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GPR mapping of karst formations under a historic building in Szydłów, Poland

Artur Zieliński [1], *Ewelina Mazurkiewicz* [2] *and Mikołaj Łyskowski* [2]

[1] Jan Kochanowski University in Kielce, Institute of Geography, Kielce, Poland

[2] AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland

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The Mid-Poland Uplands Belt is a vast area characterized by the presence of carbonate and sulphate rocks. In some parts of this region karst forming and developing processes are dynamic in character. The studied area is the terrain around a historic church in a small village of Szydłów. The building is situated on a hill which is formed by Sarmatian detrital limestone undergoing karst processes. At the foot of the hill there is a number of small caves. Characteristic geological structure and land transformations that are present due to the karst processes prompted the authors to conduct a GPR survey. The aim of this study was to verify whether there is a continuation of caves in the area around the monument. An analysis was made to estimate the risk of damaging the historic building due to the ongoing karst processes. The authors obtained good quality results from GPR measurements. The results confirmed the existence of unknown voids and loosening in rock structure. On radargrams, the authors recorded stratum mapping which confirms the existence of gravitational loosening of the rock mass near the cave ceilings and walls. The results prove that the GPR is an appropriate instrument for mapping some of the karst structures and evaluation of the orogen stability.

Keywords: Ground Penetrating Radar (GPR), karst, limestone, cave, Szydłów, Kielce Uplands

1. Introduction

Mid-Poland Uplands are characterised by the presence of carbonate and sulphate rocks (Pawłowski et al., 1985), and by the fact that this is a vast karst area. In some places of the Polish Uplands the karst processes are highly dynamic in nature, leading to the transformation of the natural environment, causing a number of possible dangers and economic losses. One of such places where karst processes are common, is the area around Szydłów (Walczowski, 1968; Czapowski, 1981; Rutkowski, 1986; Walsh and Morawiecka-Zacharz, 2001).

Szydłów is a small tourist village with well-preserved medieval monuments and an interesting legend about the specificity of the area and the caves. The village is situated on Szydłów Foothill, which is a southern subregion of Kielce Uplands, a part of Małopolska Uplands (Kondracki, 2002). Its development can be attributed to the location near a trade route. One of the primary stimulus for the development of the borough were the nearby stone resources, which were used in great quantities in Poland since the 13th century. They were necessary for building defensive walls, castles, religious buildings, and other constructions. The authors selected an old church, dedicated to All Saints, located on a limestone rock hill, as the focus of their research activities. This temple is build next to the provincial road number 765, which may have been built where the old trade route was located. The foot of the hill, on which the church is built, is characterized by the presence of numerous cracks and karst gaps, which can be observed on the cavern ceilings and walls. They emphasize the continuity of the ongoing karst processes. Similar signs of karst-weathering processes were observed in a few other caves and rock shelters a few hundred metres away from the analysed area. In addition, the emergence of a swallow hole under one of the roads near the church contributed to the decision of carrying out the research. After careful analysis of the literature, the authors decided to carry out a non-invasive GPR probing in this area. Beres et al. (2001), published a comparison of GPR surveys with microgravimetric measurements. They obtained very good results which indicate that both methods complement each other when studying formations of karst origin. Chamberlain et al. (2000) used parallel gird measuring profiles, thanks to which they received horizontal slices showing the cave system location in the limestone formations. In the same geological region, the GPR method was used for testing roads in the areas with an increased risk of karst origin deformations (Mazurkiewicz et al., 2015). El-Quady et al. (2005) presented the measurement results carried out in Egypt with the use of the electrical resistivity tomography (ERT) and GPR, which is another example of a precise cave mapping. Derobert and Abraham (2000), and Łój et al. (2014) proved that the GPR is an appropriate device not only for studying limestone orogeny, but also for locating karst structures in gypsum formations. The last to mention are Doolittle and Collins (1998), who used the electromagnetic induction method compared to GPR for the purpose of detecting and delineating major structural and solution features for improving site assessments.

Based on the above-mentioned papers and the authors' own experience, the present study aimed to verify whether there is a continuation of caves in the area around the temple or not, and if they pose a threat to the church.

2. Study area

The study was carried out around the historic gothic All Saints Church. The temple is placed in a small, yet rich in medieval monuments, village of Szydłów, which is located on Szydłów Foothill. The region is the contact zone between Świętokrzyskie (Holly Cross) Mountains and Nida Basin. On the substrate of the Palaeozoic structures, typical for the Świętokrzystkie Mountains, sea sediments from the Miocene era are deposited. They are characteristic for Nida Basin. The described area has a varied hilly landscape. Because of its high environmental value it is a part of the Chmielnicko-Szydłowski Protected Landscape Area. The temple, around which the study was conducted, was built at the turn of the 14th and 15th centuries. It is worth noting that some remains of gothic polychrome from the second half of the 14th century can be observed inside the object. The church itself was located outside the town walls (Fig. 1A).

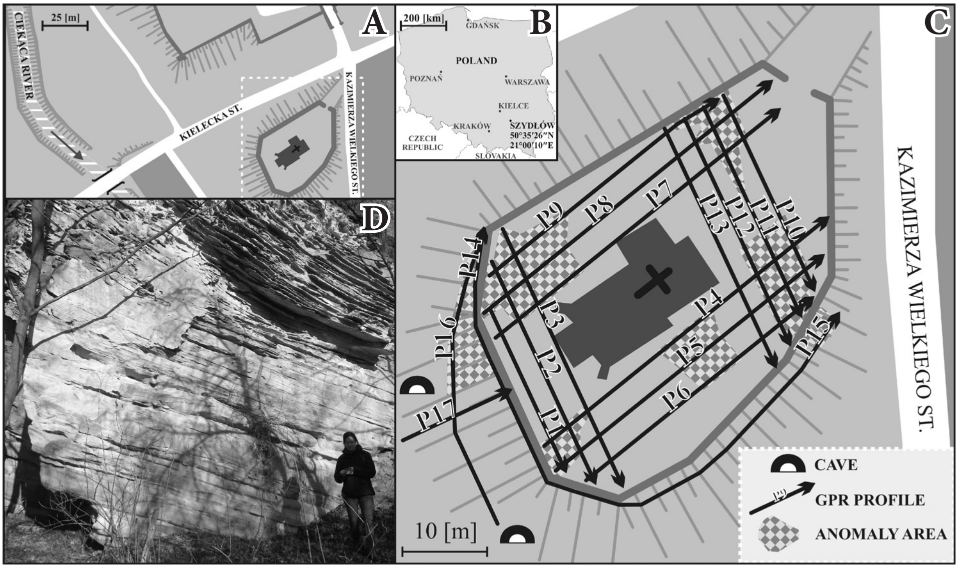

Figure 1. *A* – Schematic plan of the area where measurements took place taking into account the elements mentioned in the text. *B* – Location of the study area on the map of Poland. *C* – A map of the hill along with the GPR measuring profiles system with the anomalies marked. *D* – A general view of the Sarmatian detritial limestone outcrop with a clear stratification of formations and their inclination towards the south. Sedimental stratification was emphasized by the varied resistance to the karsting-weathering processes.

The foot of the described high ground consists of natural outcroppings and walls that remained after the stone resources exploitation (Fig. 1D). The uphill is formed by Sarmatian detritial limestone placed under a thin layer of rendzina soil. There are a few small caves in this rock mass (Komorowski et al., 2006). On the cave ceilings and walls, numerous cracks and karst gaps can be found, which are extending due to the ongoing karst processes. In some of the gaps even tree roots can be seen. In accordance with the data from the 1990's, the studied cave known as Szydło's Cave I is 5 m in length and has a small developing karst chimney. Both, Szydło's Cave I and the neighbouring Szydło's Cave II are characterised, to a certain degree, by anthropogenic widening of the entrance openings and some work done to certain elements of the chambers' walls (Gubała et al., 1998). These caves are currently circa from 5 to 8 m above the level of the small nearby river called Ciekąca (Fig. 1A) (Komorowski et al., 2006). The presence of a watercourse and its erosive activity influences the strength and dynamics of the drainage in the neighbouring rock mass.

Miocene sediments in the area around Szydłów are formed into calcaronites that have a multiscale diagonal stratification creating deposits with thickness of 10-12 meters (Stachacz, 2007). Cross-beddings are inclined towards the south. It is consistent with the course of the Ciekąca River in the vicinity of the described elevation, and the direction of terrain drainage. According to Stachacz (2007), the thickness of the described strata is getting thinner towards the north. Water moving south inside the rock mass following the incline has favourable infiltration conditions. In addition, the infiltration may be facilitated by massive numbers of molluscs remains in these rocks. Their shells are arranged according to cross-bedding and they form allochtonic aggregations. It is worth noticing that the molluscs shells are small and delicate but their surfaces are intact with no visible signs of abrasion (Stachacz, 2007). Not without significance is the fact that calcaronites are mainly composed of sand grains. It is because of them that the formations are not so densely structured. High diversification of detrital limestones in the described area manifests itself by a local slits and sometimes gravel insertions. It leads to a varied resistance of the described sediments to karst processes. Such situation may result in a dynamic emergence of different karst formations (Zieliński, 2013). One of such phenomena was witnessed in 2014 in Szydłów, about a few hundred meters away from the described area of the temple. Under an asphalt road a cavern had formed, which after further development, damaged the waterworks. This collapse resulted in a further enlargement of the formed gap up to a point that a car could fit in it. The water outflowing from the damaged waterworks enlarged the passage, taking the mineral material deeper into the karst gaps. There are more events of such catastrophic character.

3. GPR method

Ground Penetrating Radar (GPR) is a geophysical device mostly used for measurement of the earth crust surface. It uses the phenomenon of electromagnetic wave propagation, which is reflected, refracted, attenuated, and scattered in a geological medium. Due to the nature of the study, antennas operating on relatively low frequencies were used for the geological survey (Reynolds, 1997). In order to conduct the measurements, the authors used Mala Geoscience ProEx GPR with shielded antenna working at the frequency of 250 MHz. The choice of the apparatus parameters was connected with the

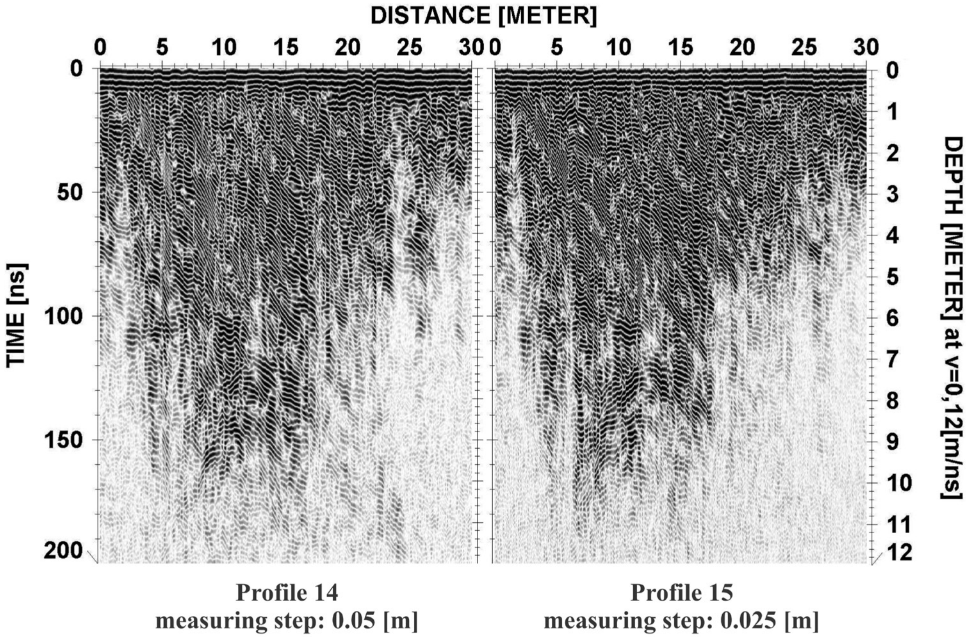

Figure 2. Radargrams fragments from profiles 14 and 15 documenting differences between GPR recoding, depending on the type of the measuring step.

expected penetration depth, satisfactory resolution, and physical properties of the medium. The distance was measured on the basis of the calibrated wheel revolved mechanism. The authors' experience in studying formations of karst origin enabled the optimal choice of the measuring parameters (Łyskowski et al., 2014). It was decided to use a measuring step of 0.05 m in length, eight-fold stacking of one trace, a time window of 355 ns and signal sampling at the level of 2653 MHz for good and proper mapping of analogue signal in conversion process to digital data set. More optimal measuring parameters were considered. The authors made a test profile (P11 and P12, which are the same profile made vice versa) and chose the more proper measuring step. An attempt was made in the study to detect stratification of the rock mass that builds the slope and to do so, the measuring step was decreased from 0.05 m to 0.025 m. Even though the change had no effect on the resolution connected with the antenna's frequency, it resulted in a radargram recorded more clearly (Fig. 2). The GPR-profile contained more useful information, and the image from body generating anomaly (in this case, the cave) was clearer. The whole study here consisted of 17 GPR profiles of total length over 600 m. Their location is shown on a plan (Fig. 1C). Geophysical images obtained by scanning the geological medium with the use of a GPR are called radargrams. They are graphs consisting of series of single traces. The vertical axis represents the double time of electromagnetic wave propagation in the medium. The horizontal axis depicts the distance on the measuring profile (Annan, 2001).

4. Data processing and results

Before the presentation, GPR-profiles undergo processing which involves the increase of the ratio between the usable information and the noise. The authors used ReflexW program. During processing, raw data is processed by mathematical functions. The sequence of filtering began with static corrections, which allowed removal of the surface wave in them, *e.g.* "time cut" function for reduction of time window below the specified value. The next step was to amplify the signal-to-noise ratio by using two filters working on single trace. First, "subtract-DC-shift" calculating the mean value of the trace ("DC-value") for the given time range and subtracting this value from all data values in the echogram. Second, "substract-mean (dewow)" creating within the moving time window (along *Z* axis) a mean value and subtracting the value from the actual data value. Along the processing, the authors used a bandpass frequency filter in the time domain on each trace on radargram, and exponential and linear amplitude amplification. Finally, the radargrams were smoothed by a filter, which stacked traces for random noise removal (ReflexW Manual, 2016). As a result of multiple processing, which the authors carried out independently using a series of similar procedures for a set of GPR-profiles, only the clearest geophysical images after individual processing were chosen for the interpretation.

In order to calculate the depth scale the program made a time-depth conversion on the basis of specified propagation velocity of the electromagnetic wave in the studied medium (Łyskowski and Mazurek, 2013). Due to the lack of technical feasibility of wide angle reflection-refraction profiling (WARR), the authors applied the hyperbola depth fitting method for proper conversion. The ceiling of assumed continuation of the cave was predicted at the depth of 7 to 8 m, in that case the proper velocity value was 0.12 m/ns. That fact was also confirmed by literature. The tabular velocity value for limestone ranks within the 0.09 to 0.15 m/ns range (OYO, 1988; Annan, 2001; Reynolds, 1997).

Figure 3 presents three parallel measuring profiles (P10, P11, P12) in which, at the depth ranging from 3.5 to 6 m, anomalies are shown from 15 r-m. They probably come from loosening or gaps of karst origin. These structures are also visible on a perpendicular, slightly distanced profile (P15). In the P4, P5 and P6 profiles, (Fig. 1C) in the vicinity of the above-mentioned structure, a very distinct anomaly that comes from the reflection above the ground can be seen. It probably partly masks the reflections coming from the underground structures.

Part of the profile P15 (Fig. 3) presents a very good example of recording a layout of stratums in rock mass. At the depth of 7.5 m between 8 and 18 r-m of

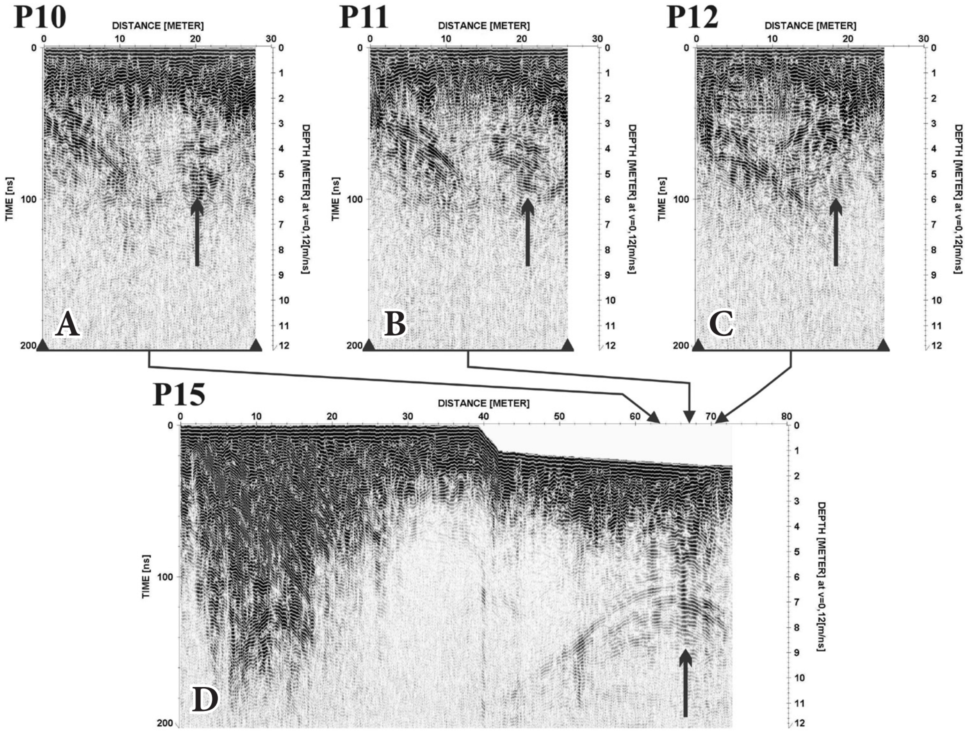

Figure 3. Selected radargrams received as a result of imaging with the use of shielded antenna 250 MHz showing the anomalous areas and forecasting occurrences of voids or loosening in rock mass transformed by the karst processes.

the profile a clear karst cave ceiling can be seen. After a thorough analysis of obtained GPR results, and the dimensions of the known part of the Szydło's Cave I, it was assumed that it is an inaccessible part of the cave. It is essential to mention that the presented part of the GPR profile was recorded with the antenna inclined at an angle of at least 30 degrees. This means that the recorded structures were further from the escarpment, thus further from the entrance to the cave (Fig. 4). This finding is based on the footprint calculation which the authors made. The reflex form a karst object is located at the depth of about 7.5 m.

Using the equation of footprint in the form of $a = (\lambda/4)+[h/(\varepsilon_r-1)^{½}]$, where λ is the wave length, ε_r is the dielectric constant (in this case 6), h is the depth, the a assumed the value of 6.53 m. In that case, shorter and perpendicular b radius is half of that value, so it is equal to 3.265 m. Thus, there is a slight possibility that the registered anomaly is generated by the existing and accessible part of the cave. On the other hand, only a small part of antenna footprint could be reflected from the existing cave. And as the angle grows, that possibility decreases (Annan, 2001).

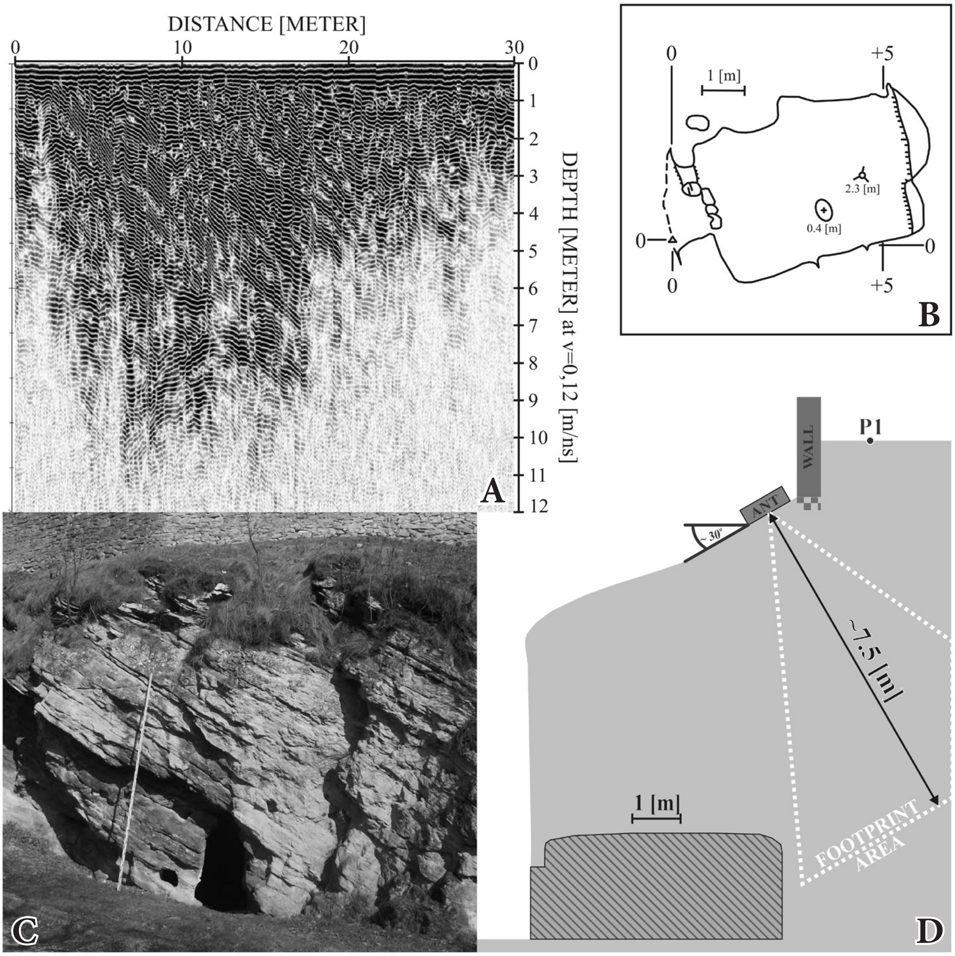

Figure 4. *A* – Radargram fragment from the profile number 15 imaging stratification and cave's ceiling. *B* – Plan of the Szydło's Cave I (Gubała et al., 1998). *C* – Opening entrance of the Szydło's Cave I with a visible stratification of limestone (a 4 m geodesic patch makes it easier to assess the size scale). *D* – Scheme showing the methodology of measuring on escarpment and the way electromagnetic waves spread.

5. Discussion and conclusion

In studies of regions where karst processes occur, a variety of geophysical methods can be applied, starting from electrical resistivity tomography (*e.g.* Epting et al., 2009), gravimetric measurements measuring the change in the intensity of the force of gravity field, ending with the GPR method (*e.g.* Beres et al., 2001). Taking into account the area's characteristics (monument of nature) and terrain conditions (limited space), the chosen method was appropriate.

Non-invasive, rapid, accurate, and high-resolution measurements resulted in receiving outcomes that are of satisfactory quality. The authors managed to locate places where previously unknown gaps of karst origin may be found. In addition, a stratum mapping was recorded, rather difficult to find in literature, which confirms the existence of gravitational loosening of the rock mass near the cave ceilings and walls. When the structure is dense, without gravel intrusions, silt, and loose rock material, a variation of physical properties would not be enough to record the change of amplitude by the GPR system. It should be mentioned that the described part of the rock mass is in an area adjacent to the surface of the slope. This leads to a stronger water drainage through the sediment, thus it results in an increase of the dynamics of the ongoing karst processes in the rocks.

The cave ceiling, which may be a continuation of the accessible part of the cave, was much more accurately imaged. At the same time, the rock mass stratification was more precisely mapped. It is vital to emphasize that stratiform rock structure has not been recorded anywhere else.

The obtained results indicate a large potential of the GPR method in studying phenomena and effects of karst processes which may pose a threat for the anthropogenic objects. Measurement results enabled recording of new structures of karst origin. At the same time it was ascertained that at the current stage of karst development and the retention of these structures at a considerable depth below the surface level, there is no threat for the nearby buildings.

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References

Annan, A. P. (2001): *Ground Penetrating Radar Workshop Notes*. Sensors & Software Inc., Ontario, Canada, 192 pp.

Beres, M., Luetscher, M. and Olivier R. (2001): Integration of ground-penetrating radar and microgravimetric methods to map shallow caves, *J. Appl. Geophys.*, **46**, 249–262, DOI: 10.1016/S0926-9851(01)00042-8.

Chamberlain, A. T., Sellers, W., Proctor, C., Coard R. (2000): Cave detection in limestone using ground penetrating radar, *J. Archaeol. Sci.*, **27**, 957–964, DOI: 10.1006/jasc.1999.0525.

Czapowski G. (1981): Spękania ciosowe w skałach detrytycznych sarmatu południowego obrzeżenia Gór Świętokrzyskich, *Kwartalnik Geologiczny*, **25-I**, 121–130 (in Polish).

Derobert, X. and Abraham, O. (2000): GPR and seismic imaging in a gypsum quarry, *J. Appl. Geophys.*, **45**, 157–169, DOI: 10.1016/S0926-9851(00)00025-2.

Doolittle, J. and Collins, M. E. (1998): A comparison of EM induction and GPR methods in areas of karst, *Geoderma*, **85**, 83–102, DOI: 10.1016/S0016-7061(98)00012-3.

El-Quady, G., Hafez, M., Abdalla, M. A. and Ushijima, K. (2005): Imaging subsurface cavities using geoelectric tomography and ground-penetrating radar, *J. Cave Karst Stud.,* **67**, 174–181.

Epting, J., Huggenberger, P. and Glur, L. (2009): Integrated investigations of karst phenomena in urban environments, *Eng. Geol.*, **109**, 273–289, DOI: 10.1016/j.enggeo.2009.08.013.

Gubała, J., Kasza, A., Urban, J. (1998): *Jaskinie Niecki Nidziańskiej*. Wydawnictwo Polskiego Towarzystwa Przyjaciół Nauk o Ziemi, Warszawa, 173 pp (in Polish).

Komorowski, A., Kasza, A. and Urban, J. (2006): *Dokumentacja i ochrona obiektów podziemnych Szydłowa*. Sekcja Speleologiczna Polskiego Towarzystwa Przyrodników im. M. Kopernika, Materiały 40. Sympozjum Speleologicznego, 43–44 (in Polish).

Kondracki, J. (2002): *Geografia regionalna Polski*. Warszawa, PWN, 441 pp (in Polish).

Łój, M., Gołębiowski, T. and Porzucek, S. (2014): Geophysical surveys and modelling for recognizing of gypsum karst, *Geoinformatica Pol.*, **13**, 83–97, DOI: 10.2478/gein-2014-0009.

Łyskowski, M. and Mazurek, E. (2013): Analysis of the consequences of incorrect choice of the electromagnetic wave propagation velocity in the interpretation of GPR measurements, *Logistyka*, **4**, 330–336, (in Polish).

Łyskowski, M., Mazurek, E. and Ziętek, J., (2014): Ground penerating radar investigation of limestone karst at the Odstrzelona Cave In Kowala, Świętokrzyskie Moutains, Poland, *J. Cave Karst Stud.*, **76**, 184–190, DOI: 10.4311/2014EX0001.

Mazurkiewicz E., Łyskowski M. and Strzępowicz A. (2015): Aplikacja metody GPR do badania dróg na terenach o zwiększonym zagrożeniu deformacjami o genezie krasowej [Application of GPR method for testing roads in areas with a increased risk of karst origin deformations], *Logistyka*, **4**, 9474–9479.

OYO (1988): *OYO Georadar I Manual*. Tsukuba, 50 pp.

Pawłowski, S., Pawłowska, K. and Kubica, B. (1985): Budowa geologiczna tarnobrzeskiego złoża siarki rodzimej, *Prace Państwowego Instytutu Geologicznego*, **114**, 109 (in Polish).

ReflexW Manual (2016): *User Guide*. SandmeierGeo, Karlsruhe, Germany, 642 pp.

Reynolds, J. M. (1997): *An Introduction to Applied and Environmental Geophysics*. John Wiley & Sons Ltd., England, 682–749.

Rutkowski, J. (1986): Budowa geologiczna Niecki Nidziańskiej, *Studia Ośrodka Dokumentacji Fizjograficznej*, **14**, 35–61 (in Polish).

Stachacz, M. (2007): Remarks on age of the Middle Miocene deposits in the Szydłów area (southern margin of the Holy Cross Mountains), *Przegląd Geologiczny*, **55**, 168–174.

Walczowski, A. (1968): *Objaśnienia do Szczegółowej mapy geologicznej Polski 1:50.000, arkusz Staszów*. Wydawnictwa Geologiczne. Warszawa, 72 pp (in Polish).

Walsh, P. and Morawiecka-Zacharz, I. (2001): A dissolution pipe paleokarst of mid-Pleistocene age preserved in Miocene limestones near Staszów, Poland, *Palaeogeogr. Palaeocl.*, **174**, 327–350, DOI: 10.1016/S0031-0182(01)00317-0.

Zieliński, A. (2013): *Rozwój jezior krasowych w Niecce Połanieckiej*. Wydawnictwo UJK, Kielce, 186 pp (in Polish).

SAŽETAK

Kartiranje krških formacija ispod povijesne zgrade u Szydłówu u Poljskoj pomoću georadara

Artur Zieliński, Ewelina Mazurkiewicz i Mikołaj Łyskowski

Brdski pojas u srednjoj Poljskoj veliko je područje u kojem prevladavaju karbonatne i sulfatne stijene. U nekim su dijelovima ove procesi okršavanja dinamičkog karaktera. Proučavan je teren oko povijesne crkve u Szydłówu. Građevina se nalazi na brdu koje je formirano procesima karstifikacije klastičnih vapnenaca sarmata. U podnožju brda ima nekoliko malih špilja. Karakteristične geološke strukture i transformacije terena koje su posljedica karstifikacije potaknule su autore da provedu istraživanja georadarom. Cilj je ove studije verificirati postojanje špilja i u prostoru oko spomenika. Napravljena je analiza rizika oštećenja spomenika krškim procesima. Mjerenjima georadarom dobijeni su dobri rezultati koji potvrđuju postojanje do sada nepoznatih šupljina i oslabljenih stijenskih struktura. Prema zabilježenim radarogramima autori su potvrdili da dolazi do gravitacijskig slabljenja stijenske mase u blizini stropa i zidova špilja. Rezultati dokazuju da je georadar prikladan instrument za kartiranje nekih krških struktura i procjenu stabilnosti stijena.

Ključne riječi: georadar (GPR), krš, vapnenac, špilje, Szydłów, pobrđe Kielca

Corresponding author's address: Mikołaj Łyskowski, AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, A. Mickiewicza 30 Ave., 30-059 Krakow, Poland; tel: +48 12 6174 464; e-mail: lyskowski.m@gmail.com