment, thus demonstrating the practical utility of integrating geophysical methods in complex historical and environmental contexts.

KEY WORDS: historical palace-park complex; elements of land development; frequency domain electro-magnetics; magnetics; electrical resistivity tomography

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1. Introduction

In Poland, historical residential buildings form a highly diverse group, encompassing both well-preserved examples of top-tier architecture and structures with moderate historical value or those in poor structural condition. These properties, mainly manor houses and palaces, constitute merely 6.84% of Poland's immovable cultural heritage among a group of nearly 80,000 protected monuments (Rozbicka, 2017; Registry of Monuments, 2023). In the 19th century, during the dynamic industrial development of Upper Silesia, numerous park and palace complexes were built as the headquarters of industrialists and landowners. Many of these residences were destroyed during World War II. In the post-war period, landed estates that survived in good condition were used as state schools, orphanages, reformatories, or state farms. Such use led many of them to a state of ruin (Kozak, 2008).

At the turn of the 20th and 21st centuries, some became private property, and new owners began to revitalize them. Abandoned palaces and park areas require effective strategies for their revitalization and redevelopment. Well-thought-out revitalization efforts involve multidisciplinary approaches. The subsurface surrounding such sites often contains hidden hazards, including buried old infrastructure, which is not included in maps. The sustainable revitalization of architectural heritage, specifically analyzing the potential for revitalizing historic buildings, is based on existing environmental and cultural factors. Developing procedural standards at the pre-investment stage is crucial to addressing various issues encountered during revitalization (Mackiewicz, 2021; Court et al., 2022).

The renovation works of the palace in Rzuchów are being conducted concurrently with an investigation of its lesser-known and poorly documented history. The location of the palace-park complex and historical records prompted the investor to commission geophysical surveys. Geophysical research offers fast, non-destructive, and cost-effective tools for site characterization. They have been applied for years in archaeology as non-invasive and are rapid methods which preceed traditional excavation works (e.g., Gaffney, 2008; Ogden et al., 2010; Grassi et al., 2023; Lindford, 1998; Keay et al., 2009; Mendecki et al., 2020; Edemsky et al., 2021), but geophysics is also an effective tool used to recognize the structure of a rock mass, including water, landslides, or mining hazards. Geophysical techniques, including, but not limited to, electrical resistivity imaging/tomography (ERI/ERT), frequency domain electromagnetics (FDEM), and magnetometry, allow for identifying hidden subsurface structures, such as building foundations, embankments, drainage systems, or underground chambers, enabling researchers to understand the spatial layout and distribution of artefacts. They also help to diagnose the technical risk of damaging objects, particularly in the context of potential hazards related to geological instability.

The main purpose of the surveys is to verify oral histories. Apart from documented historical facts regarding the conflicts in 1921, there is an oral history which suggests that after shooting at the approaching insurgents, the palace owner's son escaped from the palace through an underground tunnel. After capturing the palace, the insurgents searched for the shooter inside, but they did not find him. According to oral accounts, the tunnel was said to connect to neighbouring properties. However, a more likely scenario is its connection to nearby agricultural buildings, located approximately 30 metres from the palace. The second historical reason for conducting geophysical surveys is to locate the burial place of the first owner. Information from former residents of a children's home in the 1970s indicated the presence of remnants of a masonry structure in the park's SE corner, likely to be the tomb of the palace's founder, H. Himml. Currently, no visible traces of such a structure are apparent on the surface.

Moreover, the geophysical survey application aimed to minimize risks associated with the monument's restoration and ensure the safety of future users. The presence of undisclosed underground objects can impact the building's structural safety and future usability. During excavation works near the palace, remnants of pipes were discovered that were not evident in the geodetic maps of the Rzuchów complex. Geophysical survey results should provide vital information about terrain characteristics and unidentified underground infrastructures, aiding in planning renovation and adaptation works. Furthermore, the survey results should serve as the basis for economically justified recommendations to secure the building and utilize the revealed objects for ongoing activities.

2. Site characterization

The Rzuchów village is situated in the area of Upper Silesia, near the Upper Oder River Valley, close to the Polish-Czech border (50°04'10.48 "N, 18°21'16.17 "E) (Figs 1a and 1b). This property is adjacent to a legally protected natural area – Landscape Park of the Cistercian Landscape Compositions of Rudy Wielkie.

The earliest confirmed traces of settlement in the Rzuchów area date back to 6000 BCE (Staniczek, 2008). Fertile soils, an ample water supply, a mild climate resulting from the proximity to the Moravian Gate, and a safe location on the highland in an open area (providing far-reaching visibility) were significant factors for the location of the settlement. The oldest settlement evidence in Rzuchów itself dates back to the 13th/14th centuries. The first written mention of the village of Rzuchów dates back to 1415 (*Codex Diplomaticus…*, 1895). The village was founded on the edge of the Oder Valley, approximately 100 meters above the valley floor.

In the 19th century, Rzuchów experienced a period of economic prosperity. Thanks to the efforts of the landowner W. Mendhelsson (1831–1891), the Rzuchów estate became the best managed in the county: local fields were drained, leading to an increase in the efficiency of cultivation and breeding, and a modern distillery was built with a steam-powered engine for grain threshing (KRAJCZOK, 2023).

Additionally, since the late 18th century, the development of coal mining contributed to the region's economic importance. The nearest mine shafts were located about 8 km from Rzuchów. Gradually, more mining facilities were established, particularly to the east of Rzuchów, transforming an agricultural landscape into a mining and industrial one (ROLA, 1992).

The Palace in Rzuchów (Figs 1d-1f) was constructed in 1888 and funded by Heinrich and Stefanie Himml (*Dobra rycerskie*) (Fig. 1g). The palace was designed by an unidentified architect in the Neo-Renaissance style (see Figs 1d-1f) with characteristics of Dutch Mannerism and built in a rectangular layout, featuring a tower in the southern korner (SAWIŃSKI, 2001).

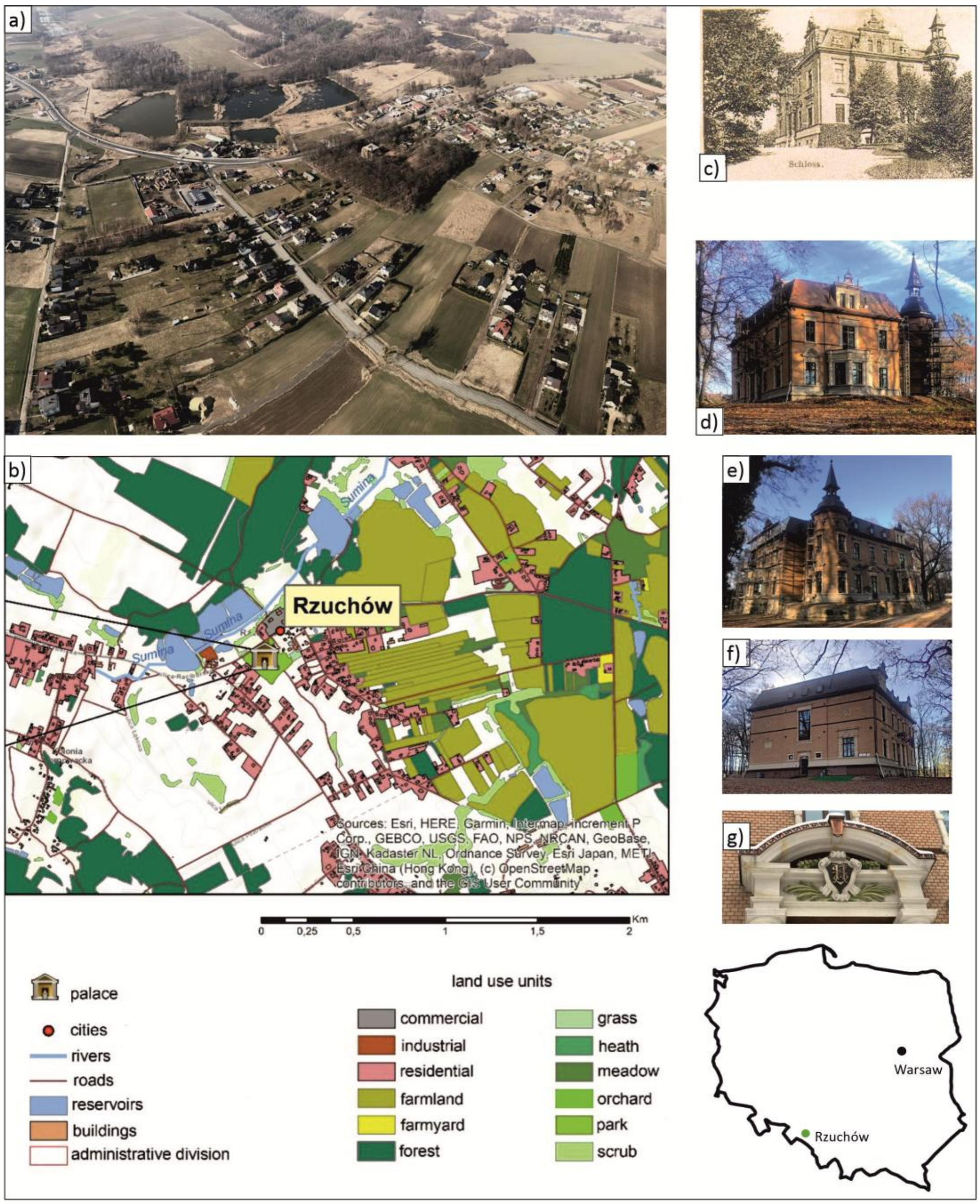

Fig. 1. Study area characterization: a) Rzuchów panorama; b) location of the Palace and Park Complex in Rzuchów; c) Rzuchów Palace western corner: historical view, 2nd decade of the 20th century; d) western corner; e) southern corner; f) northern corner; and g) portal with initials H(einrich) S(tefanie) (1d–1g photos by E. Mackiewicz)

During World War I, the palace remained unharmed, but the unrest during the time of the Silesian Uprisings left a mark on its history. Intense Polish-German fights took place for control of the palace. In the 1930s, the palace became a school of domestic economy for girls with an accompanying boarding facility. During World War II, the palace was used as a German camp for women (Mädchenlager Schönburg). According to oral accounts of the residents, upon hearing news of the Red Army's approach, the Germans ordered the building to be set on fire. The roof and a few rooms were burned. The walls remained untouched. After the war, the palace was renovated and used as a children's home until the mid-1990s. Over the next 20 years, the palace fell into complete disrepair. However, its fate changed in 2010 when it came into the hands of private owners who established the Foundation for the Protection of Cultural Heritage. Since 2018, the Foundation has been actively conducting restoration work and adapting the palace for new cultural and scientific purposes.

The original layout of the property has survived to this day (Fig. 1a). The main approach to the palace leads through a driveway connecting two gates located along the Rybnik-Racibórz road (Fig. 1b). The palace's architectural features and available iconography suggest that the main entrance to the estate was from the western side, revealing a view of the imposing front facade (northwest), an impressive projection of the southwest facade, and the corner tower (Figs 1a-b). The palace is constructed using brick masonry finished with a yellow-coloured clinker brick. A characteristic feature of the building is its richly decorated facade (Figs 1b-e). From the east, a side entrance faced the outbuildings (Fig. 1d). Near the palace, there were residential houses for the service staff and various farm buildings. The estate also included a barn, granary, stables, warehouse, and distillery (Mackiewicz, 2022). The side entrance to the palace led to the cellars, which housed the kitchen, laundry, and other utility rooms. According to oral tradition, underground tunnels in the cellars provided an escape route from the building. The available cellars have retained their arched vaults and unchanged room layout, but the entrance to the tunnel has not been discovered to this day.

Presently, the palace is surrounded by an overgrown park covering an area of 3.84 hectares, with a vast meadow on the southeast side of the building. Deciduous tree species such as maples, beeches, linden trees, and oaks dominate the park. The original layout of the park paths no longer exists. The palace is surrounded by agricultural landscapes and numerous ponds (Fig. 1f).

The investigated area represents a lowland class (121) of periglacial type (Richling & Dąbrowski, 1995) with an elevation of 250–257 meters above sea level. It is characterized by a hilly landscape with the presence of convex terrain forms and relative heights of up to one hundred metres. Lithologically, the terrain is composed of coarse-grained sediments, i.e., pebbles and coarse-grained sands, characterized by relatively high resistivity values. The top of this layer is present at 2.5 m on the eastern side and 4.5 m below the surface on the western side. Below this layer, the low resistivity layers of clays, silts, and other fine-grained fractions can be found (Sarnacka, 1968).

3. Methods

The surveys around the palace (Fig. 2) were conducted using frequency-domain electromagnetic profiling, magnetic profiling, and electrical resistivity tomography. The GPS/GNSS system positioned all points and lines.

3.1. Electromagnetic survey

Frequency domain electromagnetic (FDEM) survey, or conductometry, is a geophysical technique used to study subsurface conductivity. Conductometry measures the apparent electrical conductivity and in-phase component proportional to the magnetic susceptibility of the subsurface materials. Apparent values correspond to the resultant value of the measurement obtained for a volume of earth material located from the surface up to the maximum depth of investigation. Conversely, the interpreted value corresponds to the "real" value at a specific investigation depth, usually resulting from the geophysical inversion procedure.

The method works on the principle of inducing electromagnetic fields (primary EM) in the ground through an alternating current generated in a transmitter coil (Fig. 3a). This current produces a primary magnetic field in the subsurface, which, in turn, induces electrical eddy currents in the conductive materials beneath the surface. These currents generate the second magnetic field (secondary EM), which can be detected by a receiver coil(s). FDEM surveys provide valuable information, including high-resolution horizontal map ping (Lindford, 1998; Mendecki el al., 2020).

The conductometer CMD-Explorer (GF Instruments, 2016) was applied during this study. It is a one-man-operated multi-depth probe, which simultaneously enables quasi-continuous measurements for three depth ranges. The measurement depth depends on the spacing between coils (fixed at 1.48 m, 2.82 m, and 4.49 m) and their orientation: horizontal HD or vertical VD. In the Rzuchów case, the VD position was applied, which resulted in recognition up to 2.2 m, 4.2 m, and 6.7 m for apparent conductivity and ca. 0.4 m, 0.8 m, and 1.3 m for the in-phase component. Due to probe sensitivity varying with depth, maximal prospection depth is difficult to find accurately. Generally, it is assumed that cumulative sensitivity should contain 75% of the entire sensitivity on the plot of sensitivity vs. depth of investigation (GF Instruments, 2016).

Fig. 2. Geodetic map of the Palace and Park Complex in Rzuchów with survey lines marked

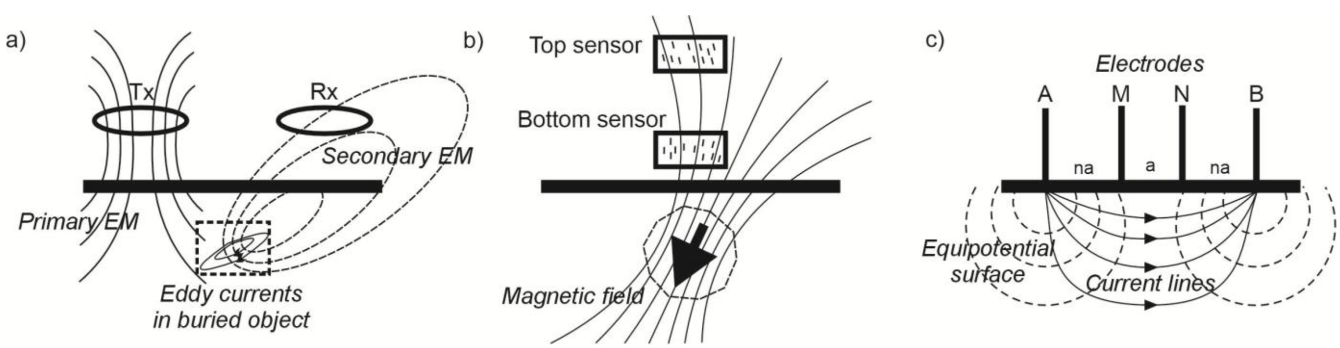

Fig. 3. Principles of the methods used: a) FDEM survey, Tx – transmitter coil, Rx – receiver coil; b) magnetic survey, dashed lines in the sensors represent an arrangement of magnetic domains in the magnetometer; c) resistivity method shown as four-electrode array of Schlumberger-Wenner, A and B – current electrodes, M and N – potential electrodes, a – spacing, n – multiple spacing

The FDEM surveys were carried out on 14 lines around the palace (Fig. 2). Three survey lines were traced on each side of the palace, and two more survey lines were set on the northwest side. The increased density resulted from oral information about the potential tunnel's course. The distance between parallel measurement lines was 10 mand on the NW side of the palace, the distance between the two lines closest to the building was 5 m which was the result of field obstacles (slope and dense bushes) present there. The measurements were performed with a sampling distance every 0.4–0.5 m. Final mapping used kriging in Surfer Software, a technique that estimates values at unobserved locations based on nearby data. The wave model was chosen for the variogram due to limited data under the palace (Menezes et al., 2005).

3.2. Magnetic surveys

Magnetic methods measure a magnetic induction based on the principle that the subsurface contains varying amounts of magnetic minerals, such as magnetite or ferrous objects, and Earth's magnetic field can induct them. Magnetic anomalies are variations in the magnetic field strength from what would be expected in the absence of subsurface magnetic sources. A proton-precession magnetometer, was used in Rzuchów, which measures the total magnetic field intensity at the Earth's surface. The magnetometer is carried along a survey grid or path during a magnetic survey. The top and bottom sensors collect data at evenly spaced intervals, providing two magnetic data sets. Interpretation of magnetic data involves analyzing magnetic anomalies to infer subsurface geological features (Milsom, 2003; Aydin, 2008; Ibraheem et al., 2021).

The proton precession magnetometer utilizes the magnetic moment of the hydrogen nucleus (proton). Its sensing element contains a bottle of low-freezing-point hydrocarbon fluid, usually high-purity decane, wrapped in a coil of copper wire. When a polarizing current runs through the coil, it generates a strong magnetic field that aligns the protons' magnetic moments. Once the current is switched off, the protons (magnetic domains) realign with Earth's magnetic field, emitting electromagnetic energy at a frequency proportional to the field strength. Measuring this frequency requires precise circuitry for high accuracy. Although the magnetometer theoretically achieves very fine measurements, practical limitations like short reading times and manageable current levels set an accuracy limit. While these magnetometers can be affected by strong field gradients and interference from external sources, they remain the preferred choice for ground surveys, providing consistent, absolute measurements of total field strength (Milsom, 2003).

The Earth's magnetic field experiences diurnal variations due to ionospheric currents influenced by solar radiation. In solar-quiet conditions, the field is stable at night, dips from dawn to late morning, rises through the afternoon, and returns to night-time levels. Mid-latitude fluctuations are typically within a few tens of nanoTesla, but differences in crustal conductivity can amplify these variations. Diurnal corrections are typically essential in fieldwork unless only gradient data is used, as gradient measurements (Fig. 3b) can remain unaffected by diurnal variations. Diurnal corrections rely on frequent revisits to a base point when only one instrument is available. Using a second, fixed magnetometer for continuous readings can enhance accuracy, though this secondary device does not need to match the field instrument in type (Milsom, 2003; Aydin, 2008).

The measurements were carried out along three lines (MAG1, MAG2, and MAG3) north of the palace (Fig. 2). The distance between the top and bottom sensor was 1.8 m, and the survey spacing was 1 m. The results obtained along the survey lines were mapped as vertical magnetic gradient values using the Kriging method. Maps were conducted in Surfer software (Wijayanto et al., 2021). The gradient lines in 1D profiles were smoothed using a 4-point moving average filter (Aydin, 2008).

3.3. Electrical resistivity tomography

Electrical Resistivity Tomography (ERT), or Electrical Resistivity Imaging, is a technique used to investigate the near-surface's electrical properties. Contrary to the multi-depth FDEM and magnetic methods, the ERT requires direct contact of electrodes with the ground, extending the measurement time and allowing for a significant increase in the vertical resolution. The 2D-ERT method involves placing electrodes in the ground surface in a linear pattern. An electrical current is injected (Fig. 3c) through one pair of electrodes (current electrodes, AB), and the resulting voltage is measured at other electrode pairs (potential electrodes, MN). Data points are collected by varying the electrode configuration sand recording the electrical potential at different locations. The collected data are processed and used to create 2D resistivity models of the subsurface below the array of electrodes. The models represent the interpreted resistivity at different depths, allowing the visualization of subsurface structures and anomalies. This method is widely used because of its non-destructive, cost- and time-effective charakter (Mol & Preston, 2010; Leucci & Greco, 2012; Chen et al., 2018; Mendecki et al., 2020; Ibraheem et al., 2021).

In this study, the ABEM resistivity equipment was used. The total number of stainless-steel electrodes was 41, and each datum point was measured using the Schlumberger-Wenner array. This array was selected due to its good sensitivity and point distribution in both directions: lateral and vertical. In this case, the minimum electrode distance (spacing), which affects the horizontal resolution obtained, was 2 m. The geometrical factor for this configuration is (Oktanius & Doni, 2016):

$$k = \pi n \, (n + 1)a$$

where the distance between the current and potential electrodes is “n” times, and “a” is the distance between the two potential electrodes for each measurement.

Five survey lines for the ERT were performed; three lines were set on the NW side and two on the NE side. The first profile (ERT3) in the northern area was located approximately 15 m from the NW wall of the palace (Fig. 2). The ERT2 profile in the NE area was placed approximately 5 m from the ERT3 profile (Fig. 2). The ERT1 profile was not set as parallel to the ERT2 due to the terrain obstacles. The first ERT1 end was located 4 m from the ERT2 and 1 m at the second end. The ERT5 was set 3 m from the NE wall of the palace, and the ERT4 was aligned parallell 20 m tina north easterly direction (Fig. 2).

The maximum current was set at 100 mA, with the possibility of automatic decay if the ground contacts were poor. However, the electrical contact turned out to be good enough due to the overgrown area and soil moisture for almost all survey lines. Only ERT5 had bad contact due to the thin gravel layer of the parking area. Adding water to each electrode did not solve the problem. Therefore, the results from this profile were interpreted with a certain degree of uncertainty. The time of current impulse was 0.5 s, and the maximum number of survey stacks per measurement was 4.

The apparent resistivity cross sections were proceeded similarly using Res2Dinv software (Loke, 2000). The inversion procedure was based on the nonlinear modified smoothness-constrained least square method. The best solution for interpreted resistivity was found after six iterations, leading to the lowest absolute error values.

3.4. Resistivity modelling

Resistivity modelling is crucial for interpreting subsurface structures by simulating how electric currents respond to different underground materials, helping predict geological formations. The modelling procedure was conducted in the Res2Dmod (Loke, 2000). It is a forward modelling software used for simulating 2D resistivity data, widely applied in geophysical investigations. During modelling, we employed a finite-difference algorithm to create a synthetic data model, which was used to study subsurface resistivity variations. We set parameters corresponding to real conditions applied in the Rzuchów area, such as electrode spacing (2 m), array type (Schlumberger-Wenner), and grid resolution (11 levels, 300 blocks).

4. Results

4.1. Mapping of the palace surroundings

Based on results from the conductometric and magnetic methods, a general map was made to look for dengerous objects, other infrastructure, or archaeological objects. Figure 4 shows the seven maps carried out around the palace. The first (Fig. 4a) represents the vertical magnetic gradient, indicating where the buried object had a stronger influence on the top records and removing diurnal variations and some local ferrous noise. However, the magnetic measurement did not provide information about the depth of the anomaly. On the contrary, the in-phase and apparent resistivity maps obtained by the FDEM method showed changes in measured values up to specified depths below the surface (Figs 4b-4g). Figures 4b-4d present the shallow results of the in-phase mapping, and Figures 4e-4g correspond to apparent resistivity mapping up to deeper parts of the study area.

Visual inspection of the data allowed the selection of two interesting areas in the N and E directions. The first corresponds to a negative anomaly indicated by magnetic measurements (the

North area), and the second is indicated by strong in-phase anomalies noticed to a depth c.a. -1.3 m below the surface (the East area). Analyzing the results in the in-phase map to a depth of -0.4 m (Fig. 4b) shows a lack of significant anomalies. It just represents the soil layer. Next, to a depth of -0.8 m, the in-phase anomalies are present inthe East area (Fig. 4c) as the strong negative anomaly. The last in-phase map (Fig. 4d) follows the abovementioned anomaly, but they are much stronger. There is no significant correlation with the strong negative anomaly of vertical magnetic gradient. At this level, additional anomalies from the West are highlighted.

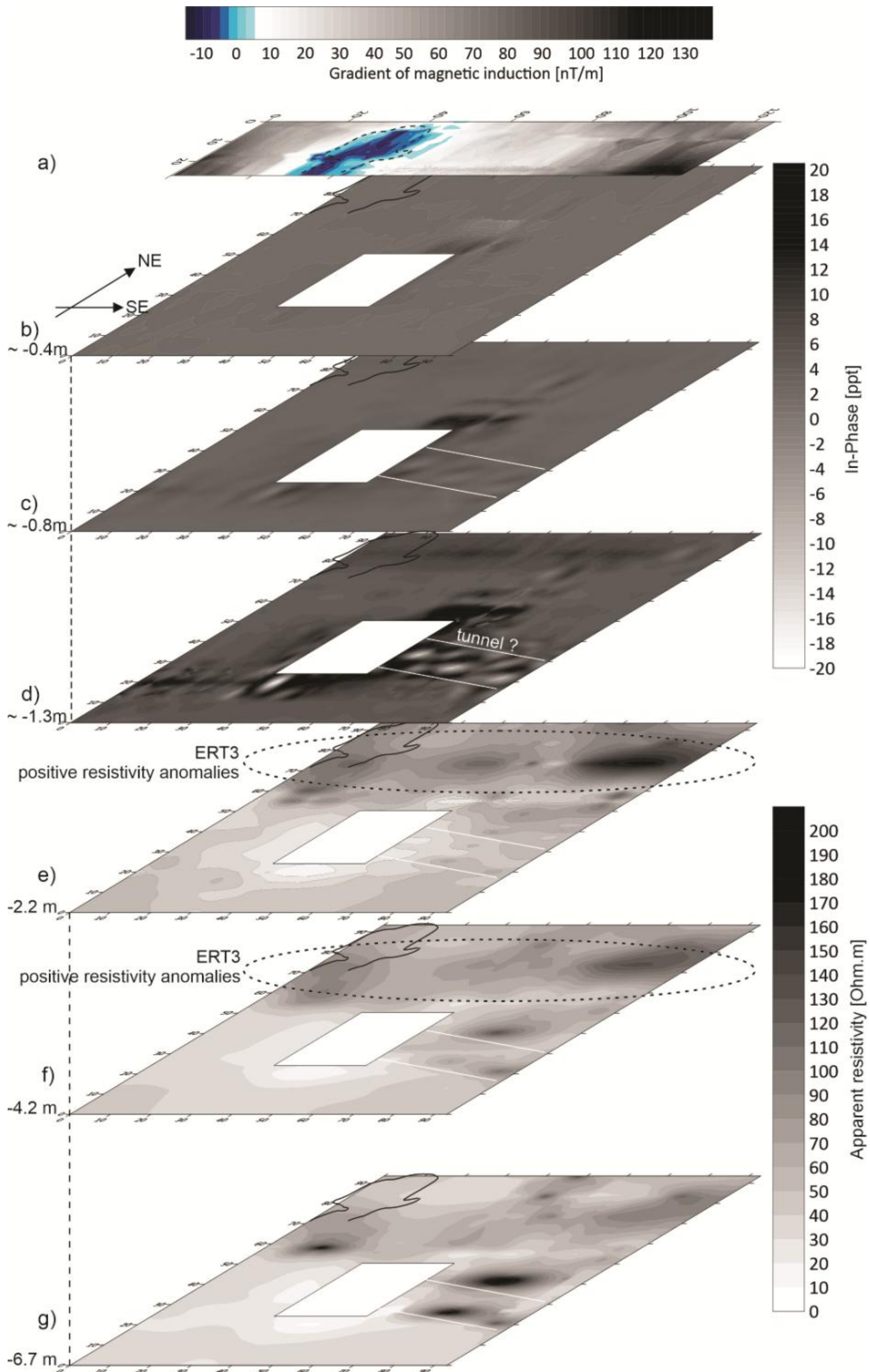

Fig. 4. FDEM maps (in-phase and apparent resistivity) obtained around the palace compared with a magnetic map: a) vertical magnetic gradient map; b-d) in-phase maps up to three different depths; and e-g) apparent resistivity maps up to three different depths

The next three maps show (Figs 4e-4g) the distribution of the apparent resistivity. The apparent resistivity values were obtained by a simple conversion of the apparent conductivity measured directly to facilitate comparison of the FDEM and ERT results. These maps cover a wider depth range than those obtained for the in-phase parameter. Generally, the maps to depths of -2.2 m (Fig. 4e) and -4.2 m (Fig. 4f) revealed the geological settings in the investigated area. The northern part of the area comprises a material with relatively high resistivity, whereas, on the southern side, sediments of low resistivity dominate. The resistivity anomalies in the North area correlate with magnetic anomalies, as well as with the shallow high-resistivity anomalies observed in the ERT-3 profile. The appearance depth is similar between the FDEM and ERT results, and range of 2–4 m.

An interesting feature was obtained for the deepest interval (Fig. 4g), where the apparent resistivity anomalies follow those from the in-phase maps. However, both anomalies (northern and eastern) are positive compared to the resistivity background. Summarizing, these two areas were related to the negative and positive in-phase anomalies, and both were positive anomalies in the resistivity maps.

4.2. Detailed study of selected areas

The interpreted magnetic and FDEM maps indicate the presence of man-made objects, especially in the northern part of the area, that may be considered as urban infrastructure or other elements related to the palace's history. Therefore, the next step was to perform geophysical cross-sections using ERT and ensure which geophysical method(s) would work best in the studied locations. The interpreted resistivity cross-sections after the inversion procedure were characterized by low absolute errors ranging from 1.5% (ERT-2) up to 3% (ERT-5).

The ERT cross-sections are consistent with the general picture of local geology. Moreover, the ERT indicated significant high resistivity gravels, with values exceeding 1500 Ωm, located in the centre of the profiles at depths ranging from 4 m to 6 m below the surface (Fig. 5). It is clearly visible in the ERT2, ERT3, and ERT4 cross-sections.

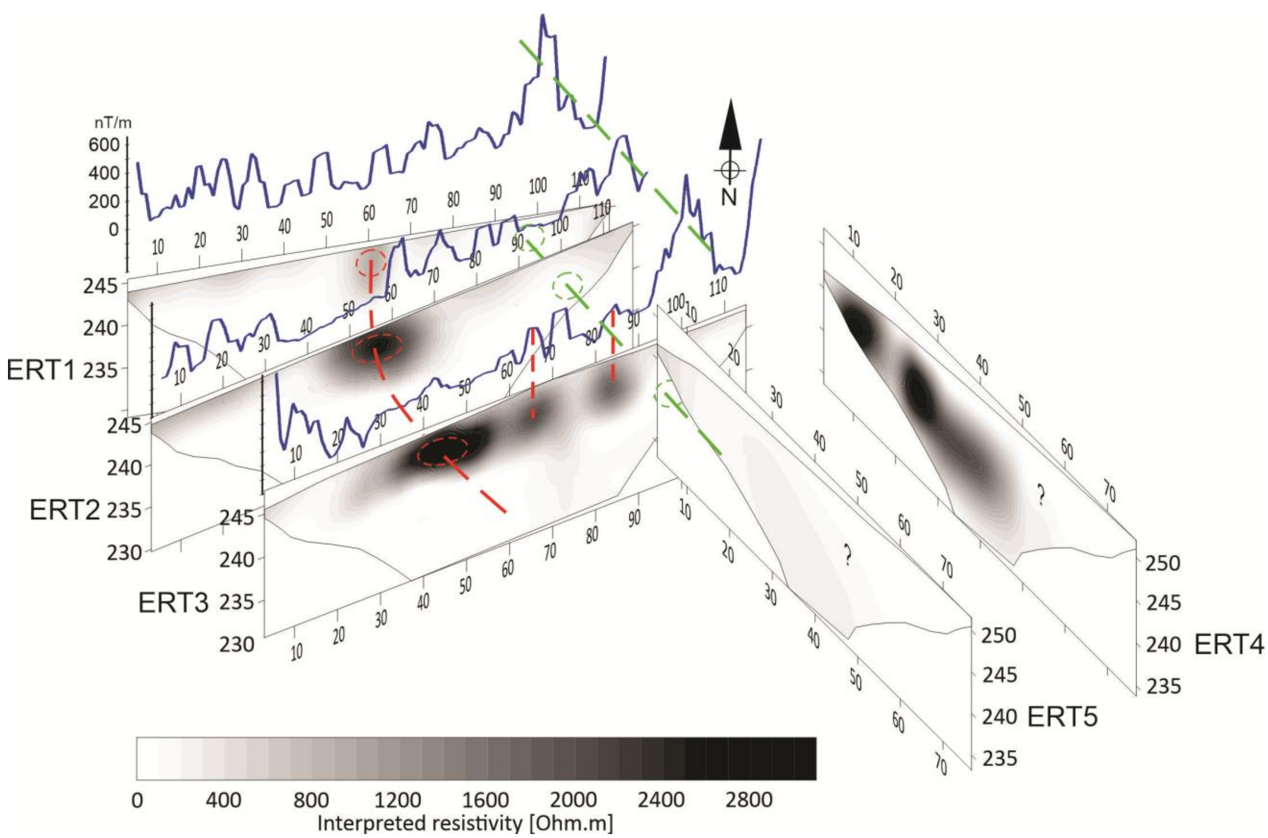

Fig. 5. Results of ERT surveys and vertical magnetic gradient profiling (blue lines); red lines – ERT anomalies, green lines – ERT and magnetic gradient anomaly correlation

Comparing these resistivity anomalies with the results of conductometry (Fig. 4e-4f) and magnetometry (Fig. 4a), the high resistivity anomalies in ERTs generally correspond to those obtained from mapping. However, as the ground level increases in the SE area, the lithology changes, and another sedimentary cover becomes visible, again fine-grained fractions represented by a low-resistivity background. Resistivity results from the ERT5 area did not show as clear high resistivity anomalies as the other ERT cross-sections. In this case, the contact electrode-ground was poor due to the gravel parking area in this location. The thin, high-resistivity layer of gravel probably hid the presence of water pipes marked on the geodetic map (Fig. 2).

Following the changes of magnetic surveys (MAG1-3) over the resistivity cross-sections (ERT1-3), a relation can be noticed showing that the reduction in local magnetic induction correlates with high-resistance anomalies (Fig. 5). Moreover, the magnetometer readings were significantly disturbed, showing many peaks that were difficult to interpret. The magnetic field inconstancy was probably produced by small objects buried in the ground, e.g., metal objects (rubbish), which affected the results. In this case, the magnetometer was more sensitive than the conductometer. However, some correlations can be distinguished. High values of vertical magnetic gradient correlate with very low resistivity anomalies in the North area (Fig. 5, green lines). ERT-3 profile contains three strong high resistivity anomalies, which occurred at 40-, 65- and 85-metres along the survey line. The 40-metre anomaly is wide, and we interpret it as a continuous structure that is present in the next cross-sections (Fig. 5, red line). This structure correlates with an anomaly of low value vertical magnetic gradient. The 65- and 85-metre anomalies correlate with positive values of vertical magnetic gradient (Fig. 5). The ERT-4 and ERT-5 do not show anomalies that might be correlated with the tunnel interpreted in Figure 4. The ERT-4 shows suspicious high resistivity anomalies in its northern part.

4.3. Possible family tomb

Historical records suggest the existence of family tomb within the park area. An approximately 10 m x 10 m section in the southeast part of the park has been demarcated for investigation. Only the conductometric method was employed, utilizing the same measurement parameters as those used for work around the palace. The findings revealed anomalies that could potentially be attributed to the existing foundations of a tomb buried at a depth of approximately 1–3 meters (Fig. 6).

The apparent resistivity maps (Figs 6a-6c) displayed geological variations. Surface sediments to a depth of 2.2 meters exhibited relatively high background resistivity values exceeding 60 Ωm. The anomaly likely associated with the tomb was characterized by a 50–60 Ωm resistivity zone. The map to a depth of 4.2 meters had a resistivity background in the lower range of 40–50 Ωm, yet the anomaly linked to the structure remained visible, with values ranging from 50–60 Ωm. The deepest map, to a depth of 6.7 m, depicted the lithology of the background composed of fine-grained materials with the lowest resistivity values falling below 40 Ωm.

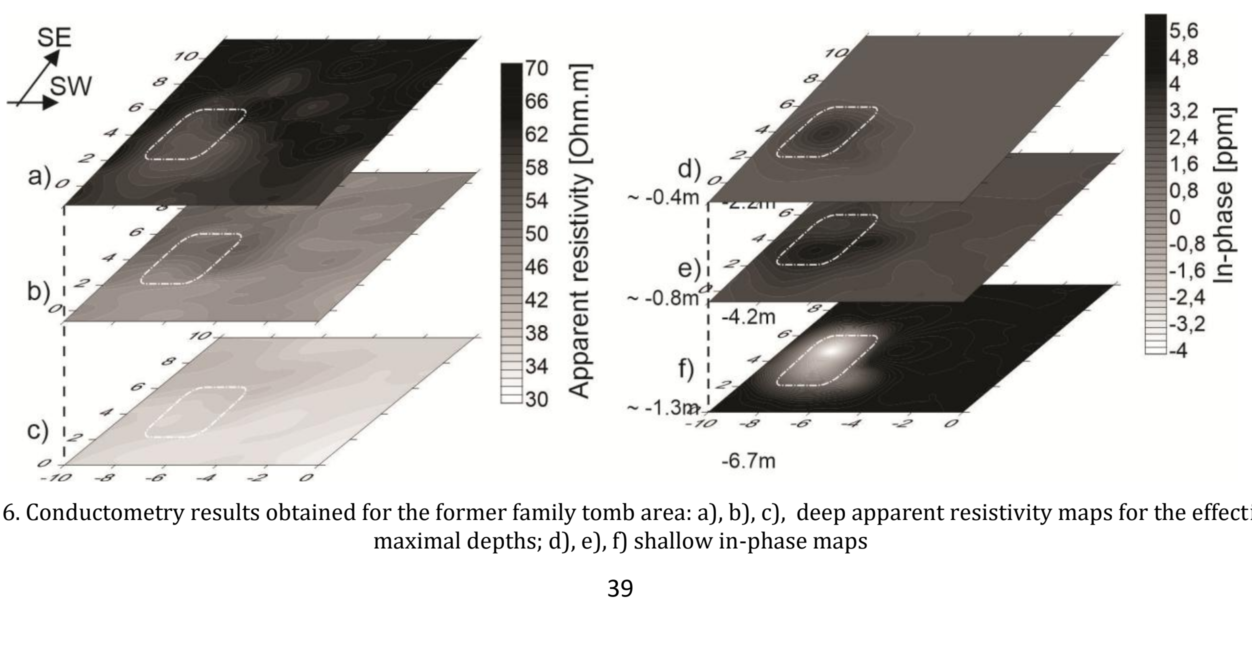

Fig. 6. Conductometry results obtained for the former family tomb area: a), b), c), deep apparent resistivity maps for the effective maximal depths; d), e), f) shallow in-phase maps

As shown in Figures 6d-6f, the in-phase component maps provide insights into the shallower depths, not exceeding ca. 1.3 m. The background exhibited a low, positive value of in-phase, greater than two ppm for each depth level. In the location of the resistivity anomaly, there was a discernible response in the in-phase component: positive to a depth of 0.8 m, transitioning to strongly negative between 0.8 m and 1.3 m. Conductometric tests performed on the castle foundations (GF Instruments, 2016) exhibited similar behaviour in the in-phase component. In the context of the analyzed case, this substantiates the presence of a stone or brick structure in this location, thereby confirming the existence of the tomb foundations.

5. Discussion and recommendations

5.1. Uncertainty analysis and comments on the used methodology

Geophysical work was carried out methodologically correctly, following each method's recommendations from a geophysical point of view. Conductometry and magnetometry tests were performed at an appropriate height above the ground surface and using sampling, which allowed for good data coverage of the measurement line. ERT tests in the field were performed with a relatively small electrode spacing, which should provide good resolution of the resistivity cross-sections (up to a depth of 15 m below the surface). All electrodes had good contact with the ground, and the signal sent, i.e., electric current, was high and stable (> 50mA). It follows from the above that the results were influenced by geology and the presence of objects buried under the surface. The arrangement of layers (alternating layers) of fine- and coarse-grained fraction resulted in two contrasting geophysical layers: a very high-resistivity layer and a low-resistivity layer.

The shallowest subsurface layer consisted of gravel, which was artificially introduced to harden the area for parking. The park around the palace is not sufficiently fenced, and special events are often organized outdoors. The result is the presence of various rubbish and metal objects left by the palace guests. This situation significantly influenced the magnetometry results. Other objects influencing the variability of physical parameters are infrastructure elements: pipes, wires, and drains. Despite complicated geological and technical conditions, geo-electrical measurements, ERT, and conductometry results gave satisfactory field data. During processing, the ERT method provided the value of the inversion error; it was very small for ERT cross-sections. The conductometry method also gave good results.

However, some of the recommendations and criteria for applying geophysics in archaeology may not have been fulfilled (Schmidt et al., 2015). The survey grid was less dense than required in archaeological prospecting, and sampling did not cover 50% of the studied area. Spatial resolution on lines was satisfied, reaching one meter for magnetic and ERT surveys and a dozen centimetres for conductometry measurements. However, the spacing between lines was much larger, varying from 10 m to 15 m. The applied methodology focused on the general recognition of the vast study area and the deeper structures located 2–6 m below the surface. Therefore, the electrode spacing was 2 m (providing a prospecting depth of 15 m below the surface), and magnetic sampling was 1 m. An additional issue that prevented the planning of more dense survey lines was the obstacles occurring in the surrounding park, like trees, shrubs, gravel parking area, benches, and fences. Nevertheless, the GPS/GNSS system positioned all points and lines.

The authors considered using ground penetrating radar (GPR), but, they abandoned this method because of the centre's high electrical conductivity and the ground's dampness (the park is densely covered with old trees), which is why the GPR method works well in high-resistivity media. It would only work properly in the gravel parking area.

Each applied method has different results in the vertical and horizontal directions. The FDEM method is characterized by dense horizontal resolution but provides data only from the three depths for resistivity and in-phase, respectively. The opposite situation is typical for the ERT method. Here, the vertical resolution is comparable to the horizontal one. The letter is limited to the minimal spacing between electrodes. Magnetometry provided only two points (from two heights) on every metre of profile; assessing the maximum depth of investigation is impossible in this case.

Therefore, the case study presented in this article highlights the practicality of employing specific geophysical methodologies. Complex geological conditions, specifically the presence of alternating layers characterized by high resistivity (coarse-grained sediments) and low resistivity (fine-grained sediments), introduce the potential for geophysical methods to either falter or yield inaccurate interpretations. Challenges also arise from human activities associated with the usage of the palace. The terrain surrounding the palace was solidified with a thin layer of gravel, further exacerbating methodological complications.

The environs of Rzuchów Palace, including the paved access road and the densely forested park, are not unique to this location but rather representative of many palatial sites within Poland and around the world. Another pertinent issue for geophysical investigations pertains to underground infrastructure, such as waterworks and sewage systems, which can influence the geological medium's response to the physical fields generated by the equipment.

Three commonly applied archaeological methods were evaluated in the context of the research presented herein: the conductometric method, ERT, and magnetometry.

5.2. ERT modelling

Another issue that should be solved and which arose during this study was the anomaly representing the tunnel in the FDEM maps but not observed in the ERT cross-sections. Based on ERT measurements, we prepared the simulation of a high-resistivity anomaly (a tunnel) buried in a very low-resistivity medium in Res2Dmod software. The model contains the same geological elements as the area east of the palace: the low-resistivity layer covers the high-resistivity layer, corresponding to fine-grained material laying over the coarse-grained fractions. The result of the modelling clearly indicated that such a layer combination typical for Quaternary geology can be a hard task during the geophysical interpretation. Figure 6 shows the theoretical model (Fig. 7a) and the result of the inversion procedure (Fig. 7b). The high-resistivity object after the processing is barely seen. A similar situation is noticed in Figure 5 (ERT4 and ERT5), where anomalies denoted with a question mark correspond to strong responses from FDEM surveys.

However, we assume that the tunnel is the one to the south of the parking area because it is not on the utility map. If it were there, the response from a possible tunnel with a specific cross-section would be visible in the geophysical image. Nevertheless, the depth of weak anomalies may indicate a reasonable escape route depth that corresponds to the depth of the basements.

Therefore, we strongly recommend using both techniques, FDEM and ERT, supported by the modelling procedure. Including the modelling stage facilitates the analysis of geophysical anomalies and makes the interpretation and inference more convenient. Strong arguments for this methodology in these specific conditions are: relatively good measurement resolutions (vertical and horizontal), time efficiency, high resistance to geological variability, and better measurement resolution over objects buried in the ground.

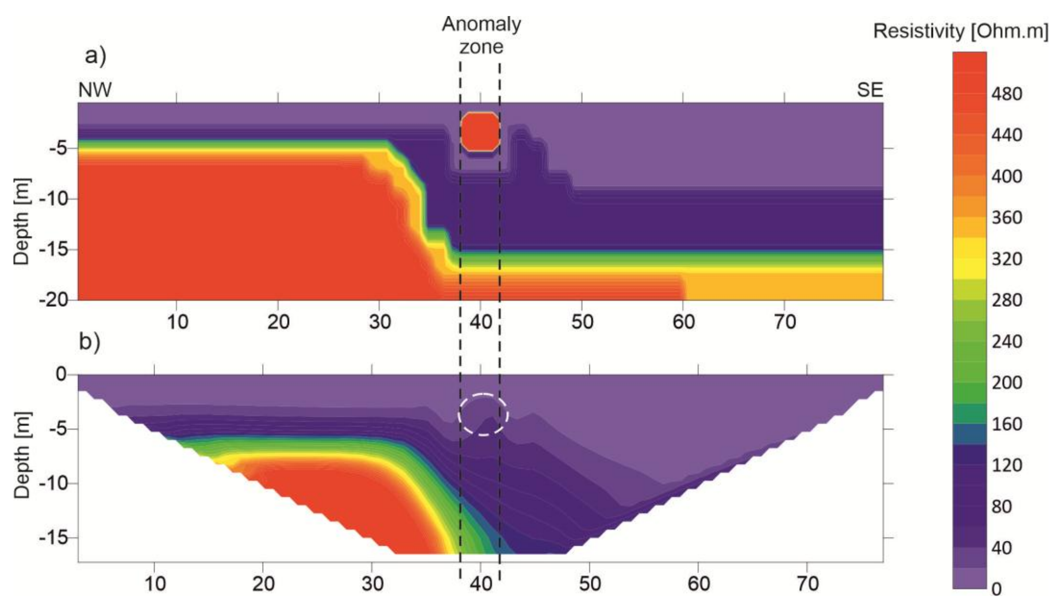

Fig. 7. ERT modeling for area E: a) prepared model with high resistivity anomaly buried in a low-resistivity medium; b) result after an inversion procedure

6. Conclusions and future study plans

This study investigates the subsurface structure around the historic Rzuchów Palace in Poland, aiming to support revitalization efforts while also validating and comparing different geophysical methods for identifying underground structures. Geophysical techniques like magnetometry, frequency-domain electromagnetics (FDEM), and electrical resistivity tomography (ERT) were employed to explore hidden subsurface features, such as potential tunnels, foundations, and a rumoured family tomb. Results indicated significant anomalies in certain areas, suggesting the presence of man-made structures and underground hazards. While FDEM was effective in identifying shallow horizontal anomalies, ERT proved valuable in deeper vertical mapping, though it struggled with complex geological layers. The findings underline the utility of combining multiple geophysical methods, as each technique offered unique insights. The study concludes that integrating FDEM and ERT, enhanced by modelling, yields a more complete picture of the subsurface, providing a robust approach for future heritage site assessments. The main three findings can be highlighted as follows:

– Detection of Subsurface Anomalies: Geophysical surveys around Rzuchów Palace identified several subsurface anomalies, including suspected man-made structures in the northern and eastern areas, a possible family tomb, and indications of underground tunnels, all relevant for both heritage preservation and structural safety.
– Comparative Evaluation of Geophysical Techniques: The study assessed FDEM, ERT, and magnetometry, revealing that FDEM effectively detected shallow, horizontal anomalies, while ERT provided clearer vertical depth profiles. However, complex geological conditions impacted each method differently, underscoring the importance of combining techniques for accurate interpretation.
– Importance of Modelling in the Interpretation: Simulations conducted to model potential tunnel structures indicated that FDEM and ERT, when supported by modelling, significantly improve anomaly analysis, offering better resilience to geological variations and enhancing the reliability of subsurface mapping for cultural and structural assessments.

The palace and park complex in Rzuchów is managed by a Foundation that intends to adapt the facility for cultural, scientific, educational, and social purposes. The goal is to fully utilize the facility and its surroundings, which entails taking action to provide access to the palace and park for a wide range of users.

Over the years, the palace's interior has undergone multiple reconstructions caused by adaptations to new purposes before finally falling into ruin. Changing functions have led to the complete deterioration of the historical value of the palace's interior. Significant and unfavourable transformations have also been applied to the surrounding park. Although the palace has lost most of its original decor and furnishings, the Foundation intends to restore and adapt the interiors for cultural purposes, creating exhibition spaces, concert halls, theatres, artistic studios, and educational rooms.

The adaptation of this historical monument for new public purposes necessitates actions related to the facility's accessibility and the elimination of architectural barriers. This involves investment activities that require a stable foundation. To enhance accessibility, parking spaces will be prepared in the area adjacent to the palace, with plans to construct a parking area in the eastern part of the park, accommodating approximately 20 cars. Research has shown that there are structures of unknown origin in the planned access road to the parking area. Based on the results, it is recommended that sufficient financial resources be collected and boreholes or excavations be conducted to determine the stability of the soil and the maximum load-bearing capacity of the proposed access road to the parking area. Accessibility for people with disabilities will be achieved by constructing a ramp on the southeast side. The absence of voids along this elevation allows for the design of a suitable infrastructure.

In addition to investment activities, the Foundation's plans include continuing research into local history. The discovery of voids that could potentially confirm the existence of escape tunnels from the palace is a significant step toward verifying local oral traditions. It is recommended that the nature of these anomalies be investigated, and research should be conducted in the palace's cellars to locate possible tunnel entrances. As demonstrated by other residential properties in the Racibórz region, palaces may have had more than one underground level.

The revelation of likely remnants of the tomb of the first owner of the palace prompts the Foundation to consider how to emphasize the place of burial within the space. However, archaeological research should be conducted first to confirm the presence of remains. The exact burial site should be marked and delineated if the result is positive. If the presence of remains cannot be confirmed, a commemorative plaque would be a suitable form of remembrance.

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Author Contributions

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