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FROM FIELD SURVEY TO 3D MODEL – APPLICATION OF GROUND-PENETRATING RADAR FOR STUDIES OF HISTORICAL ARCHITECTURE: A CASE STUDY OF THE WYSZYNA CASTLE IN POLAND

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Abstract

Non-invasive surveys are more and more frequently used in historical heritage studies because they allowed to non-destructive examination of the state of the preservation of the historical monuments. Ground – penetrating radar (GPR) method belongs to them. The most important problem limiting the use of GPR on sites with historical architecture is presence of thick accumulations of rubble, modern infrastructure elements and very often dense plan cover. Despite these restrictions, correctly performed GPR survey may deliver very important data related to the layout and also subsurface stratigraphy of studied architectural relicts as it is presented by GPR survey of the renaissance Wyszyna Castle, located in Central Poland. Field was in next steps compared and combined with available architectural, historical and archaeological records. In the finale stage, particular datasets were performed to recreate the layout of the Wyszyna Castle. This became the basis for reconstruction proposed herein in form of a scaled 3D model of this monument. Authors are convinced that complex attitude presented in this work should become a standard in architectural studies with application of geophysical methods.

Keywords*:Ground penetrating radar; Historical architecture; Data integration; 3D modeling*

Introduction

From several years, non-destructive surveys methods have been more and more frequently used in the study of the historical heritage [1]. The main advantage of these methods is the possibility of non-destructive examination of the state of the preservation of the monuments, i.e. without disturbing their internal and external structures, what can be very useful for planning conservation or protection activities [1, 2]. It is also clear that non-destructive techniques should be preferred, while destructive methods such as excavation should be minimized in cultural heritage projects and surveys [1]. For almost two decades the ground-penetrating radar has been successfully applied in archaeological surveys [3-6]. At the same time, the method is still not so frequently used in architectural investigation. The basic problem related with GPR application in sites with relics of historical architecture is the presence of thick accumulations of rubble and destruction layers. They cause that coherent

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(usable) anomalies are barely distinguished from incoherent ones, and low- and high-amplitude noise. Therefore, analysis of GPR images (time sections, reflection profiles) obtained after processing requires great experience and knowledge, and thus the interpretation stage is loaded with subjective assessment of the noted anomalies. Furthermore, the occurrence of very thick rubble layers in many cases completely hampers obtaining satisfying results with the use of GPR method. Ancient objects commonly occur in the neighbourhood of later or even modern constructions, which to a variable degree restrict access to the area designated to geophysical surveys. Other significant constraints include dense bushes or tree stands overgrowing objects preserved as partial ruins. Elements of present-day infrastructure, such as pavements, concrete driveways, large benches or streetlights are also some of the obstacles. Despite these restrictions, correctly designed and performed GPR surveys, even on a small area, may supply significant results related not only to the layout of the analysed historical building, but also to its horizontal and vertical stratigraphy, as indicated by studies of the relics of the renaissance Wyszyna Castle, currently preserved on the surface in form of a brick tower (Fig. 1).

Fig. 1. A – Location of Wyszyna Castle, B – View of the area covered by the Wyszyna Castle premises from the south (photo by K. Rabiega), C – Tower of the Wyszyna Castle complex – the only element preserved on the surface (photo by F. Welc)

The castle ruins are situated in the northern part of Wyszyna village (Władysławów commune) in the eastern part of Wielkopolska. The preserved remains are surrounded by moat and remains of a park. It belongs to the lowland castle type, located centrally in relation to the feudal estate as a residence allowing for management of the surrounding property [7]. Out of the complex only two octagonal towers surrounded by a wall remain till present, of which the five-story eastern tower is completely preserved. At a distance of c. 23m to the north lies a one-story, residential building, located directly on the foundations of the northern wing of the castle. The area covered by the castle is presently mostly covered by trees and dense bushes.

The main aim of the geophysical survey of the relics of renaissance castle at Wyszyna was to recognise the layout of this scantily preserved structure and to obtain information about the arrangement and thickness of the embankment-rubble layers and degree of wall preservation, thus enabling the determination of the preservation state of architectural relics not preserved on the surface. In the next stage, these studies became the basis to propose the

reconstruction of the spatial arrangement of the castle at Wyszyna in form of a 3D model. This aim was achieved by applying a methodology which completely integrates geophysical (GPR) data with historical, architectural and archaeological evidence.

Methods

The first stage field GPR survey within two test areas was performed, whose surface and position depended on the accessibility to the densely overgrown area (Fig. 1). Field data were then subject to processing and finale interpretation. In the second stage, the geophysical data in the form of interpreted time slices (= GPR amplitude maps) and reflection profiles (= radargrams) were compared with available data obtained in previous years during architectural studies, historical queries and results of archaeological surveys. In the final stage, detailed analysis of particular datasets was performed to retrace the spatial layout of Wyszyna Castle. This became the basis of the castle reconstruction proposed herein in form of a dimensional and scaled 3D model (Fig. 2). The complex attitude presented in this work should become a standard in architectural studies with application of geophysical methods. The particular survey stages are presented in the further part of the paper, whose final effect is the virtual reconstruction of Wyszyna Castle.

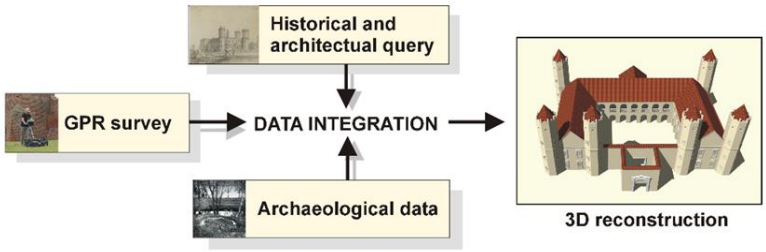

Fig. 2. Scheme presenting particular stages of the integration of archeo-architectural-geophysical data leading to the 3D spatial reconstruction of the building castile at Wyszyna (designed by F. Welc)

GPR survey and its results

The GPR – *Ground Penetrating Radar* method is based on emission of electromagnetic waves with high and very high frequencies by the transmitter antenna and the registration of impulses reflected from layers and underground objects characterised by diverse electric properties. The physical background of the method has been described in detail by *Jol* [8], *Daniels* [9], *Conyers* [3], *Karczewski* [10] and *Karczewski et al*. [11]. The basic issues related with GPR surveys are presented below. The general problem for GPR method is variability of the physical characteristics the soil. In geophysics, the properties of each geological medium (soil) are defined by three parameters [11]: permittivity – ε_r, permeability – μ and conductivity – σ. In effect, electromagnetic waves emitted into the ground are subject to reflection, refraction, interference, diffraction and attenuation. The boundary between two layers significantly differing in electric properties reflects electromagnetic waves more intensely depending on the difference between the relative permittivity of the two media [11]. Permittivity is directly proportional to the permittivity of the geological medium and inversely proportional to the permittivity of vacuum (ε_0), as in the following formula:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \qquad (1)$$

The value of the dielectric constant also has influence on the velocity of the electromagnetic wave in the medium through which it propagates. The velocity of the electromagnetic wave in a medium is described by formula [10]:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (2)$$

where: c – velocity of electromagnetic wave in air, ε_r – relative dielectric constant.

Knowledge on the value of the electromagnetic wave velocity is crucial for calculating the depth scale of the registered radargrams (reflection profiles). The most commonly applied method of determining the mean velocity of the electromagnetic wave in a soil is the geometric adjustment of the branches of diffraction hyperboles from the reflection profile to synthetic hyperboles with assumed parameters, generated by GPR data processing programs [10]. Analysis of the geometry of diffraction hyperbole branches allowed to determine the mean velocity of wave propagation in the local geological medium at Wyszyna at 0.08 m/ns. This velocity corresponds to properties of waves passing e.g. though sand-clay deposits. This is in accordance with the geological map, which for the discussed area points to the dominance of fluvioglacial sands lying on a basement of variable origin (e.g. fluvial sands of the pre-Poznań Interphase; glacial tills of the Leszno Phase; ice-dammed clays and muds, and glacial tills of the Mazovian Stadial) [12].

As usable signals in the GPR method are considered reflexes from the sought-for underground structure, therefore the main aim of GPR data processing is enhancement of the N/S ratio (noise versus usable signal) by a multistage procedure of GPR data processing. The following procedures were applied during GPR data processing obtained during survey in the Wyszyna survey: *Running average* (calculating the running average), *Dewow* (similar as previous procedure, used for removal of low-frequency noise), *DC – Shift* (subtracting the constant component of the GPR signal), *Subtract-mean* (removal of average component), *Gain* (enhancement of GPR signal), *Move start time* (correlation of first occurrence of georadar wave), *Bandpass frequency* (frequency filtration), *Background removal* (removal of random noise and direct waves), *Avarage xy filter* (summing of georadar routes) and *F-k filtration* (elimination of interference waves, whose velocity differs significantly from the velocity of usable reflexes). The effects of field data processing are refined time slices (GPR amplitude maps) and reflection profiles (radargrams) [5]. The former one, are cross-sections showing the variability of electric parameters of the geological medium. The profiles are graphic representations of the record of GPR signal amplitude with a colour scale [13]. Simply speaking, GPR anomaly corresponds to a place differing from the surroundings (background) in values of physical properties of the geological medium (soil). Places where the waves are reflected or refracted are registered as reflection surfaces (layer boundaries) or diffraction hyperboles indicating objects buried underground, which in the profiles are visible as characteristic arches or their sets (Fig. 5).

The last advanced processing procedure of selected groups of the wavegrams was their assembly in quasi 3D blockdiagrams using *3D* modules available in ReflexW software. GPR amplitude maps determined here as time slices were obtained. In comparison with single GPR reflection profiles, GPR mapping allows for determining the linear sets of anomalies, which may be generated e.g. by walls.

During the survey at Wyszyna, the Ground Explorer (GX) system of Mala Geoscience was used. The prospection was performed with the application of a screen emitter antenna, bimodal, with a nominal frequency of the emitted electromagnetic wave at 450MHz. Subsequent survey profiles were located at a constant interval of 0.40m (Fig. 3).

Survey site no. 1 was determined in the western part of remains of the castle (Fig. 3A). Its dimensions were 40x15m (the western corner was omitted in the prospection due to very dense vegetation cover). The area encompassed the largest possible range of underground relics of the western wing of the castle. The main aim of the survey was to verify the outline of the buried foundation walls and the location of the corner tower. According to the existing interpretation, the frontage corner tower, with its basement preserved only, was connected by a curtain wall with the rear corner tower, and the entire arrangement in this part of the castle

attained a rectangular shape, linking from the north with the existing – modern residential building. Moreover, an additional partition wall was suggested in this interpretation, which ran from the frontal wall of the building and joined the curtain wall [14, 15].

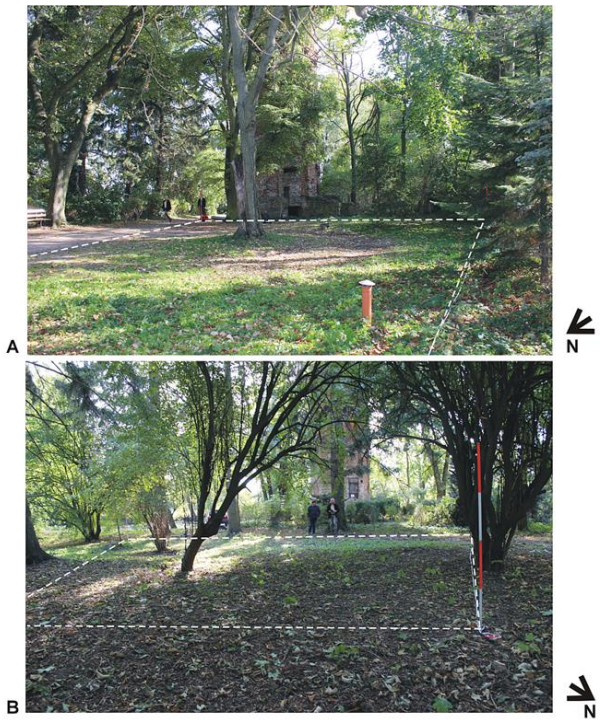

Fig. 3. Survey sites: A – site no. 1, view from the NW, B – site no. 2, view from the NE (photo by F. Welc)

Survey site no. 2 was defined in the eastern part of the study area, in the eastern castle wing. Its dimensions were 18x14m. Due to dense vegetation and the possibility of survey coverage, the survey area corresponded to the range of the alleged remains of the eastern gate tower; its relationship to the gate and the modern residential building located on the relics of the northern wing were analysed (Fig. 3B). According to the interpretation published in 1962, the tower was supposed to be connected at a right angle with the preserved towers and with the building located on the remains of the northern wing [16].

Within survey site no. 1, the time slices prepared for depth interval 0.20 to c. 2.0m have indicated sets of linear anomalies that should be interpreted as architectural relics of the western castle wing. They include mainly foundations and relics of partition (internal) walls and rubble accumulations (Fig. 4).

For a detailed analysis of the spatial stratigraphy of this part of the castle, the GPR plan at the depth of 2m was compared to the reflection profile no. 20 (Fig. 5).

Both the time slice and the profile show the foundations of internal walls of the western castle wing on this depth level (Fig. 5B: 1–3). In the northern part of the surveyed area, a GPR signal attenuation zone is visible (Fig. 5B: 4), which may be interpreted as a wide depression filled with mixed material with the domination of the clay fraction.

It can be interpreted as demolition trench for obtaining bricks and stones, which may be dated back to the 19th or 20th century (Fig. 6: 4). In the south-eastern part of the survey site occur less regular linear anomalies, which are probably the echoes of partition wall foundations (Figs. 5B and 6). The GPR profile indicates their distinct reflection surfaces, which represent boundaries between particular layers corresponding to stages of rubble accumulation within the

cellar rooms that have been deprived of ceilings (Fig. 5B: 5 and Fig. 6). One of them is visible in the GPR plan as a GPR signal enhancement zone with a regular outline. The reflection profile also shows the interior of the cellar filled with rubble (Fig. 6: 2). It is also possible that relics of a staircase are preserved in the central part of the study area, as indicated by the concentration of anomalies within a rectangular space close to the external wall of the castle wing (Fig. 5B: 6).

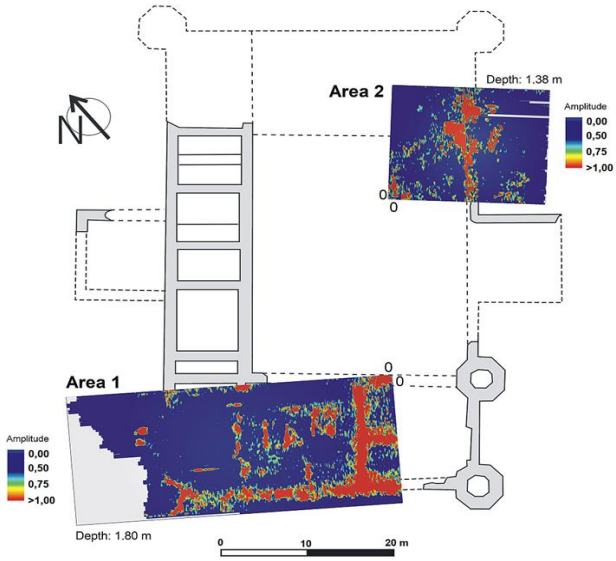

Fig. 4. Selected GPR plans within survey sites no.1 and 2, superimposed on the plan of the Wyszyna Castle suggested by Reichert-Hirschowa and Hirsch [16] (processed and drawn by F. Welc)

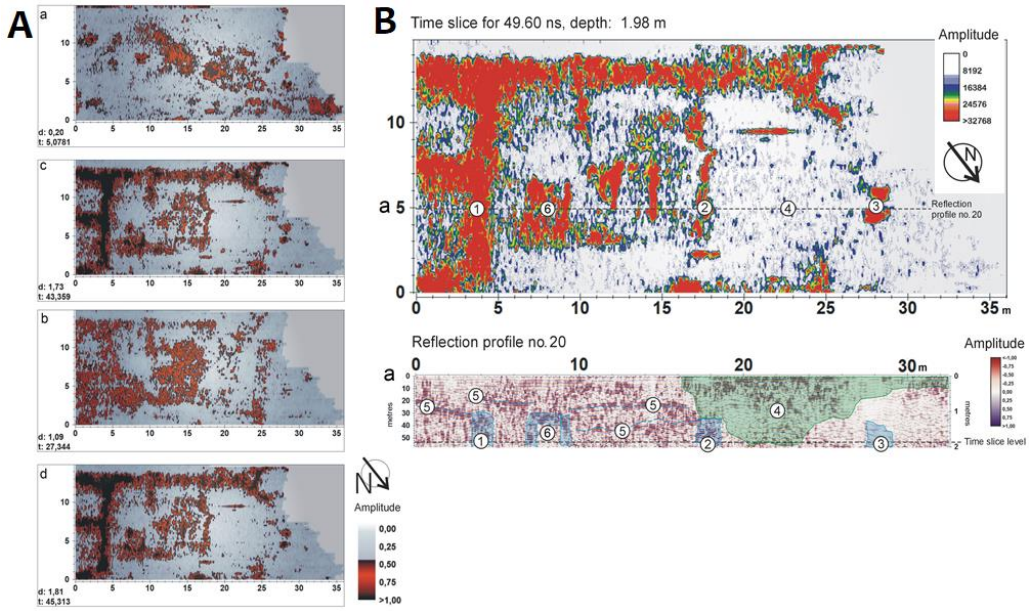

Fig. 5. A – Selected time slices (GPR maps) from survey site no. 1, B – GPR map for depth level 1.98m superimposed on reflection profile no. 20, for detailed description see text

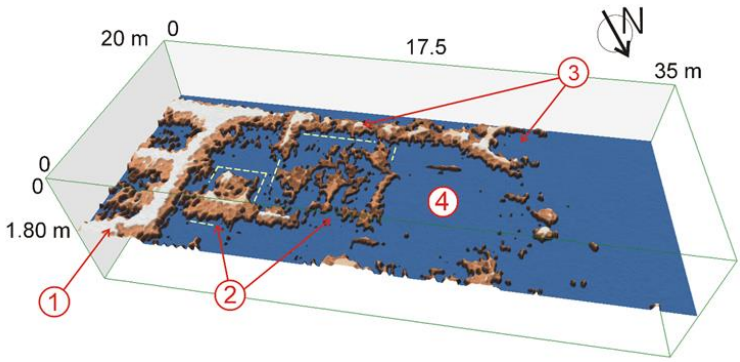

Fig. 6. Spatial (3D) model of anomalies within survey site no. 1 with interpretation: 1 – relics of foundation walls, 2 – relics of cellar with rubble (to the left) and alleged staircase (to the right), internal subdivision of the castle wing and alleged staircase, 3 – relics of corner tower and external wall of the western castle wing, 4 – zone devoid of anomalies, most probably disassembly excavation

The generated 3D model of recorded anomalies shows the outline of the northern corner tower and the external wall (Fig. 6: 3), connected with the southern corner tower presently preserved on the basement level. Additionally, the cellar structure and alleged staircase are clearly visible (Fig. 6: 2).

Survey site no. 2 registers mainly anomalies corresponding to the foundations of the eastern gate tower and its connection with the entrance gate (Figs. 7 and 8).

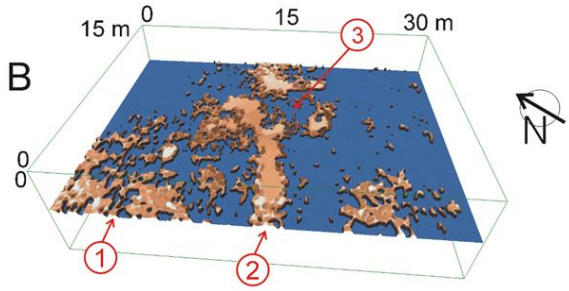

Fig. 7. Spatial (quasi 3D) model of anomalies recognised within survey site no. 2 with interpretation: 1 – vast disassembly excavation, 2 – relics of the external castle walls, 3 – tower relics

It was possible to e.g. depict the external castle wall, which runs to the north-east (Fig. 8A). Analysis of the GPR map superimposed on the reflection profile indicates that the foundation of this tower is largely destroyed by disassembly–illegal excavations that most probably originated in modern times. Only a fragment of the tower foundation is visible in the analysed GPR images (Fig. 8B: 1) with a vast demolition trench on its north-western side, within which subsequent inundation stages can be distinguished (Fig. 8B: 2).

Historical-architectural query

The Wyszyna Castle was erected most probably in 1556 by the Grodziecki family [17–19]. The edifice had a regular projection, comprising three single-bay, two-storey wings with cellars. Most probably, stone or wooden galleries ran along all courtyard walls. Four octagonal towers were located in the castle corners and two additional towers, symmetrically flanking the southern sides of the walls of the castle wings, were additionally erected [20]. The building encompassed elements of a medieval castle and a renaissance palace. The entire premises were surrounded by a wide moat filled with water [18, 20, 21]. After a fire in 1617, the residence was partially refurbished in the baroque style. Adam Grodziecki (c. 1590–1646), the castle owner at that time, did not finish this refurbishment and parts of the castle remained destroyed. The

surviving cellars were used as storage rooms, the ground level of the refurbished construction was turned into a kitchen, pantry and armoury, whereas the upper levels played representative and residential functions for the castle owners [18, 20].

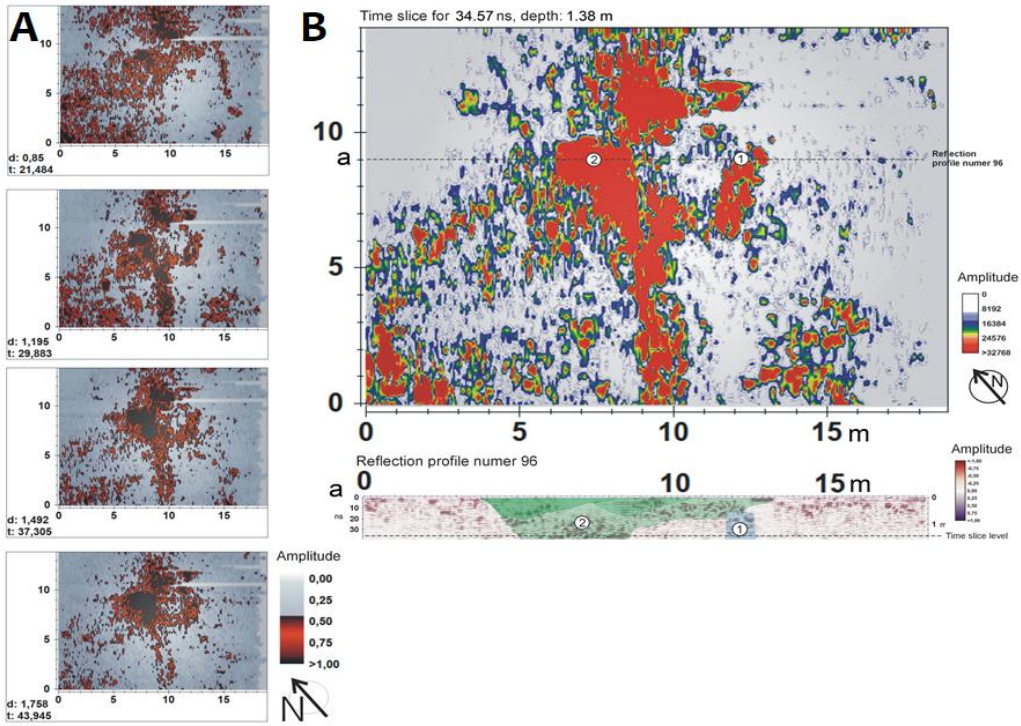

Fig. 8. A – selected time slices (GPR maps) from survey site no. 2,
B – GPR map for depth level 1.38m superimposed on reflection profile no. 96,
for detailed description see text (original study by F. Welc)

In the second half of the 17th century, the new castle owners rebuilt the complex, changed the function and decorations of the castle rooms [22]. During the war activities of the Bar Confederation in 1768, the eastern castle wing was blown up [20]. The residence, which remain uninhabited from 1781 progressively turned into ruin. In the 19th century, the castle ruins were gradually torn down (Fig. 9). A modern residential building, existing till present, was built on the preserved fragments of the castle walls and partially on the cellars of the northern castle wing [20].

The oldest known images of the Wyszyna Castle and its surroundings come from about the mid-19th century. Of particular importance is the steel engraving from 1843 [23]. It shows the two-story castle wings (western and northern) and three octagonal towers, of which two were topped with parapets (Fig. 9A). It is worth noting that if these towers were actually erected in the mid-16th century, they represent unique forms, because polygonal towers became popular architectural objects in Poland as late as at the turn of the 16th and 17th centuries [24]. A rectangular, storeyed avant-corps was situated in front of the northern castle wing. The elevations were divided by window openings with baroque-style stone casings. The castle towers and elevations also had a horizontal articulation in form of band and crown courses. In a picture from before 1860, the castle still possesses three towers (Fig. 9B). This illustration indicates e.g. the two-story western castle wing and three octagonal corner towers. Another illustration published in 1870 presents a view of the castle ruins from the west (Fig. 9C). Similar ruins can be seen in a painting from 1878–1880 (Fig. 9D). In turn, the watercolour

painting from 1881 (Fig. 9E) displays the castle from the south-east. This painting shows for the first time four castle towers, the entrance wall and the eastern section of the northern wing wall.

Fig. 9. Selected historical iconographic presentations of the Wyszyna Castle:
a – Konstancja Raczyńska (1781–1852), ca 1842, steel engraving, paper, © Piotr Ligier/National Museum in Warsaw, Inv. No. Gr. Pol.15431/33 MNW; b – Stanisław Bracikowski (ca 1832–after 1897), 1850–1860, pencil on paper, © Piotr Ligier/National Museum in Warsaw, Inv. No. 32922; c – Ignacy Chełmicki (1850–after 1890) according to Bronisław Podbielski (1835–1890), 1870, wood engraving, paper © Piotr Ligier/National Museum in Warsaw, Inv. No. DI 21002 MNW; d – Napoleon Orda (1807–1883), 1878–1880, watercolour and pencil on paper, © National Museum in Cracow, Inv. No. MNK III-r.a-4609; e – Alojzy Kwiryn Kuczyński (1865–1938), 1881, watercolour and pencil on paper, © Piotr Ligier/National Museum in Warsaw, Inv. No. Rys. Pol. 160071.

Archaeological data

The first architectural-archaeological investigations were performed within the castle premises in 1959 [14–16]. The outline of the western corner tower foundations with foundations of the avant-corps located in front of the northern wing were exposed at that time [16] (Fig. 10A). Next, fragments of foundations of two towers from the western wing as well as relics of the frontal avant-corps, which was the entrance gate to the residence, were also excavated. These investigations led to a conclusion that the Wyszyna Castle was a regular development with a three-winged plan and two sub-rectangular avant-corpses located on both sides of the fortification (Fig. 10B). The entire complex was surrounded by six octagonal towers – four located in the corners and two additional ones in the front [16].

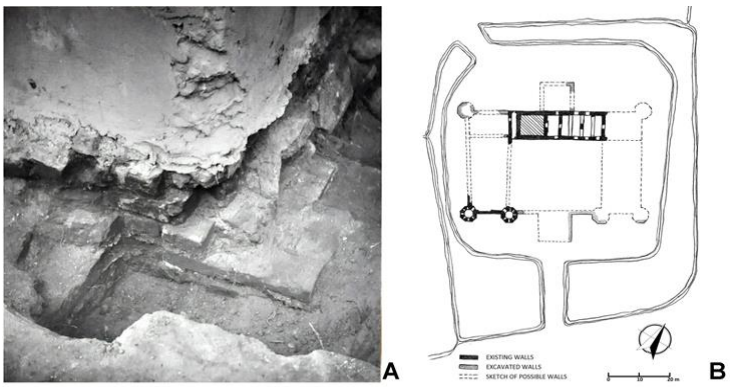

Fig. 10. Archaeological and architectural research in 1959:
A – Corner connecting the north and west castle wing (photo by Z. Hirschowa),
B – Reconstruction of the castle complex at Wyszyna after the second phase of investigations in 1959 (drawn by K. Rabiega, after: Reichert-Hirschowa and Hirsch [16])

Comparison of geophysical results with architectural-archaeological data and 3D reconstruction

As mentioned above, the architectural-archaeological investigations from 1959 [14–16] allowed to present the first spatial reconstruction of the development, according to which the three-winged castle was built on a rectangular outline with a northern avant-corps (probably playing the role of a chapel, erected for the castle owners) and an entrance gate. The construction was supplemented by six octagonal towers [16] (Fig. 11A). The western and eastern wings had representative roles. Most probably the courtyard and all castle wings had stone or, which is more plausible, wooden galleries and stairs leading to the *piano nobile* (representative halls and chambers for the owners noted in the XVII century). Vertical communication was achieved through external stairs located on the galleries/cloisters or in the tower staircases.

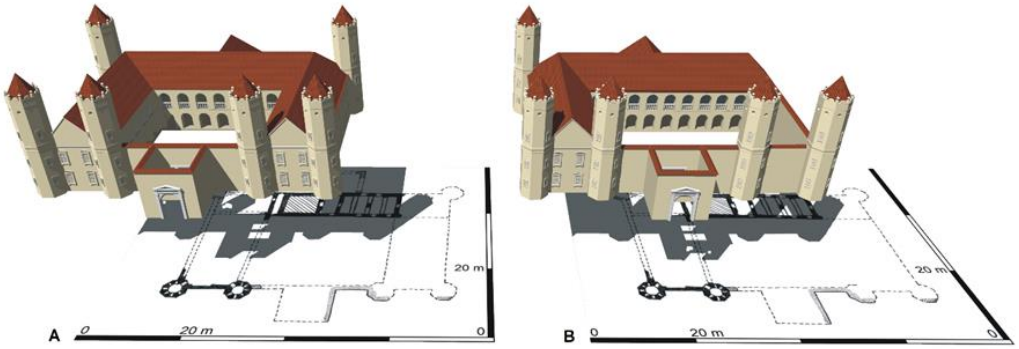

Fig. 11. 3D model of the Wyszyna Castle:
A – reconstruction proposed on the basis of architectural-archaeological investigations in the 1950-ies,
B – reconstruction of the development proposed herein on the basis of geophysical survey (drawn by F. Welc)

The obtained results of GPR surveys superimposed on the plan of the castle complex prepared in 1959 [16] significantly supplement our knowledge on the spatial plan of the residence at Wyszyna. As mentioned above, the main anomalies corresponding to the foundations of the eastern gate tower and its connection with the entrance gate have been registered in survey site no. 2 (Figs. 7 and 8). It was possible to depict the external castle wall, which runs towards the north-east (Fig. 8A). The most interesting issue is the lack of anomalies to the north-west of the tower. This challenges the earlier interpretation of the existence of a rampart connection between the tower and the existing residential building [16]. On the other hand, it is hard to imagine that the designer of the Wyszyna Castle development would not plan the construction of six towers. It is highly probable that they were designed along with the walls, thus the north-eastern tower must have existed along with the entire eastern wing but could have been destroyed after the gun powder explosion in 1768 [20]. However, there are no traces of the wall and of disassembly excavations in that part of the premises. It is worth noting that the available iconographic sources display the Wyszyna Castle with a maximum of four towers. Excavations designed during the excavations in the 1950ies were located in places where the relics of the western wing would be excavated; this wing is clearly seen in the illustrations (its presence is now confirmed by geophysical surveys), but the eastern part of the complex was not recognised adequately at that time. At present, due to dense vegetation, geophysical surveys of this part of the castle premises are very difficult, nevertheless the surroundings of the eastern gate tower, which was not connected by a wall with the northern wing could be depicted. Following these uncertainties, a second 3D reconstruction is proposed (Fig. 11B). Worth noting is the fact that this reconstruction shows a roof on the western castle wing, despite it not being indicated on any historical image. Such roofing must have existed, as

indicated by cornices visible on the wall curtains in the iconographic records, as well as to nothings preserved on the existing relics. Moreover, results of geophysical surveys, performed in this study, seem to confirm this hypothesis.

Conclusions

The basic issue related with GPR application in studies of architectural relics are thick accumulations of rubble and embankments which cause that usable anomalies are attenuated by incoherent anomalies, as well as low- and high-amplitude noise. Despite numerous restrictions, correctly performed GPR surveys, even for a small area, may supply crucial data not only about the outline of the analysed monumental construction, but also on its vertical and horizontal stratigraphy, as evidenced by the investigations in the relics of the renaissance castle at Wyszyna (central Poland). Their main aim was not only recognising the layout of this presently almost destroyed structure, but also obtaining information on the vertical stratigraphy, i.e. the pattern and thickness of the rubble-embankment layers. In a subsequent stage, geophysical data were compared with available historical, architectural and archaeological data obtained during earlier investigations at Wyszyna. Finally, detailed analysis of particular datasets was performed to recognise the spatial development of the Wyszyna Castle. This also became the basis for the new reconstruction of the development in form of a dimensional and scaled 3D model. According to the authors, the complex approach presented herein should be a standard procedure in architectural surveys with application of geophysical methods, the GPR in particular.

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