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Original Research Article

IDENTIFICATION OF ALTERNATIONS IN THE STRUCTURE OF HISTORICAL MASONRY WALLS USING THE GPR METHOD ACCOMPANIED WITH ARCHITECTURAL SURVEY IN THE FORMER PIAST GYMNASIUM IN BRZEG

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A b s t r a c t

Widely used in civil engineering, GPR (ground penetrating radar) is increasingly being used to survey historic structures. However, there are still no conclusive directives on the use of GPR in the identification and diagnosis of masonry structures. The current state of the art allows only on the example of individual case studies, to draw conclusions about the effectiveness of the use of this tool. One such area, where the effective use of GPR has been experimentally confirmed, is the historic architectural survey of a heritage buildings. Due to diversity in the dielectric properties of individual construction materials, it is possible to observe on radargrams the change of electromagnetic wave patterns by materials from different phases. Traditional approach require extensive excavation efforts or core drilling, which may not always be acceptable for conservation reasons. Hence the GPR method could be interesting, non – destructive option for identification and diagnosis of historical masonry walls. The authors used the architectural survey and accompanying excavations at the former Piast Gymnasium in Brzeg to conduct a survey campaign using the GPR method. The brick walls of the building's nave have been scanned. The nave have undergone numerous alterations over hundreds of years. The GPR data has been subjected to adequate post-processing and then correlated with architectural surveys and validated on the basis of available excavations at the site. The authors highlight that GPR surveys, when combined with architectural investigations, offer a less invasive approach to examining historic structures, thereby mitigating the need for problematic excavation work.

Keywords: ground penetrating radar, non-destructive testing, NDT, masonry structures, GPR

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1. INTRODUCTION

The Ground Penetrating Radar (GPR) testing method is a non-invasive geophysical method that utilizes the phenomenon of electromagnetic waves reflecting on different layers and objects inside the examined structure. During GPR surveys, electromagnetic impulses are emitted by an antenna and propagate inward into the investigated medium. As the electromagnetic wave propagates through various materials, it is partially reflected, and some of the energy is absorbed by the medium. The antenna records the signals reflected and propagated through the medium under examination, and the captured signals are then processed to obtain a geo-radar cross-section - the so-called radargram. The GPR method is being applied in many domains: geology, archaeology, geotechnical engineering and civil engineering. In the field of heritage preservation, it is especially useful for analysing the electric permeability of structural elements [1], [2]; measurements of thickness of elements and identification of depth of construction layers [3], [4], [5], [6], [7]; detection of metal intrusions [8], [9], [10]; identification of air voids [11], [12], [13], [14] as well as for the analysis of historical stratification and remodelling [11], [15]. Among the advantages of the GPR method can be mentioned the speed of test completion, low invasiveness, high spatial resolution, as well as the ability to perform real-time measurements. However, the method is sensitive to the type of medium under examination, and in particular to its dielectric properties, which impact the speed of propagation of the electromagnetic wave and its reflection. The GPR method is also relatively inexpensive compared to other testing methods, including core drilling or destructive testing.

Many researchers emphasize the importance of an interdisciplinary approach in the field of monument preservation due to the complexity and variety of materials and structures used in historic buildings. A proper intervention should commence with a precise diagnosis of the building to minimize interference with its substance and avoid incompatibilities between existing materials and those used for restoration. Understanding the geometry, texture characteristics, the type of connections between layers, and the physical, chemical and mechanical properties of the components is crucial. Non-destructive (NDT) and minor destructive techniques (MDT) play a pivotal role in identifying hidden features. However, the application of these techniques requires precise calibration and harmonization of results, which is a challenging issue due to the variety of masonry types and their high heterogeneity [16], [17]. Therefore, complimentary diagnostic techniques and rigorous cooperation between experts from different disciplines are essential. This article outlines the complementary interaction between GPR and architectural studies.

2. THE ARCHITECTURAL SURVEY [18], [19]

The Piast Gymnasium was designed and built in the Renaissance era, and opened in the summer of 1569. The construction was supervised by the builder Jacob Parr of Milan. The entire project was patronized by the then Duke of Brzeg - George II (representative of the Silesian Piast dynasty). The importance of the undertaking at that time should be evidenced by the fact that the building was situated in very close proximity to the duke's castle. From September to November 2022, under the direction of Dr. Eng. arch. Andrzej Legendziewicz, architectural research was carried out to comprehensively identify historical transformations of the building and prepare for conservation and adaptation works. The research covered local inspections, the measurement and photographic documentation, as well as the analysis of the digital mapping and available archival sources. The research concentrated on the excavations carried out in the building's interiors and the probing established on the facades, making it possible to identify the stone and brick patterns and to distinguish subsequent construction phases. The recognition of archival iconography was also significant (Fig. 1.).

Fig. 1. A view of the eastern facade of the Piast Gymnasium at various ages [20]

The building was originally constructed on a rectangular plan, measuring 17.5 by 70.7 meters, located in the northwest quadrant of the square at Wrocławska Gate (now Moniuszki Square). The three-story block with a subbasement, covered with a four-sided roof, was decorated with nine dormers. A tower in the southwest corner, covered with a domed roof with a spire, supplemented the Renaissance décor. The front facade was characterized by an eighteen-axis window composition with a gate portal and a gatehouse with a semicircular opening. The interior included a vaulted passage hallway and a cloister with arcades supported by massive pillars. The exterior walls of the gymnasium building were made of fieldstones (eratics), which were lightly treated and laid irregularly. The window lining was made of fired bricks in red hues ranging from light to cherry, measuring 7.0-7.5 cm / 12.0-13.0 cm / 25.0-26.0 cm. The mortar used for construction was lime-sand, quite hard, with a light brown color, containing grains of unquenched lime.

Reconstruction after the Prussian siege in 1741 introduced modifications to the facades design, including window ear moldings and a mansard roof with dormers. The interiors were reshaped, including the re-bricking of the chimneys and the introduction of new chimney louvers. Sections of the Baroque walls were composed of bricks laid in block pattern, characterized by uneven firing in various shades of red, from light to cherry. The bricks had dimensions of 6.2-6.5 cm / 13.0-13.5 cm / 27.0-28.0 cm. A lime-sand mortar, fine-grained, of relatively low strength and sandy-yellow color, was used to bond them together.

After damage during the Napoleonic Wars in 1807, the building gained a new hipped roof and a simplified facade with risalits spanning the central window axes. Baroque details were removed, and strip rustications were introduced in the ground floor. In 1884, a remodeling project was prepared for the Gymnasium - it was partially implemented during a Neo-Renaissance reconstruction completed on July 1, 1897. The reconstruction included the introduction of three gables on the east elevation axis and the resizing of the windows above the gate portal. The arcades of the Renaissance gallery were partially walled off, introducing new windows, and the former staircase was replaced with a cross vault and ceilings. Instead, a three-flight staircase was added on the side of the courtyard, enclosed in a separate block covered with a triple-pitched roof. As the result of the architectural survey, it was determined that the aforementioned work was carried out using well-fired machine-made bricks with dimensions of 6.5

cm / 12.5 cm / 24.5 cm. These bricks were bonded using hard lime-sand mortar with the addition of cement.

Between 1910 and 1938, further construction work was carried out, including the strengthening of the pillars of the arcade gallery, the introduction of two new staircases, and the overbuilding of the block on the side of the courtyard. The building of the Piast Gymnasium in Brzeg, which was destroyed during World War II, was rebuilt in 1962 based on a project prepared by Z. Szczurowski at the Monuments Conservation Workshop in Wrocław, and it has been preserved in this form to this day.
Since most of the identified phases of reconstruction have always included the main hall on the ground floor to some degree in their scope - this is where most of the historical alterations in the wall area are found. This is clearly illustrated by the view of a section of the load-bearing wall with the established plaster excavations (Fig. 2). The walls of this hall were subjected to a hand-held GPR survey in the next stage.

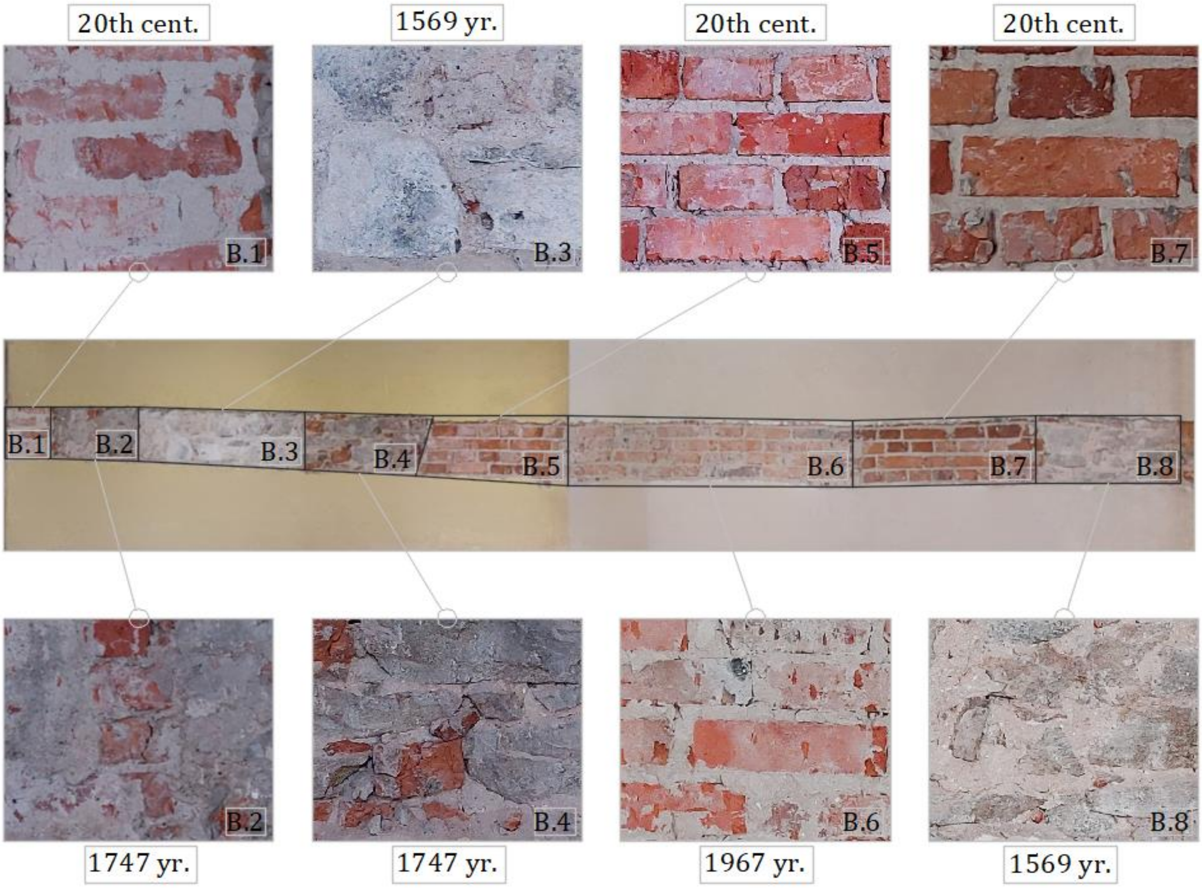

Fig. 1. A view of a segment of the bearing wall of the main hall of the ground floor. Age dating based on architectural analysis. Division into sections subjected to GPR survey in the next stage

3. THE GPR SURVEY

The GPR survey campaign was carried out in the Gymnasium building in April 2023. As previously mentioned, the walls of the main ground floor hall, which are also the load-bearing walls of the building, were designated for the test (Fig. 3).

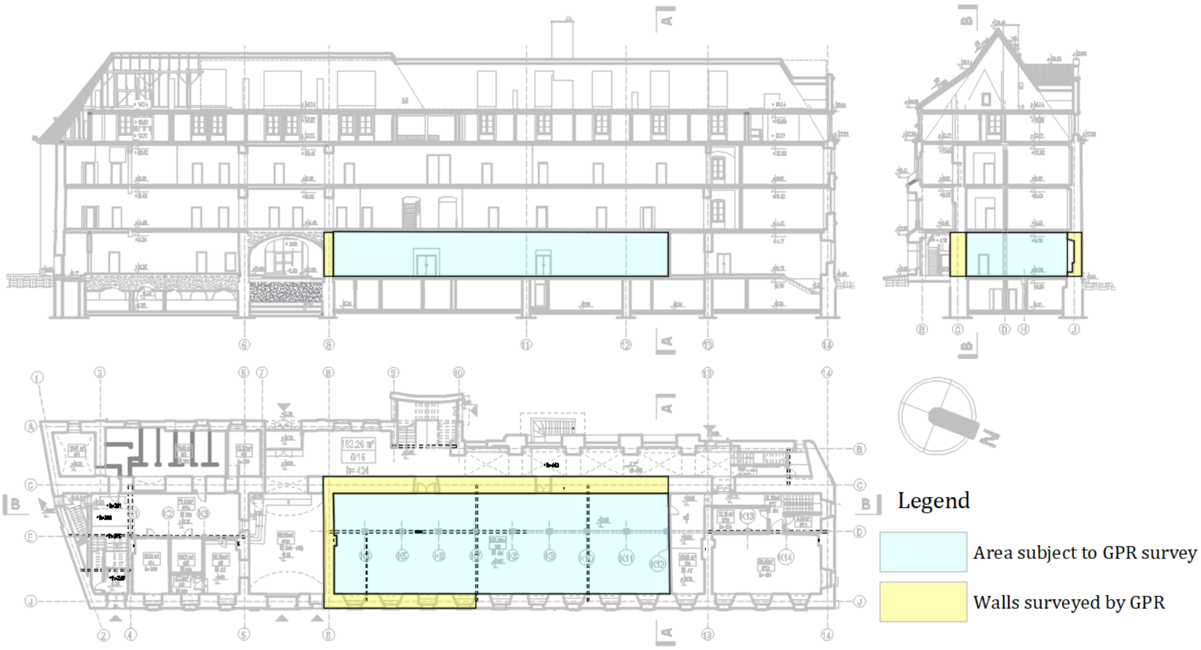

Fig. 2. Situation plan showing the subject of the GPR survey. Elaboration based on [19]

A handheld IDS C-Thrue GPR device, equipped with a set of two pairs of transversely polarized transmitting and receiving antennas operating at 2 GHz frequencies, was utilized for the measurements. Multiple vertical and horizontal scans were conducted on the walls; however, for the purposes of this paper, the results of scanning two fragments (Path A and Path B) of the inner load-bearing wall are presented. Only Path A was analyzed in detail. In the authors' opinion, this scope is sufficient to formulate clear conclusions regarding the survey. Each path consists of two horizontal scans taken above and below the strip with the plaster excavations (Fig. 1); in Fig. 3 two paths are marked in greater detail along with the direction of scanning. The GPR data collected in this manner were then subjected to post-processing. Post-processing is the stage of GPR data analysis and treatment that occurs after in-situ data acquisition. It involves performing a series of operations on the GPR signals to enhance understanding and interpretation of the data. The results of GPR surveys are typically presented in graphical form as radar cross sections or radargrams. A radar cross section is a graphical representation of GPR data as a function of depth (or wave propagation time) and distance. One of the fundamental stages of post-processing is the initial interpretation of these data, which involves analyzing the shape and characteristics of the received signals. For certain areas, a detailed analysis of the averaged signal power was also performed.

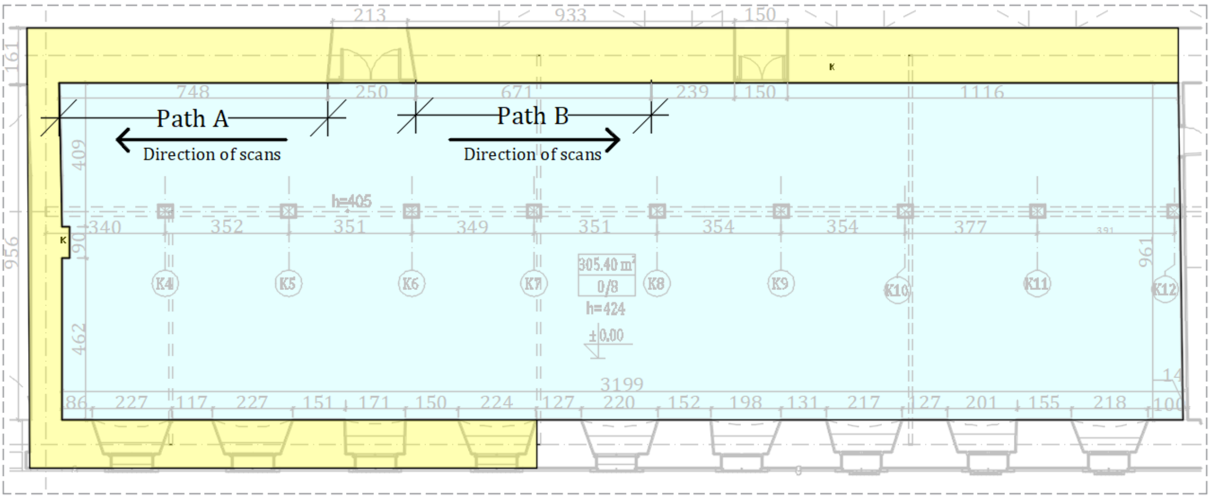

Fig. 3. Excerpt from the ground floor plan indicating the two scan paths analyzed along with the direction of scanning

During post-processing, the following operations were performed on the signals:

- Time Domain Bandpass Filter - applied within the frequency range of 650 MHz to 5000 MHz, attenuating signals outside this range.
- Time Zero Correction – adjusted the time domain offset to "truncate" the indication between the antenna and the surface of the test item.
- Back ground removal – implemented a filter in the spatial domain to remove background interference within a depth range of 0 cm to 10 cm.
- Smoothed gain – Utilized an STC (Sensitivity Time Control) algorithm with a window size of 4 cm.
- Notch filter - applied a time domain slit filter to eliminate a specific frequency range from 3000 MHz to 20000 MHz.

After the post-processing stage, the radargrams were compared with a view of the wall with the plaster excavations – Fig. 4, Fig. 5. Both radargrams in each figure present a cross-section of the same wall, one above the plaster excavation and the other below, allowing for more data and a more precise interpretation of its structure. The radargrams have been divided into areas A.1 to A.11 and B.1 to B.8, corresponding to the historical remodeling visible after uncovering the plaster and the different types of masonry. The divisions of these areas align with the structures uncovered beneath the plaster. The slight lateral shifts are a result of the data acquisition process, during which the GPR occasionally skips over uneven surfaces. Significantly, the areas revealed under the plaster correspond with what the radargrams show. The dimensions of these areas, measured in situ with a tape measure, coincide with those obtained from the GPR data processing program. The most important hyperbolas, representing the vectors of electromagnetic wave reflection from significant elements in the wall structure (such as larger stones or bricks, material changes, and voids), were marked on the radargrams. Some structural layers were also labeled based on the interpretation of the hyperbola patterns. In the next step, a more detailed analysis of some areas, expanded to include adjacent fragments, was carried out.

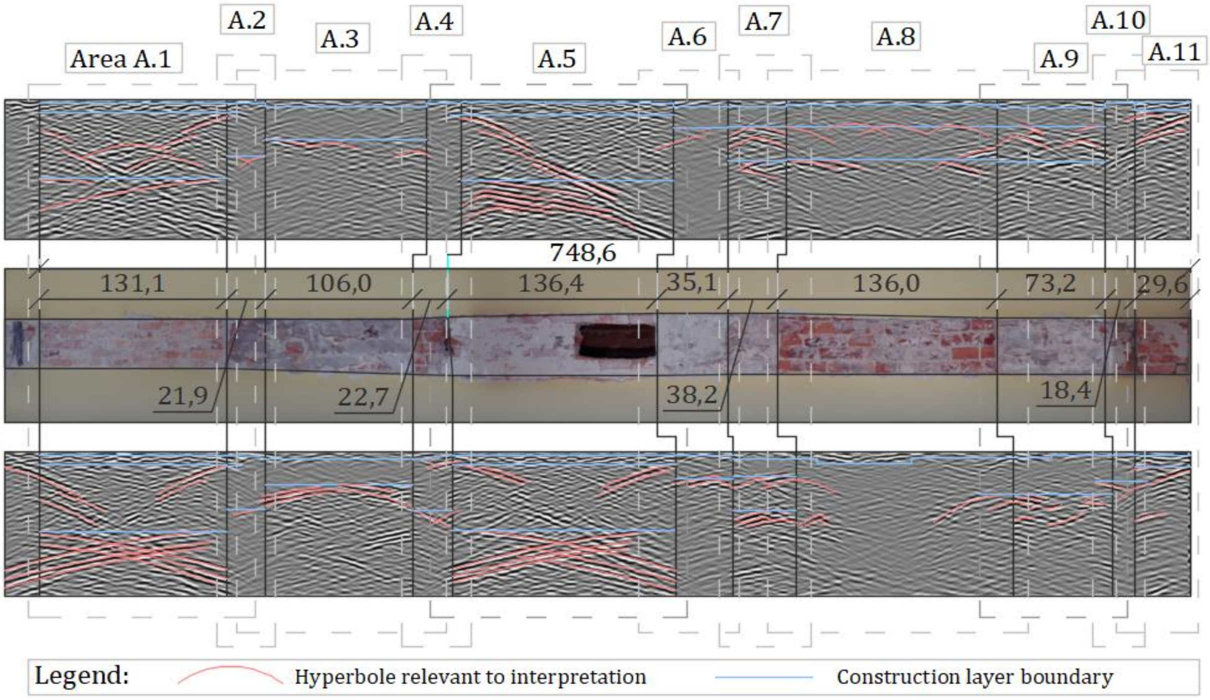

Fig. 4. General view of radargrams collected along path A compared with the view of the wall. Division into sections according to sections of masonry visible after plaster removal

Even a superficial analysis of the individual patterns in the form of a pattern of characteristic hyperbolas suggests similarities between some parts of the wall. And so it can be observed that the area marked A.1 presents a very similar pattern to area A.5.

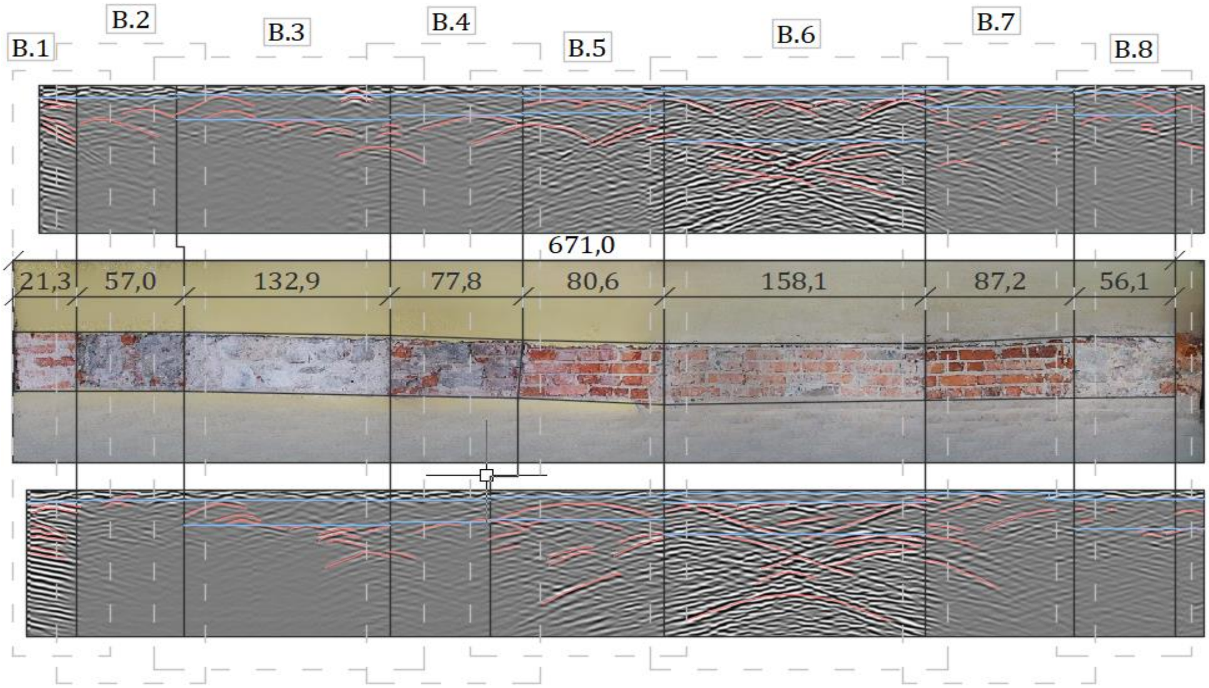

Fig. 5. General view of radargrams collected along path B compared with the view of the wall. All symbols analogous to Fig. 4

In addition, in area A.5, a bricked-up void was revealed during the architectural research stage. The considerable similarity of the radar patterns suggests that a similar void is located in areas A.1 and B.6, which was not revealed during the architectural excavations. A section of wall A.8 also exhibits similarities to the aforementioned areas (similar brick pattern and specified width of this section); however, this is not confirmed by the overall patterns on the radargram. To verify the similarity of the wall section, a comparative analysis of the average signal strength with analogous areas was conducted. Below, Figure 7 shows a cutout from a detailed analysis of the radargrams.

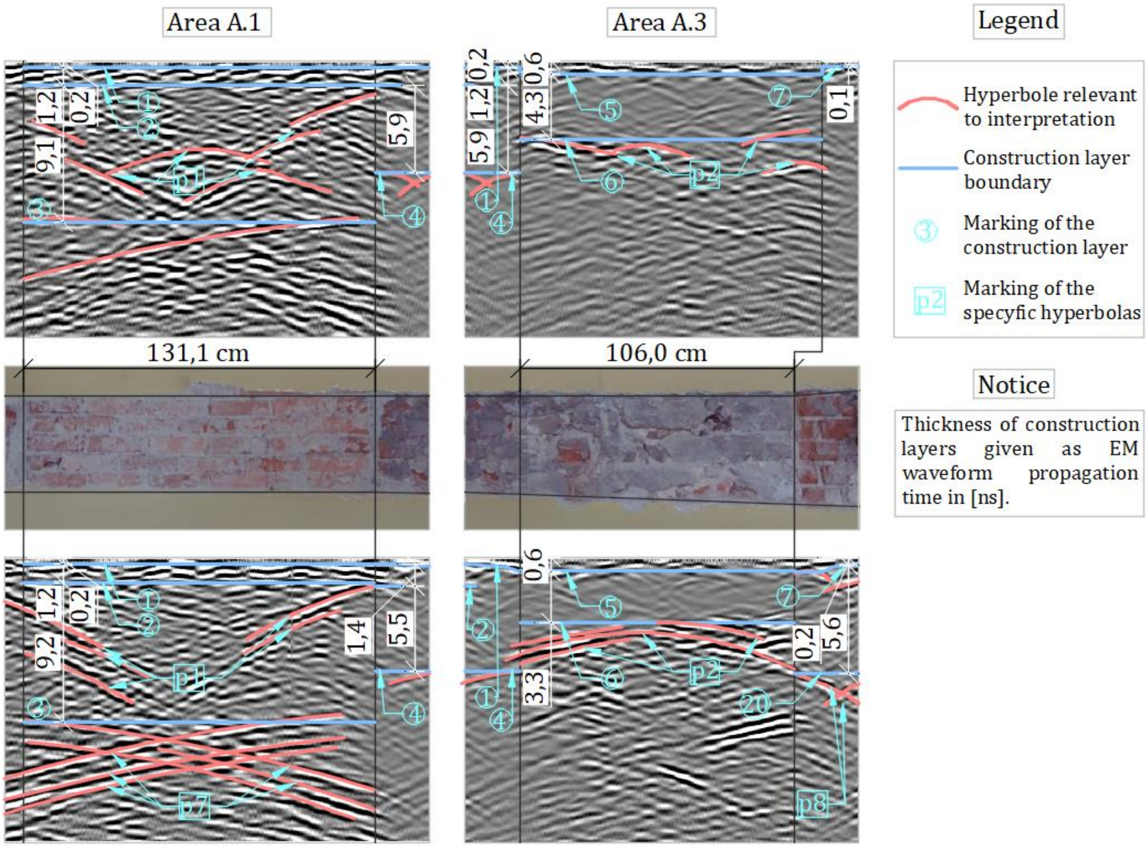

Fig. 6 Excerpt from the detailed analysis of radargrams divided into individual areas. Explanation in the text

All identified structural layers are derived from the corresponding system of hyperbolas. Due to the presence of various materials within the masonry structure, GPR calibration cannot be performed once to determine the exact thickness values of the layers. Instead, it is only possible to ascertain the travel times of electromagnetic waves through a given layer, expressed in nanoseconds. In area A.1, a layer of plaster (1), a single layer of bricks (2), and an air void (3) were identified. Significant interference of electromagnetic waves reflected from the side surfaces of the void was observed (p1). After passing through the void, there is notable interference of waves (p7), making it impossible to determine the thickness of the subsequent structural layer. A layer of plaster (5) was also identified in area A.3, which is much thicker than in neighboring areas (1 and 7) due to the use of erratics instead of regular bricks. The thickness of this stone layer (6) was also determined, thanks to the clear reflections of electromagnetic waves from the outer plane of the layer.

As previously mentioned, a comparative analysis of the average signal power in different areas was conducted (Fig. 7), to assess the material compatibility of the layers indicated by the hyperbola patterns. The comparison of areas A.1 and A.5 demonstrated their twin similarities, particularly evident in the convergence of the average signal power between 2 and 7 nanoseconds. For area A.8, suspected of containing an air void and being similar to A.1 and A.5, there was no correspondence in average signal power, indicating a different structural nature.

For areas B.2, B.3, and B.4, analyses showed that B.2 and B.4 are constructed of the same materials, as confirmed by the excavations (mixed masonry). Conversely, B.3, built of erratics, exhibited a lower average signal strength than the other two areas. The analysis of the average signal strength confirmed the dissimilarity of these structures, suggesting that they were built at different times, as documented during the architectural analysis.

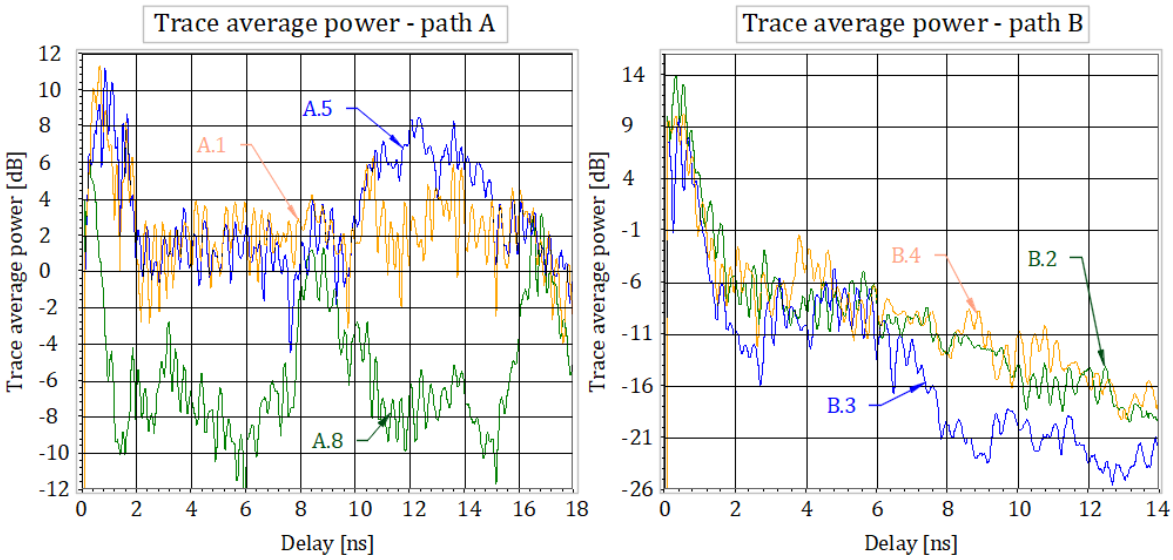

Fig. 7 Selected graphs of the conducted comparative analysis of average signal power for specific area

The general analysis of the hyperbolic patterns on the radargrams presented above, followed by detailed analysis from individual areas and analysis of the average signal strength, combined with information from in-situ architectural surveys and measurements, makes it possible to present in tabular form data on the various layers from which the load-bearing wall in the main hall is constructed. **Błąd! Nie można odnaleźć źródła odwołania.** presents an excerpt from this extensive catalog, including information on calculated wall thicknesses and the dielectric constant that characterizes a given construction material.

Table 1. An excerpt from the listing of identified layers along path A

Area	Layer	Delay [ns]	Thickness [cm]	Dielectric const. ε_r	Dated	Characterization
A.1	1	0,2	1,5	4,00	N/A	Plastering
	2	1,7	11,5	4,92	1967 yr.	Brick layer
	3	9,1	130,5	1,09	N/A	Air void
A.2	4	5,9	36,1	6,01	1747 yr.	Mixed masonry layer
A.3	5	0,6	4,5	4,00	N/A	Plastering
	6	4,3	22,7	8,07	1569 yr.	Layer of erratic masonry
A.8	15	0,4	3,0	4	N/A	Plastering
	16	3,1	21,0	4,92	20th cent.	Brick layer
	17	4,2	Unk.	Unk.	N/A	Unspecified layer

It should be noted that it was not possible to examine the entire thickness of the wall using GPR waves. In some sections, where there were air voids, the total depth of wave penetration reached 143.5 cm, compared to the approximate 161 cm thickness of the wall. In other areas, the layered structure of the wall was revealed; however, GPR with a 2000 MHz antenna is not capable of covering a wall of such considerable thickness. Consequently, we do not have complete information on the entire section of the wall.

4. DISCUSSION AND CONCLUSIONS

The paper presents the interdependence of GPR and architectural surveys. Architectural analysis provides essential information for the accurate interpretation of radargrams, while GPR tests offer additional data for architects and conservators. Based on the research presented, it can be hypothesized that a more optimal approach to conducting architectural surveys exists. Utilizing GPR, a single room or the most significant surfaces can be scanned to identify areas of interest and their characteristics. In the subsequent step, excavations are conducted only in a limited zone to determine the properties of individual structures. With the information obtained, the rest of the building can be scanned by analogy, allowing inferences to be made about the structure beneath the plaster without necessitating the excavation of the entire building. However, it should be remembered that the GPR method is still under development and is by no means a complete and universal method. In order to obtain information about the mechanical properties of materials or knowledge about the stability of the structure, it is necessary to perform associated minor destructive (MDT) or destructive tests (DT).

Key conclusions from GPR associated with architectural surveys:

- Along path A, a bricked-up void (A.1) unidentified at the architectural survey stage was revealed, as was along path B (B.6).
- The layered structure of all areas of the load-bearing wall was revealed.
- Dielectric constants were calculated for the various construction materials: 1967 brick masonry εr = 4.92; 1747 mixed masonry εr = 6.01; original 1569 eratics masonry εr = 8.07.
- Material similarities between different areas of the wall were indicated using average signal power analysis, e.g: A.1 and A.5 and B.2 and B.4

ADDITIONAL INFORMATION

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