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FEASIBILITY ANALYSIS OF USING GPR METHOD FOR THE EXAMINATION OF POST-GLACIAL DEPOSITS IN MOUNTAINOUS GEOLOGICAL ENVIRONMENT

Analiza możliwości użycia metody GPR do badania utworów postglacjalnych w rejonach górskich

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Abstract: The Ground Penetrating Radar (GPR) measurements presented in this paper had two main objectives. The first was to analize the possibility of using GPR method in examination of sediments in a mountainous geological environment and the second objective was to assess the special distribution of post-glacial sediments and their thickness at a selected site. The experimental measurements were carried out on in the alp of Ornak in the western part of Tatra Mountains This article provides a brief theoretical analysis of possible use of the georadar method in post-glacial sediment examination. The results of GPR surveys done in the reflection profiling mode enable the distinction of zones with different amount of till, clay, sand, gravel and rock debris in the post-glacial sediments.

Key words: Ground Penetrating Radar, post-glacial sediments, Quaternary deposits

Treść: Badania GPR prezentowane w artykule miały dwa cele: pierwszym było określenie możliwości zastosowania metody GPR do badania utworów osadowych w górskich warunkach geologicznych, a drugim – określenie przestrzennego rozkładu i miąższości utworów postglacjalnych w wybranym miejscu w górach. Badania eksperymentalne przeprowadzono na hali Ornak we wschodniej część Tatr. W artykule zamieszczono krótką dyskusję teoretyczną na temat możliwości zastosowania metody georadarowej do badania osadów postglacjalnych. Zaprezentowane w artykule wyniki badań GPR wykonanych w technice refleksyjnej pozwoliły na wyróżnienie w osadach postglacjalnych stref z różnym nagromadzeniem glin, piasków, żwirów oraz odłamków skalnych.

Słowa kluczowe: GPR, utwory postglacjalne, osady czwartorzędowe

INTRODUCTION

Ground Penetrating Radar (GPR) is a non-destructive, geophysical method, which uses electromagnetic waves ranging from 10 MHz to a few gigaherz to examine geological media. This method has many different applications in: geology, hydrogeology, glaciology, geotechnics, mining, archeology, examination of buildings and underground structures, military and forensic investigations, localization and monitoring of underground infrastructure, contamination detection, ground testing in agriculture and many others.

As stated previously, despite the fact that GPR method has many applications it was rarely used in mountainous geological conditions, which is why such an approach was undertaken in this paper. The first objective was to analyze the possibility of using GPR method for sediment examination and the second was the assess the Quaternary post-glacial sediments distribution in a selected mountain site. The experimental measurements were carried out on the alp of Ornak (western part of the Tatra Mountains).

Our GPR measurements in this region supplement Kenig & Lindner's (2001) laboratory investigations of post-glacial sediments, taken from three boreholes within the Ornak alp. Our GPR surveys were conducted near one of these boreholes, named "Ornak-K", and the results of the geophysical measurements provided additional information about sediment distribution in the investigation area, especially at greater depths.

Kenig & Lindner's results (2001) indicate that the thickness of the investigated deposits is highly variable. The thickness of sediments in three different boreholes varied from 2 m to almost 8 m (borehole: "Ornak-K"). The authors reported that in the upper part of Koscieliska Valley, where the alp of Ornak is located, three layers of moraine deposits, separated by sediments of various fractions exist. The bottom part of this structure is mainly composed of coarse and middle-grained gravel fraction, crystalline rocks, small proportion of sand fraction, and a few percent clay fraction. However, Kenig & Lindner (2001) do not explicitly state that their drilling penetrated the full thickness of the sediment and reached the bedrock.

GPR MEASUREMENTS AND INTERPRETATION

GPR surveys were conducted along three profiles, in the central part of the alp of Ornak (Fig. 1). Recordings (i.e. traces) in on all profiles were collected every 0.25 m and stacking was used 32 times during data acquisition for better signal/noise ratio. Measurements, in mode of constant-offset reflection profiling (Fig. 2), were carried out using RAMAC/GPR georadar system of the Swedish firm of MALA Geoscience.

The results of GPR reflection measurements depend mainly on contrasts of the dielectric constants ε_r [–] between different geological media. It can be described by the reflection coefficient formula (1).

$$R^* = \frac{\sqrt{\varepsilon^*_{r1}} - \sqrt{\varepsilon^*_{r2}}}{\sqrt{\varepsilon^*_{r1}} + \sqrt{\varepsilon^*_{r2}}} \tag{1}$$

where:

$$\varepsilon^*_r = \varepsilon_r - \frac{i\sigma}{\omega\varepsilon_0} \tag{2}$$

R^* – complex reflection coefficient [–],
ε^*_{r1}, ε^*_{r2} – relative complex dielectric constants for two adjoining geological media or for anomaly and surrounding medium [–],
σ – electrical conductivity [S/m],
ε_0 – dielectric constant in vacuum [F/m],
ω – angular frequency [Hz].

Reflection coefficient R^* delivers information of what fraction of electromagnetic wave energy is reflected from the boundary between two layers which are characterized by different complex dielectric constants. Reflexes from boundary or anomaly body can be recorded by measurement set (Fig. 2) when the value of reflection coefficient is sufficient. Different values of ε_r between crystal basement (i.e. Tatra granite) and Quaternary post-glacial sediments (Tab. 1) should make a good reflector boundary. Additionally, rock debris inserted in the deposits should be clearly visible on the GPR recordings (named radargrams) and this effect might be helpful for outlining of different parts of the post-glacial sediments.

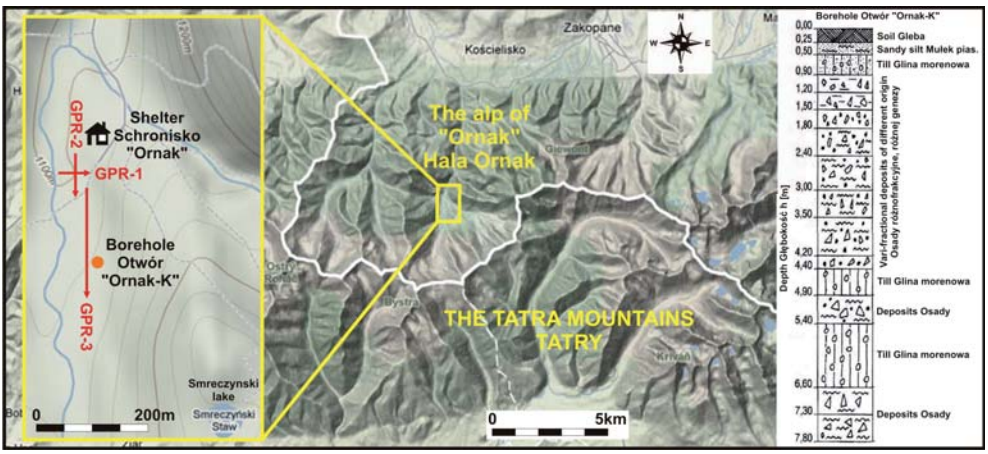

Fig. 1. GPR measurements site and project of preliminary georadar surveys in the alp of Ornak and information from the borehole "Ornak-K" (Kenig & Lindner 2001)

Fig. 1. Miejsce badań GPR i projekt wstępnych badań georadarowych na hali Ornak oraz informacje z otworu „Ornak-K" (Kenig & Lindner 2001)

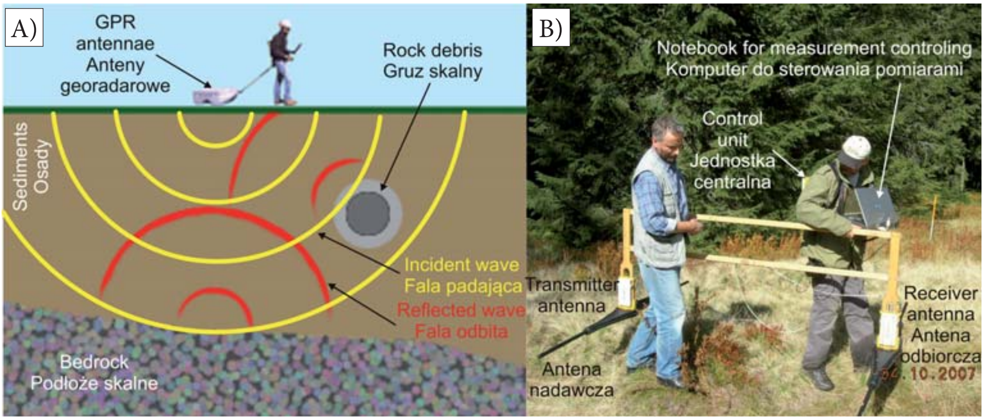

Fig. 2. GPR reflection measurements (MALA 2009) (A); GPR surveys on alp of Ornak using of 50 MHz antennae (B)

Fig. 2. Idea refleksyjnych pomiarów GPR (MALA 2009); badania GPR na hali Ornak z użyciem anten 50 MHz (B)

Table (Tabela) 1
Electromagnetic properties of examined geological media (Annan 2001)
Parametry elektromagnetyczne badanych utworów geologicznych (Annan 2001)

Geological media *Ośrodek geologiczny*	Relative dielectric constant *Względna stała dielektryczna* ε_r [–]	Electrical conductivity *Przewodnictwo elektryczne* *s* [mS/m]
Granite (solid – fractured) *Granit (lity – zeszczelinowany)*	4–6	0.01–1
Till, clay (dry – wet) *Gliny morenowe, glina (suchy – mokry)*	4–40	2–1000
Sediment (averaged values for mixture of sands, gravels, clays, tills) *Osady (uśrednione wartości dla mieszaniny piasków, żwirów, glin)*	4–30	0.1–10

Depth penetration of electromagnetic waves is a different problem. General dependence between depth penetration, signal amplitude and wave frequency is as follows:

$$A(z) = A_0 e^{-k'' z} e^{i(\omega t - k' z)} \tag{3}$$

where:

$A(z)$ – signal amplitude at depth z,
A_0 – signal amplitude in source,
t – time,
k' – propagation coefficient.

In the formula (3) k'' denotes the attenuation coefficient, described as follows

$$k' = \sqrt{\mu\varepsilon} \cdot \omega \sqrt{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]} \tag{4}$$

It can be noted that k'' depends mainly on electrical conductivity (σ) and wave frequency (ω). When the electrical conductivity of a medium and wave frequency increases, the attenuation coefficient also increases and the depth penetration decreases. Therefore, for results (reflexes) at great depths, GPR measurements should be carried out with relatively a small frequency, i.e. from range 10–50 MHz.

The predicted thickness of the Quaternary deposits at the investigation site should be at least 8 m (Kenig & Lindner 2001) therefore, for this project antennas with a frequency of 50 MHz was used (Fig. 2B). These antennas give a good compromise between depth penetration and resolution. The maximum. depth penetration for 50 MHz antennas in the investigated medium is expected to be 15–20 m and their mean resolution is 0.5 m. Antennas with such parameters seemed adequate for finding the boundary between sediments and bedrock located at a depth of a dozen or so metres and for recording reflexes from pieces of rock debris located in the post-glacial deposits.

Lack of precipitation onsite for a long period during the GPR measurements allowed us to record reflexes at great depths, even though the geological medium in this site was partly built of tills and clays with a relatively high value of electrical conductivity (Tab. 1), and high attenuation.

The results of terrain surveys were processed digitally using ReflexW software from the German firm SandeierGeo. The following procedures were applied (ReflexW Manual 2009): amplitude declipping, interpolation in x, y and z directions, subtraction of mean trace, DC shift, gain function, background removal, Butterworth filter, smoothing, amplitude threshold adjustment, stacking.

All radargrams were presented in the form of energy distribution, because there is a direct relationship between signal energy and the reflection coefficient. Additionally, energy distribution allowed for better visualization of the analysed anomalies. GPR energy signals were calculated by counting signals envelopes using Hilbert transformation (Annan 2001). Afterwards, radargrams in the form of energy decays were processed with morphological filters and 2D smoothing where averaging filters were applied (ReflexW Manual 2009).

The radargrams were presented with normalization up to maximum amplitude of a direct air wave. Presentation in such form allows the comparison of recordings directly between profiles without the necessity for a detailed color scale. Violet and red colors depict the regions with the highest values of energies, yellow and green colors show regions with the mean energy values and regions with the lowest energies are presented in blue.

The mean velocity v_{mean} = 0.08 m/ns was used for time-depth conversion of the vertical axis. Such a velocity is typical for deposits with changeable amount of clays, tills, sands, gravels and rock debris.

Figures 3 and 4 present the measurement results (i.e. radargrams) for adequate profiles. In these figures a white dashed line indicates different anomalous zones.

Since the tills and clays possess a high value of electrical conductivity (Tab. 1), which influences GPR signal attenuation, the regions rich in such media should be correlated in the radargrams with regions of the lowest signal energies (blue color).

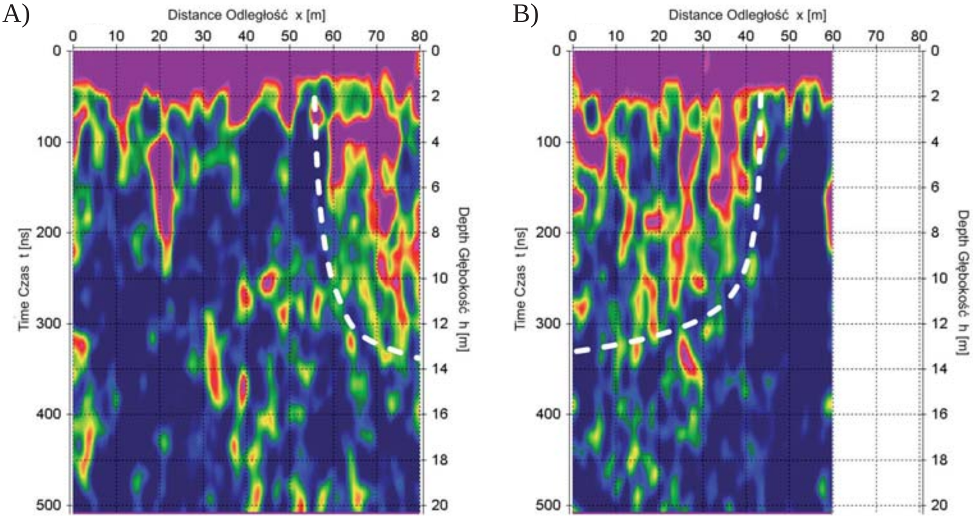

Fig. 3. Radargram for profile GPR-2 (A); radargram for profile GPR-1 (B)

Fig. 3. Echogram dla profilu GPR-2 (A); echogram dla profilu GPR-1 (B)

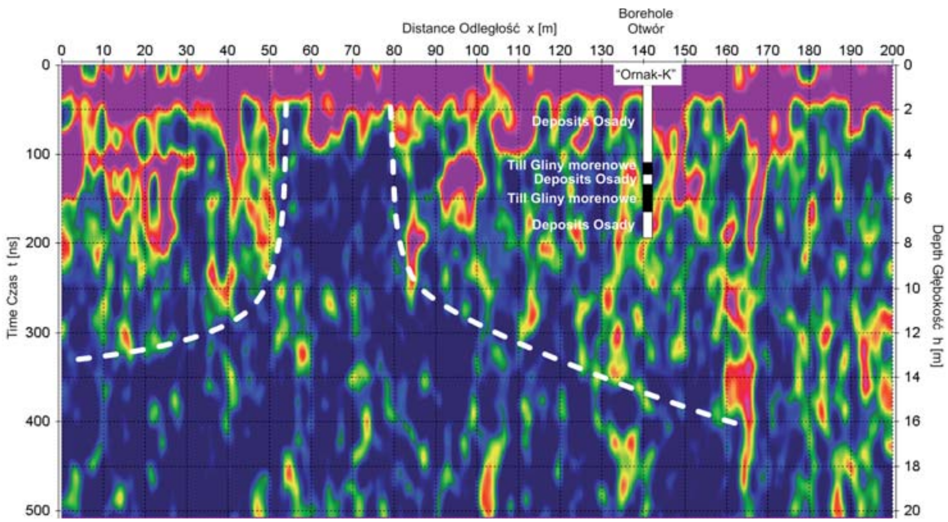

Fig. 4. Radargram for profile GPR-3

Fig. 4. Echogram dla profilu GPR-3

Sediments with great amount of sands, gravels and rock debris have low attenuation values, so GPR recordings for such media will be presented in radargrams in red and violet (i.e. regions with the highest energies).

Considering information from borehole "Ornak-K" (Fig. 1) in the investigated geological medium, randomly distributed sands, gravels and rock debris in post-glacial deposits should be expected and therefore the radargrams distribution should also be stochastical. Random distribution of the recorded reflexes (energies) is easily visible in Figures 3 and 4. Based on the characteristic energy features described above zones with great amounts of tills and clays as well as zones with great amount of sands, gravels and rock debris in sediments may easily be separated (Figs 3, 4 – white line)

It should be mentioned that despite the fact that Kenig & Lindner (2001) reported the depth of "Ornak-K" borehole to be around 8 m they did not state that it completely penetrated the Quaternary sediments and reached the bedrock. In such situation the results of the preliminary GPR surveys presented in the paper show that the sediments thickness in this site should be over 8m, which was confirmed by the energy distribution for greater depths (Figs 3, 4).

Neither the boreholes data presented in Kenig & Lindner's (2001) paper nor the results of preliminary GPR surveys provide the location of bedrock in the alp of Ornak as well as any detailed and spatial information about post-glacial deposits distribution. To obtain such information three-dimensional (3D) GPR measurements should be performed using antennas with lower frequency (e.g. 10 MHz or 25 MHz) and with deeper penetration. In anomalous zones interpreted from 3D GPR measurements additional boreholes should be drilled for complex geological-geophysical interpretation.

CONCLUSIONS

As was presented in the paper the GPR method seems to be a useful tool for examination of post-glacial sediments in a mountainous geological environment. The only limitation of the GPR method is depth penetration of electromagnetic waves. As was discussed depth penetration is strongly dependent on the amount of clay minerals in the geological medium.

Preliminary results of borehole measurements and 2D GPR surveys are very promising though it is difficult to draw definite conclusions on the basis of only three shallow boreholes and three preliminary GPR profiles. For quantative interpretation both 3D GPR measurements and additional boreholes are, necessary; however, our preliminary results suggest that the thickness of post-glacial sediments in the alp of Ornak is more than 8 m.

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