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GROUND PENTERATING RADAR METHOD IN SURVEYING OF SACRAL BUILDINGS AND POST-MILITARY STRUCTURES

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A b s t r a c t

The article presents selected examples of use of the ground penetrating radar method in surveying sacral buildings and post-military structures. This surveying method and its use are synthetically characterized. The GPR equipment, research methodics and results are described for the performed search of an unknown crypt in the catacombs of the church of Our Lady of Can-dlemas in Kożuchów and the historical escape tunnel from the Second World War in the area of the Stalag Luft III Allied Prisoner-of-war Camp: The Site of the 1944 “Great Escape”, Zagan (Ger.- Sagan).

Keywords: ground penetrating radar method (GPR), archaeology, sacral buildings, post-military structures

1. GROUND PENETRATING RADAR METHOD IN SURVEYING OF SACRAL BUILDINGS AND POST-MILITARY STRUCTURES IN SCIENTIFIC WORKS

The ground penetrating radar method is used more and more frequently to search and survey inaccessible underground hollows, which are i.a. historical mining sites or underground structures. The method is based on the phenomenon of propagation of electromagnetic waves in the orogen and their reflection from boundaries of rock masses featuring different physical properties (especially rock/hollow). Application of this surveying method enables non-invasive surveying of surface ground layers, usually to the depth of a few dozen meters – which proves especially significant in case of surveying archaeological sites or surveying of historical buildings. The radar intended for this surveying is called a ground penetrating radar and the surveying method - the GPR (Ground Penetrating Radar) method [1, 2, 3, 4, 5, 6, 7]. The result of measurements constitutes so-called radargrams, the analysis of which allows for location of anomalies in the base surface structure caused by presence of the searched objects, e.g. workings, crypts, or archaeological relics. Knowledge of the physical properties of the rock mass surveyed with the GPR method and first of all of the electromagnetic wave propagation velocity characteristic for this mass allows to determine the depth, on which the searched object is located.

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The minimum size of the detected object and the depth range of the radar depend on the frequency of the antennas used, as well as on the electrical properties of the geological medium, the technical parameters of the GPR equipment and the selection of measurement parameters. Empirical values of the minimum detected object size and radar depth range depending on antenna frequencies are summarised in Table 1. The averaged measurement range is given assuming the absence of layers strongly attenuating electromagnetic wave (well-conductive) in the surveyed geological profile. The attenuation of the electromagnetic wave in the geological medium has a decisive influence on the depth range of the GPR method. The attenuation coefficient depends on the conductivity of the geological medium. The higher the conductivity, the higher the attenuation and the lower the depth range. Any measurements made under conditions of high soil moisture reduce the GPR depth range (even by several times). The GPR method has the greatest depth range in rock salts and dry sand, and the smallest in clay formations, silts and shales. In a medium highly attenuating electromagnetic waves, the depth range of GPR decreases dramatically. Layers of clay, silt and mud are virtually a screen for electromagnetic waves [1].

Table 1. Dependence of minimum detected object size and radar depth range on antenna frequency (according to [1])

Antenna frequencies MHz	**Object size** m	**Maximum theoretical range** m
25	>1.0	35-60
50	>0.5	20-35
100	0.1-1.0	10-25
200	0.05-0.50	5-15
400	~ 0.05	3-10
1000	~ 0.01	0.5-4.0

The greater the difference in the dielectric constants of two media, the greater the reflection coefficient of the electromagnetic wave at the boundary between the two media. The dielectric constant of the ground depends on the degree of moisture in the ground. For example, the dielectric constant of wet (water-saturated) sand is $\varepsilon r = 20$, while that of dry sand is $\varepsilon r = 3$, giving a reflectance at their boundary of $r = - 0.44$. In comparison, the value of the reflectance at the boundary between dry sand ($\varepsilon r = 3$) and clay ($\varepsilon r = 25$) is $r = - 0.48$ [1]. This makes it possible to interpret the location (depth) of groundwater table.

Despite that the GPR method features relative speed and simplicity of taking the measurements, as compared to other geophysical methods and their undisputed advantage is nondestructive character and possibility of the insight into the results of the measurements even in the course of taking them, it is one of the most difficult methods for interpretation of the results. It is due to influence of numerous and diverse factors influencing effectiveness of examining of the solid mass with use of propagation of electromagnetic waves. Correct interpretation of the results of the GPR testing requires application of complex interpretation procedures and the measuring equipment and the parameters of performance of the measurements should be individually selected for the conditions, in which surveying is going to be performed. The flagship example of an erroneous interpretation of the results of searching performed using the GPR method was presentation in the media of pseudoradargrams, which were to confirm hiding of the whole train in a camouflaged tunnel in the vicinity of Wałbrzych.

Since 2010 the GPR method has been used in surveying former mining sites in the area of Lower Silesia in scientific works of Faculty of Geoengineering, Mining and Geology Wroclaw University of Science and Technology [8,9]. A separate area of application of this method is surveying in buildings – chiefly in catacombs of churches and searching of underground structure relics. Two selected examples of such works are presented below, which deserve special attention from the historical perspective of the meaning of the places where they were performed and the interesting results of the performed searches.

2. SURVEYING IN THE HISTORICAL CHURCH IN KOŻUCHÓW

2.1. Objective and place of surveying

Surveying of the catacombs of the 13-th century church of Our Lady of Candlemas in Kożuchów was performed upon the request of the "Society of Friends of the Land of Kożuchów" (TPZK), supported by the Lubuskie Voivodship Conservator of Historical Monuments in Zielona Góra. Its objective was verification of suppositions concerning existence of inaccessible crypt in the catacombs. Lack of possibility of making a larger number of surveying boreholes in the historical floor in connection with the importance of the potential discovery of burial places of the last Piast Dukes of Głogów - Henry IX and Henry XI, indicated advisability of surveying of the church crypt with a noninvasive GPR method.

2.2. GPR equipment and surveying methodics

A K2_FW ground penetrating radar set made by the Italian company IDS (Ingegneria dei Sistemi) was used for surveying. The RIS MF HI-MOD unit is a high class device intended for performance of the GPR surveying, especially for locating of underground structures, identification of layers and hollows. The set cooperates with dedicated antennas of diversified frequency. The set of equipment used in surveying comprised the following basic elements: a control unit IDS DAD FAST WAVE (with recording software RIS K2), data recorder (notebook) - computer Panasonic CF-19, antenna set (array antenna) by IDS installed in a single housing (200 and 600 MHz), measurement dial for antenna positioning. The whole set is installed on a measurement trolley. The DAD FastWave device features so-called "interlaced" mode of data collection, which enables simultaneous data collecting through two channels – during operating with the composite antenna used in surveying. Configuration of the device, data collection, its recording and viewing of the results of the surveying during execution of field measurements is ensured by the K2_FW recording software.

The surveying was performed with the method of typical, linear (2D) reflexive GPR surveying – constituting over 90% of the performed GPR surveys. In this surveying methodics both of the antennas: transmitting and receiving are simultaneously passed along the profile – which allows to obtain information concerning construction of the base on the particular section subject to surveying. In the result of this surveying a time section is obtained, which illustrates propagation of the electromagnetic wave in the surveyed mass, where time is the measure on the Y-axis. In order to determine the actual depth of location of the searched objects on the obtained profile it is necessary to determine or assume the correct velocity of propagation of the electromagnetic wave on site of performance of the measurement (0.1 m/ns was assumed as a standard). For the sake of correctness of the obtained results of surveying the antenna must be guided with sufficient precision and as far as possible with constant speed of its pass, along the designed measurement lines.

2.3. Processing and analysis of results of surveying

The dedicated software GRED3D by I.D.S. was used for processing and analysis of the obtained radargrams, which is intended for processing and advanced visualization of the results of measurements using the GPR RIS system [10]. It enables visualization of the radar data in a two- and tree-dimensional form with full utilization of the possibilities of the 3D processing algorithms.

In addition to the non-destructive nature of the surveys, a key advantage of GPR surveys is the possibility of an immediate, but only preliminary, evaluation of the survey results in the field [1]. The correct interpretation of GPR results is relatively complex and difficult compared to other geophysical methods and requires complex interpretation procedures, using sophisticated recording and processing software supplied by GPR equipment manufacturers.

A number of functions of the processing software was used, which allowed for processing of radar maps by application of two-dimensional filtering algorithms -menu Filter of the processing program (Fig. 1), including i.a. commands: Move start time - to calculate the zero point between the surface of the transmission signal (antenna) and the surveyed mass, Background removal - to remove continuous components along the X axis (horizontal direction) according to the previously defined user parameters, User defined horizontal filter – application of the gain curve for the radar (user defined horizontal filter), Vertical Bandpass filter – (application of the user defined frequency interval filter) and Subtract mean (Dewow) – filtering algorithm for removal of continuous elements along the horizontal map direction of the radar map (deduction of mean values).

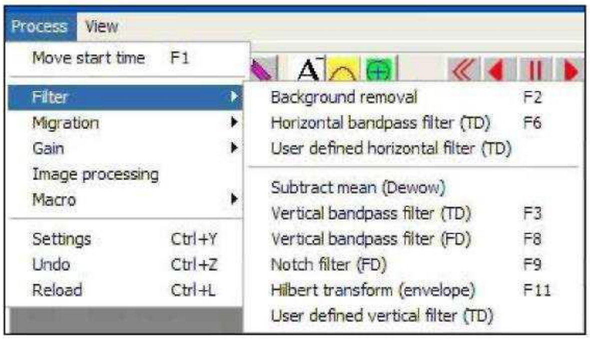

Fig. 1. Menu “Filter” in the processing software GRED3D [10]

Correct operating with the signal gain is crucial in the analysis of the obtained radargrams. The GRED3D menu of Gain available in the software was used in the analysis of the obtained results, which included a group of algorithms used to level the radar signal (Fig. 2): the command ”linear gain” – used for application of the filtering algorithm levelling the signal force for a series of collected data on the basis of estimated linear reduction, the command Smoothed gain used to level the signal strength along the series for a passing window, the command User defined gain – application of user’s own curve of the user defined gain. The best effects were given by the Linear gain.

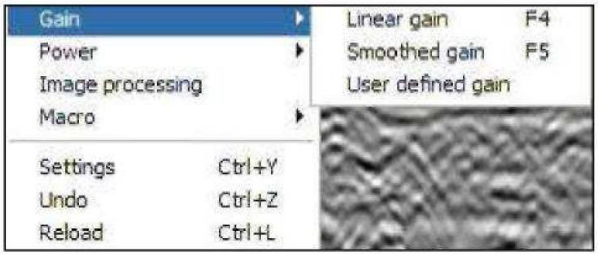

Fig. 2. Menu “Gain” (amplification) in the software GRED3D [10]

In order to process many GPR surveys quickly the option Macro was used, which allows for complex processing of the radar data in compliance with the sequence of the filters preset by the operator. The following visualization modules were used in the analysis of the surveying results, available in the program GRED3D: B-Scan (a single radar section) and 3D (three-dimensional visualization). However, a detailed presentation of the full process of processing and analysis of the results of the GPR surveying exceeds the volume of this publication by far.

2.4. Results of surveying

Already the preliminary assessment of the results of the taken measurements performed in the course of execution of the surveying unambiguously demonstrated occurrence of characteristic anomalies in the base structure of the surveyed building. Their location on the background of the church plan is presented in Figure 3. These anomalies were recorded under the stone floor of the so-called former Mansionaire Chapel – in two neighbouring elongated areas and in the chancel. The performed analysis of radargrams confirmed with high probability the existence of hitherto unknown rooms (crypts) in the church catacombs. A particularly clear GPR image indicating a disturbance in the structure of the base ground was recorded in the former Mansionaire Chapel (Fig. 4). On the basis of the obtained results of the GPR surveying the high probability of existence of an unknown underground room (crypt) under the former Mansionaire Chapel was discovered. It featured elongated shape and its position was rectangular to the longitudinal axes of the church and the chapel. No reflections from the bottom limit of the presumed hollow were recorded indicating e.g. its partial filling up. The character of the reflection from the ceiling of the presumed rooms allowed to assume that the identified crypt features a stone arch shape ceiling when the first anomaly – from the side of the main entry to the church could also be a picture of a massive stone wall neighbouring the crypt. The analysis of the GPR surveying performed in the area of the chancel proved to be more difficult for interpretation (Fig. 5). However, there were also visible anomalies indicating disturbances of the base (ground) structure under the church, which could be fragments of walls of structures located previously in the present area of the church or the searched crypt.

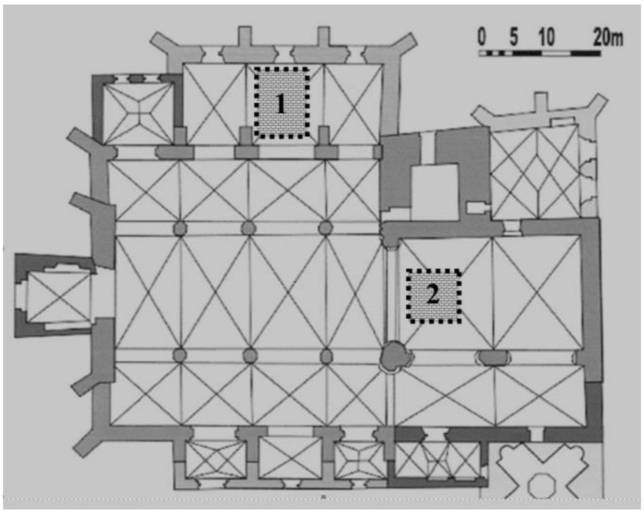

Fig. 3. Location of the detected anomalies in the church catacombs (crypt)

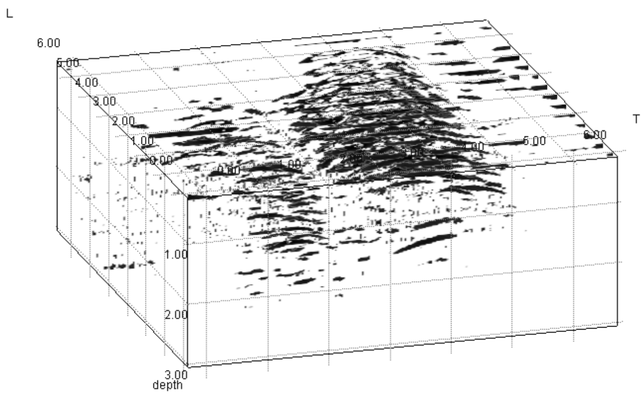

Fig. 4. Three-dimensional visualization of the anomalies (crypt) under the former Mansionaire Chapel

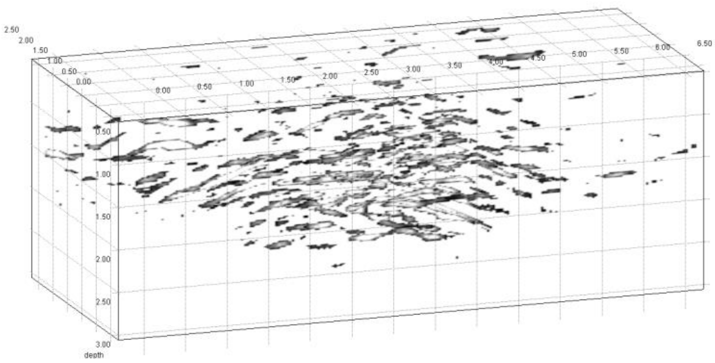

Fig. 5. Three-dimensional visualization of the anomalies (crypt) located under the chancelccc

3. SURVEYING IN THE AREA OF THE FORMER GERMAN ALLIED PRISONER OF WAR CAMP "STALAG LUFT III"

3.1. Objective and place of surveying

The objective of the surveying was an attempt to verify location of the historical escape tunnel (Fig. 6) made in years 1943/44 by the prisoners of war imprisoned in German camp "Stalag Luft III". The remnants of this camp are located nowadays in the area of Poland, in the vicinity of Żagań. "The Great Escape" took place at night on 24/25 March 1944 and was the largest POW escape during the Second World War [11]. 600 people participated in preparations for it who besides of construction of the tunnels prepared false ID documents, clothes and maps. It was planned that about 200 POWs would escape the camp, however it did not work and finally 80 of them succeeded but some of them were captured immediately. In the end only three runaways managed to get to the United Kingdom (two Norwegians and one Dutchman). The remaining POWs were recaptured and fifty of them were murdered by the Gestapo upon a personal order of Hitler. This crime found its conclusion during the famous war criminal trial in Nurnberg. All the six Polish airman, POW-s, who took part in the escape were among them - Hail to their memory!

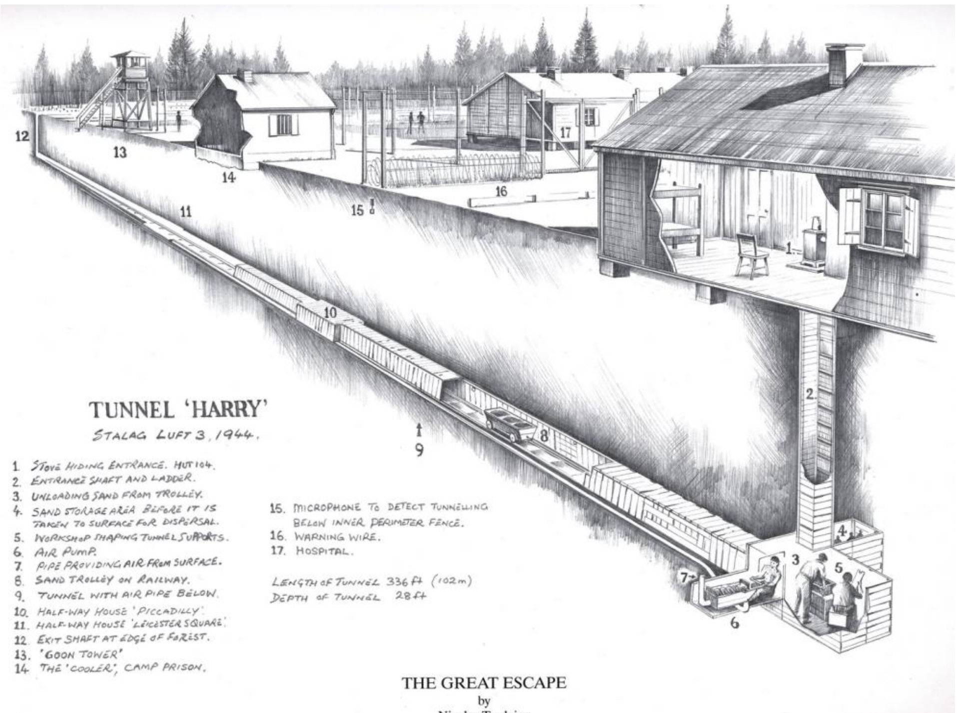

Fig. 6. Construction and equipment, the tunnel "Harry" [11]

Construction of the escape tunnel "Harry", as well as of the two other tunnels related to preparations to „The Great Escape" – "Dick" and "Tom", constituted a unique engineering operation, which was executed in complete conspiracy. The tunnel "Harry" located on the depth of ab. 8 m under the surface of the terrain was 111m long. Over 2,000 planks were used for its lining, which were taken from camp beds and barracks and 750 cans from canned food were used to make its ventilation duct. Tunnelling works required extraction to the surface and dumping of over 130 ton of sand and clay in complete conspiracy (as they were of different colour than the surface soil, the winnings required concealing). A rail transport system was installed in the tunnel, including trolleys moving on wooden tracks, some necessary loops and electric lighting. The outlet of the tunnel was in barrack No 107, hidden under operational stove and the starting section of the tunnel was constructed in a barrack pillar of masonry construction [11].

3.2. GPR equipment and surveying methodics

A GPR set of IDS make was used in the surveying. Its detailed description is in point 2.2. Due to location of the searched escape tunnel on the depth of about 8 m, a set of antennas (transmitting and receiving) was used featuring the frequency of 80 MHz Right selection of the measuring antennas considering the estimated depth of the location and size of the searched object has the crucial meaning – the relation between the frequency of the probing impulse and the GPR scanning range to the measurement resolution is inversely proportional. With the increase of the frequency of the electromagnetic wave emitted deep into the geological mass the depth of penetration decreases and measurement resolution increases.

The survey used 200/600 MHz antenna array due to the shallow depth of the location of the searched underground structures, the favourable ground conditions for the use of the GPR method and the compact design of the composite antenna facilitating the measurements. The use of the composite antenna allowed for comparison and verification of the results obtained with antennas of different measurement frequencies, guided along an identical measurement route (composite antenna), which supported the correct interpretation of the profiling results.

Scanning with 200 and 600 MHz array antennas was performed using a measurement trolley while using a low frequency 80 MHz antenna without a trolley – pulling the antenna directly on the ground, which guaranteed a good contact with the bed and minimized the loss of energy of the electromagnetic wave on the boundary antenna/air/ground. In the course of measurements the control unit, accumulator and Panasonic computer were carried in a backpack. The surveying was conducted with the method of typical, linear (2D) reflexive GPR surveying. During the tests the method of triggering the radar signal (impulse) at fixed distance intervals was used - carried out by means of a measuring wheel attached directly to the array of 80 MHz antennas. According to the principles of the GPR surveying the profiles were started and finished outside the zone of the surveyed area (in the particular profile), in order to notice transition from the unchanged area to the changed area (anomaly). The time of performing of such an additional profile is minimal when the benefits in the scope of interpretations of the achieved results are significant. The GPR surveying was performed in the parallel grid, which additionally enabled compilation of the results in the form of the three-dimensional visualization (3D) and tomography (C-scan). The coordinate system of performing the surveying was attached to the determined measurement points, which allowed to determine the location of the searched anomaly in the base construction. A general diagram of the data collection system (measurement grid geometry) is presented on Figure 8. The Coordination step applied in the parallel profiling performed within the frames of the conducted surveying was 0.5 m.

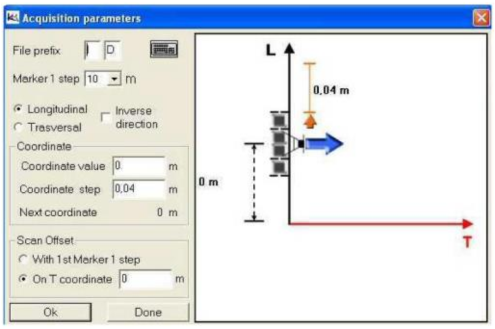

Fig. 8. Diagram of the data collection system (measurement grid geometry) in the recording software K2_FW [10]

3.3. Processing and analysis of results of surveying

The dedicated software GRED3D and the procedures described in point 2.3 were used for the processing and analysis of the results of the surveying. Moreover, in order to estimate the actual radio wave propagation velocity in the surveyed mass (ground) the command Propagation velocity estimation was used for the radar map, on the basis of the recorded shape of the hyperbola of the reflection from the object. The velocity of propagation determined in this way allowed to determine the real depth of location of the searched object and amounted about 0.12 m/ns. Thus the reflections visible on the radargrams in the depth range 6–7 m were in fact located on the depth of about 7–8.4 m, which corresponded to the location of the tunnel “Harry” known form the historical data [11] (The visualization modules available in the program GRED3D: B-Scan (a single radar section), 3D (three-dimensional visualization) and in addition C-Scan (tomographic maps) were used in the analysis of the surveying.

The use of GRED3D software enabled precise and compelling3D visualisation of the results in parallel grid profiling. This method of visualisation, requiring a special measurement methodology, is highly illustrative and at the same time the easiest to understand even for person with no previous experience with the GPR method. Although constructing a correct 3D image is a relatively difficult task, the GRED3D software proves to be simple and intuitive here, also with regard to its other functions.

3.4. Results of surveying

The undertaken attempt of locating the relic of the escape tunnel Harry with the GPR method in the area of the former German Stalag Luft III Allied Prisoner-of-war Camp can be considered a success. The determined course of the anomaly appearing with a variable intensity on the consecutive GPR profiles (with large probability related to a relic of the historical tunnel) is moved for just 1 m out of the symbolic tunnel route marked on the surface – on the basis of historical information and memories of the living witnesses of “The Great Escape”. Due to the permissible volume of the present publication, only examples of single radar sections were presented below (so-called B-Scan) for antenna 80 MHz (Fig. 9) and 200 MHz (Fig. 10), on which the reflections from the presumed relic of the searched tunnel are presented (marked with a cross).

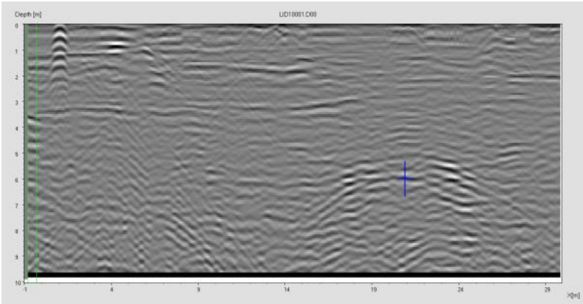

Fig. 9. Visualization of the surveying results in form of a single radar section (so-called B-Scan), for a single GPR profile (antenna 80 MHz)

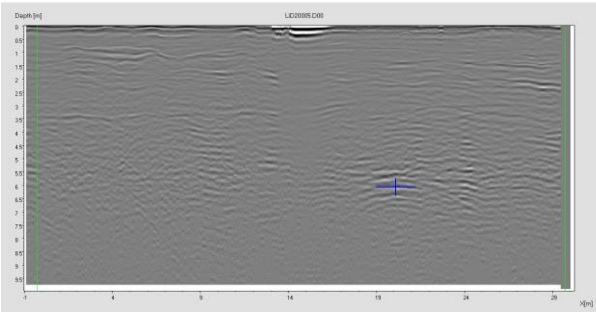

Fig. 10. Visualization of the surveying results in form of a single radar section (so-called B-Scan), for a single GPR profile (antenna 200 MHz)

The relation of the anomalies recorded on the radargrams to the remnants of the construction of the historical tunnel is demonstrated by:

- repetition of similar reflections on a series of radargrams performed in the parallel grid,
- repetition of similar reflections on radargrams recorded with use of the 200 MHz antenna and 80 MHz antenna,
- analogous depth of location of the anomalies interpreted as reflexions from the relic of the escape tunnel on the presumed tunnel route on the road along the fencing of the former camp and on the forest road
- similarity of the obtained images of the detected anomalies on the presumed route of the tunnel on the road along the fencing of the former camp and on the forest road,
- no information concerning the existence in the surveyed area of underground installations (pipelines, cables, etc.), which could be the source of this kind of the reflexions, despite of the fact that their distinguishing should not make a problem.

4. CONCLUSIONS

The confirmation of the results of searching for the underground crypts in the catacombs of the church of Our Lady of Candlemas in Kożuchów performed with the GPR surveying method was provided by archaeological surveying commenced in 2017. A crypt and its entrance filled up with rubble were discovered on the location selected in the course of the presented surveying in the catacombs of the Mansionaire Chapel. In total a dozen or so of coffins was discovered in the catacomb – including the destroyed sarcophagus, in which Daniel Preuss von Preussendorff (1529 – 1611) was buried, an important person in Europe in the 16-th century (Fig. 11). Unfortunately, the expected burials of the last

Piast Dukes of Głogów were not found. The condition of the crypt and coffins indicated that the place had been ravaged.

Fig. 11. The crypt discovered under the stone floor of the so called Mansionaire Chapel [12]

The discovery of the crypt in the archaeological surveying confirms correctness of the accepted measurement method, in connection with the right selection of the measurement equipment and the GPR filtering parameters. Also the three-dimensional visualization (Fig. 4) of the radargrams compiled using the processing software GRED3D and interpreted as rooms featuring arch ceiling turned out to be correct.

The results of the GPR surveying performed in the area of the former German Stalag Luft III Allied Prisoner-of-war Camp turned out to be interesting and continuation of these works is planned. Location of the relics of the famous escape tunnel ”Harry” (Fig. 12) is supposed to be the trigger of an attempt to reach to the remnants of this unusual construction related to one of the most famous episodes of the Second World War.

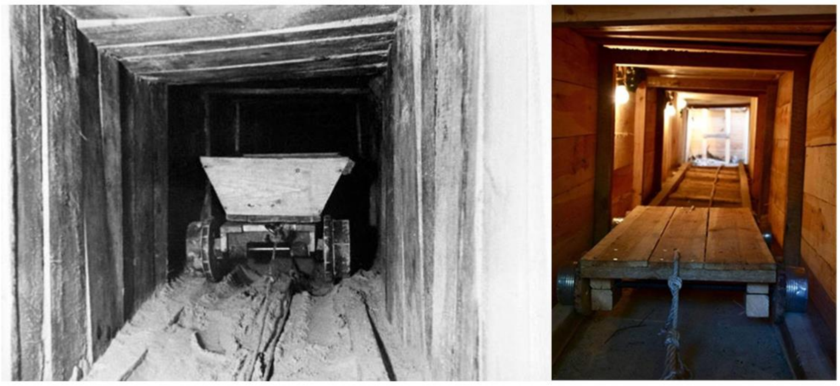

Fig. 12. The tunnel ”Harry” on a photo from 1944 and its contemporary replica [13]

AUTHOR CONTRIBUTIONS

Conceptualization, M.M. and D.Sz.; Investigation, M. M.; Methodology, M.M. and D.Sz.; Software, M.M. and D.Sz.; Project administration, D.Sz.; Resources, M.M., and D. Sz.; Supervision, M.M., and D. Sz.; Validation, M.M., D. Sz.; Visualization, M.M., D. Sz.; Writing—original draft, M.M., D. Sz.; Writing—review and editing, M.M. and D.Sz. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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