# GROUND-PENETRATING RADAR METHOD APPLIED TO HYDROGEOLOGICAL SUBSURFACE CHARACTERIZATION

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## ABSTRACT:

This paper investigates the application of the Ground-Penetrating Radar (GPR) method for hydrogeological characterization of the subsurface, with a focus on investigations conducted at a dimension stone surface quarry in the settlement of Čelina (Republic of Croatia). GPR represents an efficient and non-invasive geophysical technique that enables high-resolution imaging of subsurface structures based on the reflection of electromagnetic waves at the boundaries of layers with contrasting dielectric properties. Data analysis confirmed the presence of active aquifer zones, including surface accumulations and artesian discharges, indicating a pronounced hydrogeological influence on the formation and dynamics of subsurface water flows. GPR profiles revealed changes in lithological composition, the presence of discontinuities, and fault zones that facilitate vertical infiltration and lateral groundwater movement. The results demonstrate the potential of the GPR method for rapid and reliable identification of subsurface watercourses, delineation of lithological unit boundaries, and assessment of hydrogeological conditions at the investigated site. Nevertheless, the interpretation of GPR data requires careful consideration of local geological factors and, in most cases, integration with other geophysical and hydrogeological methods to ensure more reliable conclusions.

## KEYWORDS:

ground-penetrating radar, geophysical investigations, dielectric constant, signal reflection, non-invasive methods, data interpretation, radargram.

## 1 INTRODUCTION

The ground-penetrating radar (GPR) method is a non-invasive geophysical technique used for investigating subsurface structures through the transmission and reflection of high-frequency electromagnetic waves [1–3]. Initially developed in the early 20th century, the method underwent significant technological advancements during the 1980s with improvements in data acquisition instruments and processing techniques [4]. Today, GPR is widely applied across various disciplines, including geology, hydrogeology, archaeology, and civil engineering [5,6].

Hydrogeological characterization of the subsurface is essential for understanding groundwater dynamics, identifying aquifers, and evaluating the permeability of rock materials. GPR enables high-resolution imaging of subsurface features based on the reflection of electromagnetic waves at interfaces between layers with contrasting dielectric properties [7]. This approach allows for the detection of changes in soil moisture, identification of groundwater flow paths, and analysis of geological formations that directly influence the hydrogeological behaviour of a site [8].

The investigations presented in this paper were conducted in the settlement of Čelina, municipality of Sirač, Bjelovar-Bilogora County, Republic of Croatia [9], within the exploitation field of a surface quarry for dimension stone. This natural construction material of mineral origin is obtained through the processing of sedimentary, igneous, or metamorphic rocks and is widely used in both construction and industrial applications [10–13]. Previous hydrogeological studies indicated the presence of active aquifer zones, including surface water accumulations and artesian discharges from earlier exploratory boreholes [14].

A particular challenge in this study was the geological complexity of the terrain, influenced by the heterogeneous structure of carbonate formations and the presence of groundwater, both of which significantly affect electromagnetic wave propagation. Previous research has demonstrated that GPR can be effectively used for identifying hydrogeological structures, with the ability to accurately analyse moist zones and their dielectric properties [15]. The use of high-frequency antennas, coupled with advanced data processing techniques, enhances the differentiation of subsurface layers, thereby improving the understanding of permeability and the lithological composition of carbonate rocks [16].

Figure 1 shows a panoramic view of the southern part of the investigation plateau at an elevation of +208 m a.s.l., where surface water accumulations are visible, initially suggesting the presence of subsurface water inflow.

Figure 1: Panoramic view of the plateau section where seismic investigations were conducted [14]

## 2 METHODOLOGY

The Ground-Penetrating Radar (GPR) method is a non-invasive geophysical technique used for investigating subsurface structures by means of high-frequency electromagnetic waves [17,18]. The operating principle of GPR is based on the emission of short electromagnetic pulses into the ground, which are then reflected and attenuated as a result of interactions with materials possessing different electromagnetic properties [19].

A typical GPR system consists of several key components that work together to enable efficient data acquisition and subsurface interpretation. The core element of the system is the control unit, which is usually battery-powered to ensure mobility and independence during fieldwork [20]. Antennas are connected to the control unit via specialized cables designed to optimize signal transmission and reception due to their specific electrical characteristics [21].

The antennas serve a dual function: they transmit electromagnetic pulses into the subsurface [2] and simultaneously detect the reflected signals that arise at the interfaces between subsurface layers with contrasting dielectric properties. Figure 2 shows a typical GPR antenna during signal transmission and reception [22].

The propagation velocity of electromagnetic waves in the ground depends on the dielectric constant of the material through which they travel [24]. The penetration depth of electromagnetic waves in GPR surveys depends on the antenna frequency and the properties of the materials the signal traverses. The approximate penetration depth of the electromagnetic signal can be estimated using the following expression [8]:

$$d = \frac{v}{2f\sqrt{\pi}} \qquad (1)$$

where:

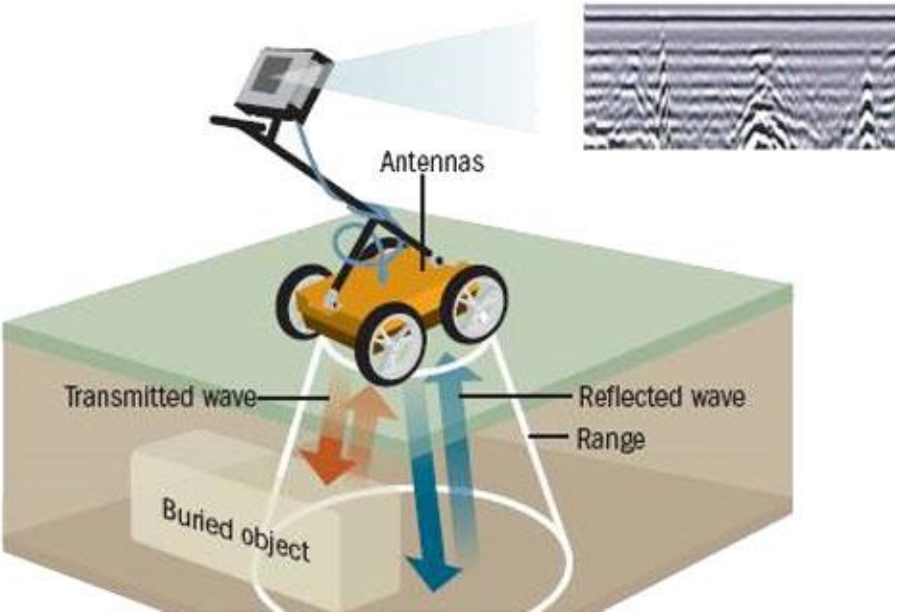

Figure 2: Illustration of the main components and operation principle of the ground-penetrating radar system [23].

*d* – penetration depth,

*f* – antenna frequency,

*v* – velocity of the electromagnetic wave in the medium.

The velocity decreases as the dielectric constant increases, which is expressed by the following mathematical relation [25]:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{2}$$

where:

*v* – wave velocity in the material,

*c* – speed of light (~30 cm/ns),

$\varepsilon_r$ – relative dielectric permittivity of the soil [5].

The dielectric constant is one of the key parameters in GPR investigations, as it directly affects the propagation velocity of electromagnetic waves, the reflection intensity at boundaries between different materials, as well as the vertical and horizontal resolution of the imaging [26].

Changes in the electrical conductivity of the medium lead to increased wave absorption, while variations in permittivity influence the electromagnetic impedance, which directly determines the strength of the reflected signal and the penetration depth through subsurface layers [27].

Water, due to its very high dielectric constant (around 81), significantly contributes to the attenuation of electromagnetic pulses and limits the effective range of the GPR method.

Increased moisture content in the soil causes a rise in the dielectric constant, resulting in a decrease in wave propagation velocity and increased attenuation [28,29].

Conversely, dry sand and most rocks have significantly lower dielectric constant values (e.g., dry sand ranges between 3 and 5), allowing deeper penetration of the electromagnetic signal with minimal energy loss [30].

Table 1 shows typical values of selected electromagnetic parameters of materials at an antenna frequency of 100 MHz. For example, the average wave velocity in limestone is approximately 0,12 m/ns, while in freshwater it is much lower - around 0,033 m/ns - illustrating a pronounced contrast in propagation velocities [31].

Table 1: Typical values of dielectric constants (ε), electrical conductivity (G), electromagnetic wave velocities (cm), and attenuation coefficients (α) for selected materials at 100 MHz [32].

| Material | ε | G [mS/m] | Cm [m/ns] | α [dB/m] |
|---|---|---|---|---|
| Air | 1 | 0 | 0,3 | 0 |
| Distilled water | 81 | 0,01 | 0,033 | 0,002 |
| Freshwater | 81 | 0,5 | 0,033 | 0,1 |
| Seawater | 80 | 30 000 | 0,01 | 1000 |
| Dry sand | 3 – 5 | 0,001 | 0,15 | 0,01 |
| Saturated sand | 20 – 30 | 0,1 – 1 | 0,06 | 0,03 – 0,3 |
| Shale | 5 – 15 | 1 – 100 | 0,09 | 1 – 100 |
| Dust | 5 – 30 | 1 – 100 | 0,07 | 1 – 100 |
| Clay | 5 – 40 | 2 - 1000 | 0,06 | 1 – 300 |
| Granite | 4 – 6 | 0,01 - 1 | 0,13 | 0,01 – 1 |
| Dry salt | 5 – 6 | 0,01 - 1 | 0,13 | 0,01 – 1 |
| Limestone | 4 – 8 | 0,5 – 2 | 0,12 | 0,4 – 1 |
| Ice | 3 - 4 | 0,01 | 0,16 | 0,01 |

Table 2: Dependence of electromagnetic wave penetration depth on frequency [33].

| Frequency [MHz] | Penetration Depth [m] | Size of Detected Object [m] | Application |
|---|---|---|---|
| 1600 | 0,5 | 0,05 | concrete quality assessment and reinforcement detection |
| 900 | 1 | 0,1 | detection of buried utilities, pipes, and voids |
| 400 | 4 | 0,4 | engineering and environmental protection (detection of underground tanks, assessment of pavement and embankment conditions) |
| 270 | 6 | 0,6 | engineering and geotechnics (detection of installations, geological and archaeological investigations) |
| 200 | 7 | 0,7 | geotechnics, construction, environmental engineering |
| 100 | 20 | 2 | geotechnics, environmental engineering, blasting |
| 16 – 18 | 35 – 50 | 3,5 – 5 | geotechnics |

Higher frequencies of the ground-penetrating radar (GPR) signal provide better resolution but have a shallower penetration depth due to stronger attenuation, whereas lower frequencies penetrate deeper with reduced resolution. The relationship between these parameters is shown in Table 2.

The results of the ground-penetrating radar surveys are presented as radargrams, where the horizontal axis represents the distance along the survey profile, and the vertical axis indicates the travel time of the electromagnetic wave, which can be converted to depth [34]. The presence of hyperbolic reflections on the radargram indicates anomalies within the subsurface, which may exhibit various shapes and characteristics (see Figure 3) [31].

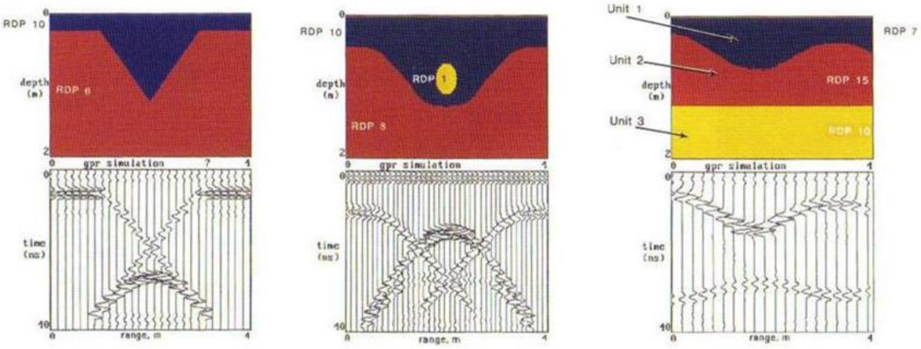

Figure 3: Various forms of subsurface anomalies observed in the soil [31].

## 3 RESULTS AND DISCUSSION

Ground Penetrating Radar (GPR) surveys were conducted at the technical stone open-pit quarry located on the southern edge of the Čelina excavation field – southern section. Within the study, five GPR profiles (GPR-1 through GPR-5) were established, all at an elevation of +208 meters above sea level. The profiles were arranged along five lines, with two longer profiles oriented in the north-south direction and three shorter profiles positioned transversely in the east-west direction. Conducting all profiles at the same elevation enabled a consistent analysis of the collected data and an accurate assessment of the hydrogeological conditions of the site. The spatial layout of the GPR profiles is shown in Figure 4.

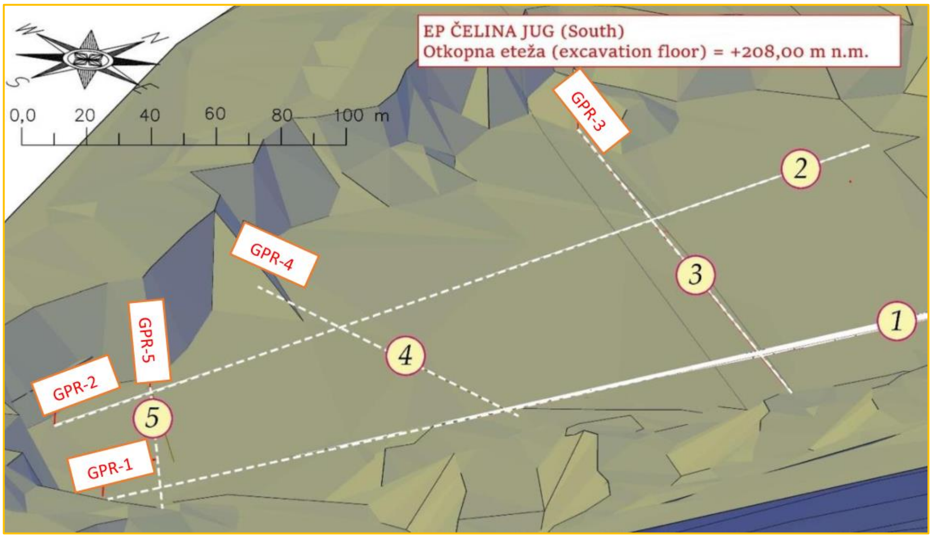

Figure 4: Location of the ground penetrating radar profiles within the investigation area [14]

The survey results are presented through the GPR profiles GPR-2 and GPR-3, which serve as representative examples in the following analysis (Figures 5a, 5b, and 6).

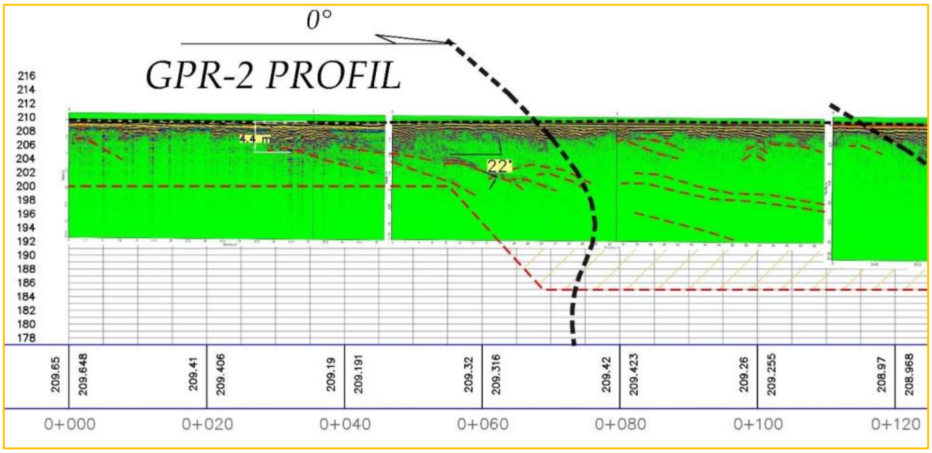

Figure 5a: GPR-2 profile, from station 0+000 to 0+120 m [14]

The GPR-2 profile extends from station 0+000 to 0+220 m, where significant reflections at various depths were recorded, potentially indicating the presence of groundwater or changes in geological layers. In the initial section of the profile (0+020 to 0+050 m), shallow reflections are observed, suggesting the existence of thin layers with increased moisture content. These reflections may represent localized infiltration zones, where water percolates through porous materials.

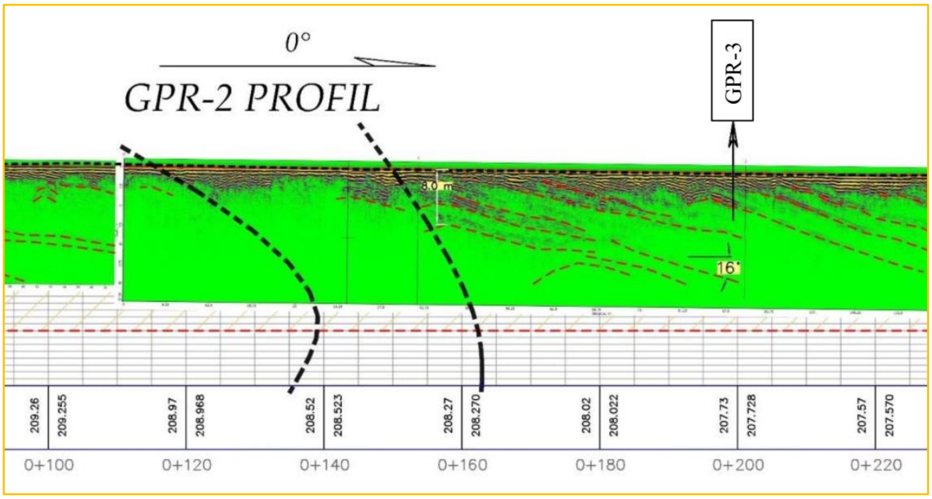

Figure 5b: GPR-2 profile, from station 0+120 to 0+220 m [14]

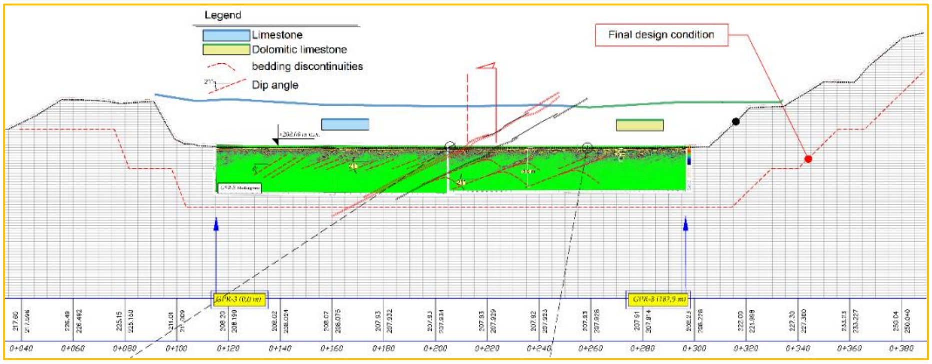

Figure 6: GPR-3 profile with a length of 182.90 m [14]

The central part of the profile (0+100 to 0+160 m) is characterized by more pronounced reflections at depths ranging approximately from 2 to 8 meters, which can be attributed to the boundary between dolomite and stratified clastic sediments. Such boundaries act as potential barriers directing the horizontal flow of groundwater. Deeper reflections within this segment indicate the presence of saturated zones, correlating with previously identified faults.

In the final section of the profile (0+180 to 0+220 m), discontinuities in reflections appear, which may be interpreted as zones of fractures or faults.

Similar anomalies, expressed as layered discontinuities or faults, were also identified in the GPR-3 profile in the segment from 0+200 to 0+260 m. These zones often serve as preferential pathways for subsurface flows, especially within carbonate rocks. Figure 6 also depicts the geometry of excavation benches, defined according to the final mining excavation profile. The assumption of a fault contact on the southern part of the deposit, presented in the mining project, is supported by the absence of the dolomite roof in that area.

Based on the obtained results, it can be concluded that the ground penetrating radar method enables effective identification of underground water flows, delineation of layer boundaries, and analysis of hydrogeological conditions in the field. However, interpretation of these data requires careful consideration of geological and hydrogeological factors that may influence the accuracy of the results.

## 4 CONCLUSION

The ground penetrating radar (GPR) method has proven to be an effective tool for the hydrogeological characterization of the terrain, enabling detailed imaging of subsurface structures and identification of active groundwater flows. The investigation conducted at the technical stone surface quarry in the settlement of Čelina confirmed the capability of GPR to accurately detect layer boundaries, faults, and zones of water infiltration. These findings are consistent with the results of Minghe Zhang et al. [35], who demonstrated that GPR can be useful for analysing water dynamics in the vadose zone.

The methodological approach, which included the use of high-frequency antennas and the analysis of reflected electromagnetic waves, allowed for differentiation of hydrogeological structures and a better understanding of the permeability of carbonate formations. J. Tronicke et al. [36] confirm that ground penetrating radar tomography can be used for precise delineation of hydrostratigraphic units, which is highly valuable in groundwater studies.

The results revealed discontinuities in reflections, suggesting the presence of fractures or faults favourable for subsurface flows, thereby confirming previous hydrogeological assumptions about the study area. These characteristics are crucial for the planning of mineral resource exploitation and groundwater protection, as emphasized in [37], who highlights the importance of hydrogeological investigations for the conservation of water resources.

Although the GPR method provides a rapid and non-invasive means of investigating subsurface features, data interpretation requires careful consideration of geological and hydrogeological factors. The Hydrogeology Journal [38] stresses that further research in this field is necessary for the development of more accurate models of groundwater flow. It was established that water, due to its high dielectric constant, significantly affects the attenuation of electromagnetic signals, which may limit the penetration depth of waves; however, proper data interpretation can help overcome this challenge.

These findings underscore the significance of GPR in modern geophysical investigations and confirm its application in groundwater analysis, identification of geological anomalies, and optimization of mineral resource exploitation. Integration of georadar data with other geophysical methods can further enhance the understanding of hydrogeological conditions in this and similar areas.

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