DETECTING KARSTIC ZONES DURING HIGHWAY CONSTRUCTION USING GROUND-PENETRATING RADAR

MATEVŽ U. PAVLIČ and BLAŽ PRAZNIK

about the authors

corresponding author
Matevž U. Pavlič
Building and Civil Engineering Institute ZRMK d.o.o.
Dimičeva 12, 1000 Ljubljana, Slovenia
E-mail: matevz.pavlic@gi-zrmk.si

Blaž Praznik
Building and Civil Engineering Institute ZRMK d.o.o.
Dimičeva 12, 1000 Ljubljana, Slovenia
E-mail: blaz.praznik@gi-zrmk.si

Abstract

Ground-penetrating radar (GPR) has been applied to determine the subsurface karstic features during the construction of the national highway in the south-eastern part of Slovenia. The highway construction is situated mostly in the dinaric karstic region with a high density of karstic features visible on the surface. Ground-penetrating radar prospecting was done in all areas where a slope was cut into the limestone bedrock. The main purpose of the survey was to map potentially hazardous zones in the highway subsurface and to detect and characterize the karst. The ground-penetrating radar method was used because of the heterogeneous nature of the karst. With its high degree of karsticifaction and geological diversity all conventional methods failed. One of GPR's main advantages is that, while the penetration depth is limited to several meters, the obtained resolution can be on the scale of centimeters and the measured profile is continuous. Because of the ground-penetrating radar's limitations with respect to depth, the range surveying was done simultaneously with the road construction using 200-MHz bistatic antenna on the level of the highway plane. All the 2D radargrams were constructed in 3D models where the measurements were made in raster with 2 meters between a single GPR profile. This two-meters spacing was determined as the optimal value in which only a minimal resolution-price tradeoff was made. The gathered results were tested and compared to experimental drillings and excavations so that any anomalies and reflections were calibrated.

The drilling was conducted twice, first to calibrate the radargram reflections and secondly to check and confirm the calibration success. Altogether, over 30 boreholes were drilled at various previously selected locations. The data obtained from the drilling proved to be very helpful with the calibration since anomalies found during the drilling were almost exclusively (over 95%) a result of the propagation of radar waves from the limestone to an air void or from the limestone to a clay pocket.

Drilling test boreholes proved to be a very useful tool for the calibration of the GPR anomalies recorded in 2D radargrams. Such a process showed a near 100 % accuracy with respect to interpreting the subsurface features, with 77% correctly interpreted as caves or clay pockets and 23% wrongly interpreted, where the interpretation was a void but it was indeed partly a clay-filled and partly an air-filled void. The completed survey also showed simultaneous surveying with GPR and road construction is a very efficient and economical way to predict various karstic features and the density of the karstic forms.

keywords

karst, ground-penetrating radar, geotechnics, cavities detection

1 INTRODUCTION

More than half of Slovenia is karst. With the construction of the national highway, a lot of stability problems emerged where constructions was being made on the karstic surface. In previous years a collapse of the highway's structure has occurred because of cavities under the surface of the road. A large hole emerged in the middle of the fast lane, causing great danger to anyone included in the traffic. Fortunately, however, no one was hurt. Since then karstologists have been included in the planning and construction of national highways ([4],

[5], [13], [6], [7], [8], [18]). During one of the highway constructions in the south-western part of Slovenia the largest cave was found, measuring 460 meters in length and 70 meters in depth [9]. Ground-penetrating radar was first used in Slovenia to survey highways constructed over a karstic terrain in 2003, between Unec and Postojna, with the goal to create a map of potentially hazardous areas ([14], [15]). Komel and Pavlič [10] showed the results of a GPR survey on a karstic surface near Sežana, which was done with the same goal of determining the cavities and other karstic features. The results of various ground-penetrating surveys in the past over the karstic surface have shown that this method is very successful at determining karstic features and potentially hazardous zones in the karstic subsurface. For that and many other reasons (mostly economic) investors decided that during the construction of the final highway part, Pluska–Hrastje, which is largely situated in a dinaric karst (also called Dolenjski kras), all the parts of the highway where slope cuttings were planned, were surveyed for cavities and other karstic features that could potentially undermine the stability of the road. The ground-penetrating radar method was used as the main surveying technique over intervals where the slope was cut in the karstic limestone. Altogether, more than 50 km of 2D ground-penetrating radar profiles (radargrams) were taken over a length of approximately 3600 meters of highway. Radargrams were taken in raster (rectangular) patterns with 5 or 11 radargrams constructing each raster. These radargrams were ultimately used to construct a 3D model of the GPR anomalies. This article describes various karstic and geological features that were found during the survey.

2 STUDY AREA

The survey area is located in the south-eastern part of Slovenia (Figure 1), where a missing part of the national highway A2 is being constructed. An area over which roughly 15 kilometers of highway is planned is situated on Jurassic limestone with some small percentage of dolomite. Because of the relatively large presence of ground water, this area was developed as dinaric karst, also known as Dolenjski kras.

Ground-penetrating radar was used simultaneously with the construction of the highway because of the noticeable silty and clayey sediment cover over the limestone and the karstic nature of the terrain. The studied area is densely covered with surface karstic features, such as karren, uvalas and also with underground features, such as sinkholes and caves. There a few registered karstic caves in this area (determined by the speleologists) and a few more were found during the geological mapping of the terrain. Highway A2 is situated in the slopes of hills above the town of Trebnje and planned so that significant slope cuttings will be made in the

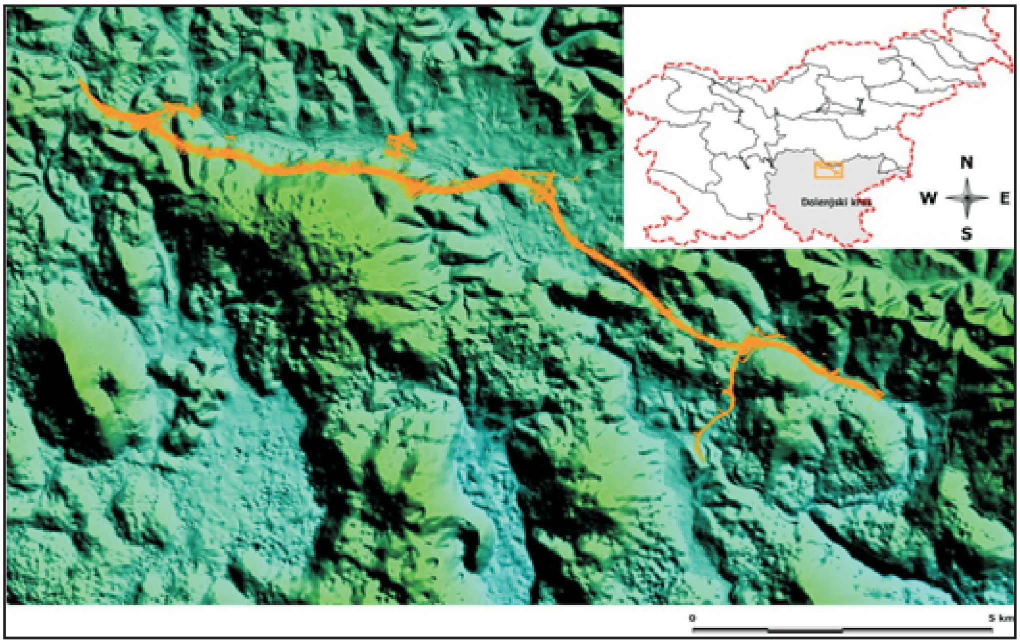

Figure 1. Location of the construction site of the last part of highway A2 Karavanke–Obrežje.

limestone bedrock and epikarstic zone above. The limestone terrain, when the highway's deep slope cuttings (the slope was cut up to 40 meters in limestone bedrock) were constructed, was surveyed with ground-penetrating radar to determine possible voids and other karstic features under the planned road.

3 GROUND-PENETRATING RADAR BASICS

Ground-Penetrating Radar (GPR) is a geophysical imaging technique used for subsurface exploration and monitoring. It is widely used within the forensic, engineering, geological, mining and archeological communities. GPR provides an almost ideal technique for karstic surface evaluation, especially if the upper clayey and silty cover is removed.

In general, GPR is a non-destructive technique that emits a short pulse of electromagnetic energy, which is radiated into the subsurface. When this pulse strikes an interface between layers of materials with different electrical properties, part of the wave reflects back to the surface where the reflection is detected, and the remaining energy continues through the medium. GPR evaluates the reflection of electromagnetic waves at the interface between two different dielectric materials. Two electrical properties are of great importance to a GRP survey. The first is the electrical conductivity (σ) and the second is the electrical permittivity, also known as the dialectic constant. Electrical conductivity is the ability of a material to conduct electric current. The water content and the porosity can have a large impact on the conductivity values (1) [3].

$$\sigma = n(1-s)\sqrt{\sigma_a} + ns\sqrt{\sigma_w} + (1-n)\sqrt{\sigma_s}\ ; \qquad (1)$$

In the above equation σ, σ_a, σ_w, and σ_s represent the overall conductivity, the conductivity of the air, the conductivity of the water and the conductivity of the soil particles. n is a porosity factor and s is the degree of saturation.

The other important factor for the propagation of radar waves into the subsurface is a dimensionless constant called the relative dielectric constant (ε), which is the capacity of media to store a charge when an electric field is applied [3]. The relative dielectric constant (ε) of a non-metallic medium is a function of three different materials within the medium – solid, fluid and gas [2]. If a material is dielectrically homogeneous, then the wave reflections will indicate a single thick layer. The reflection coefficient (2) can be analyzed and sometimes used to distinguish between the types of medium from which the electromagnetic waves are reflecting.

$$r = \left[\frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}\right]; \qquad (2)$$

Equation for the reflection coefficient r [1], where ε_1 is the dielectric constant of the first medium and ε_2 is the dielectric constant of the second medium.

The problem with ground-penetrating radar is that it is in general a contrast method, meaning that the reflections that we obtain during requisition are merely reflections between the different electric properties of a medium. There is no way of knowing which exact medium the amplitude of the reflections belongs to. In theory, you can get the same reflection coefficients from materials, e.g., where ε_1=9 and ε_2=1 or where ε_1=36 and ε_2=4. In both cases the reflection coefficient is r = -0.5. The dielectric constant is inversely proportional to the velocity of the propagation of radar waves through a medium. The dependency of the reflection coefficient (r) on the dielectric constant (ε) is shown in Figure 2 (a). The velocity of the radar waves' propagation through different media is shown in Figure 2 (b).

The signal polarity (whether the reflection coefficient is positive or negative when it passes from one medium to another) can also provide valuable information about the subsurface material. Signal polarity is a function of the dielectric constants between two media [2]. Figure 3 shows the oscillation of a radar wave as it passes through different materials. From the signal polarity we can assume relative changes in the dielectric constants of the media.

The karstic formations in the survey mainly consist of karstic high-plasticity clay, voids and karstic limestone rocks in which the electric constant is roughly 24, 1 and 12, respectively (the values were obtained during an analysis of the reflections' hyperbolas). Water poses a big problem in analyzing the reflection coefficient and its polarity because it changes the electric properties of the medium drastically (it changes the conductivity of the medium). Typical values for the electric properties of different media are presented by Daniels [16].

For a successful GRP survey a compromise between the required range (depth) and the ability to resolve one feature from another (resolution) has to be made. Both range and resolution are functions of the GPR antenna and the electromagnetic properties of media. The higher the antenna frequency, the smaller the range of EM waves' penetration.

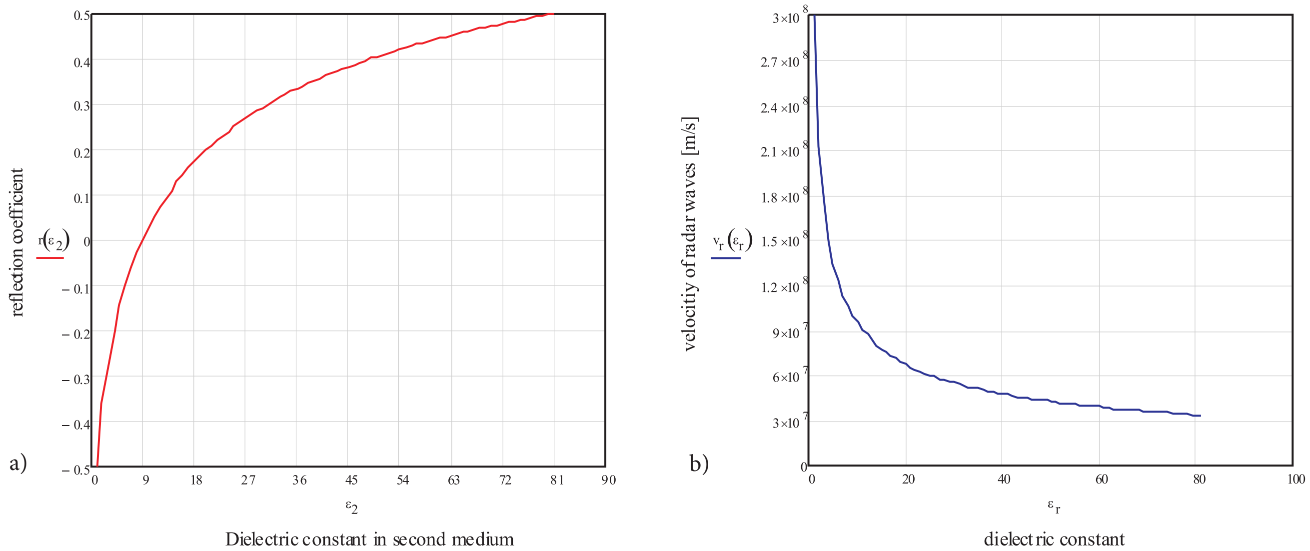

Figure 2. **a)** Dependence of the reflection coefficient (*r*) on the dielectric constant (*ε*) of the materials. In the figures ε_1=9 and ε_2 range from 1 (in air) to 81 (in high mineral soil containing water), **b)** The velocity of the radar wave's propagation (m/s) in relation to different dielectric constants *ε*.

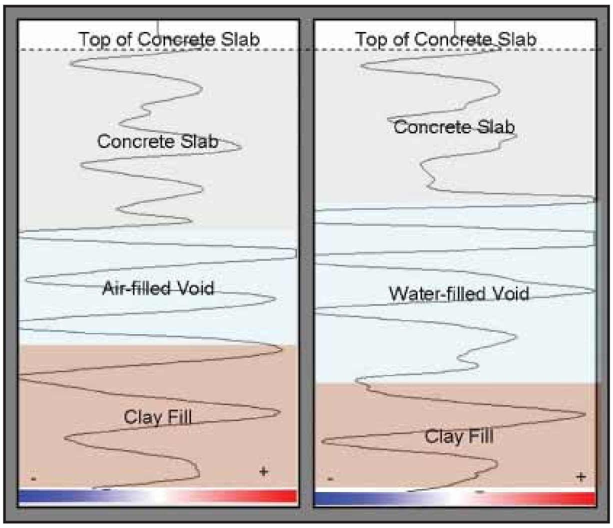

Figure 3. Different signal polarities of the GPR signal as it passes through media [2].

With the GPR equipment used, bistatic shielded antennas (bistatic – transmitter and receiver in one antenna) were employed, which send a signal in an ellipsoidal, cone-shaped pattern into the ground. If unshielded antennas were to be used, the GPR emits a signal in 3D space, so more noise is recorded.

Two different resolutions (horizontal and vertical) are of great importance in the GPR survey and are a function of the choice of the antenna and the media. Figure 4 (a) shows the relation between the horizontal resolution and the depth for various frequency antennas. The horizontal resolution varies with depth and can be roughly estimated from the radius of the first Fresnel zone [17] (3).

$$H_r = \sqrt{\lambda \cdot d + \frac{1 \cdot \lambda^2}{4}} \qquad (3)$$

where *λ* is the wavelength of the EM waves through the media and *d* is the depth.

The vertical resolution can be estimated with equation (4) below:

$$V_r = \frac{c}{4 + \nu \cdot \sqrt{\varepsilon}} \qquad (4)$$

where *ν* is the central frequency of the antenna and *ε* is the dielectric constant of the media.

The range of penetration is also dependent on the dielectric constant of the media, i.e., if the maximum range for a 200-MHz antenna would be 10 meters in certain media, a 900-MHz antenna would have a range up to 1 meter in the same media. The determination of the velocity is of great importance in order to change the time sections into depth. For that, a hyperbola approximation was used, with which the average velocity for the karstic limestone was determined as v = 8.4cm/nsec. Figure 4 (b) shows the hyperbola approximation for determining the velocity of the radar waves' propagation through the media.

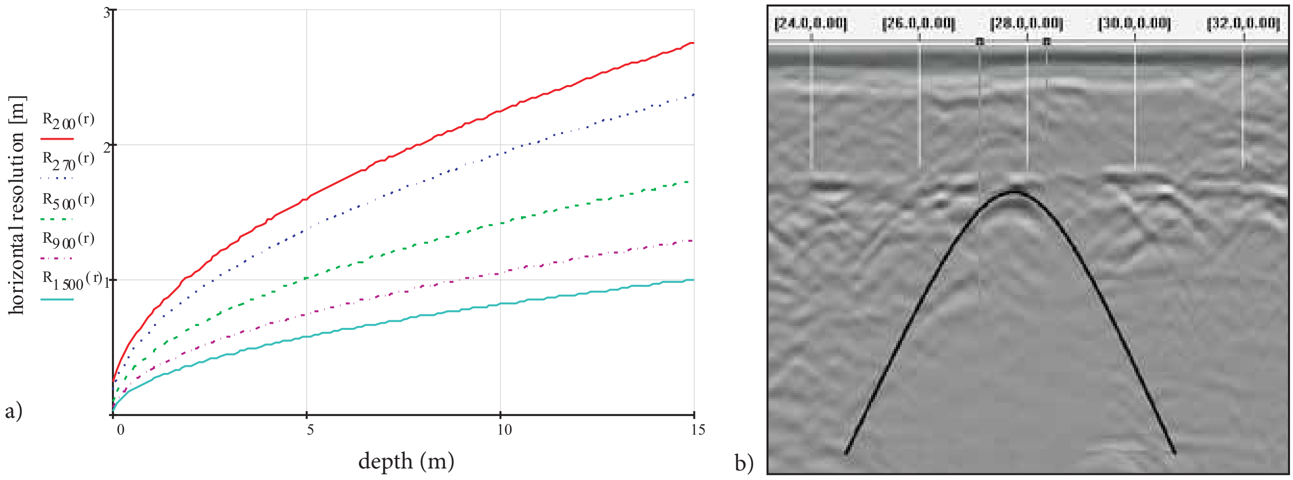

Figure 4. **a)** Relation between the depth and the resolution for various antennas.
b) Hyperbola approximation for a determination of the radar waves' propagation through the media.

4 METHODOLOGY

A ground-penetrating radar survey was conducted simultaneously with the construction of a major highway A2 Karavanke–Obrežje in the sub-section of Pluska–Hrastje. First, major ground work was done to excavate the rock to the final planum of the highway. After that, the GPR survey was conducted in several profiles along the planned road surface (Figure 5).

GSSI's SIR – 3000 system was used with a bistatic shielded antenna to measure over 100 grids in parts where the highway construction was cut in karstic limestone. The acquired profiles in grids, consisting of either 5 or 11 2D profile lines (radargrams), amount to over 50 kilometers in length. These grids were used to construct three-dimensional models for each separate slope cutting in order to see the propagation of the karstic features in space. A study was made where several different variants of the 2D profile line distribu-

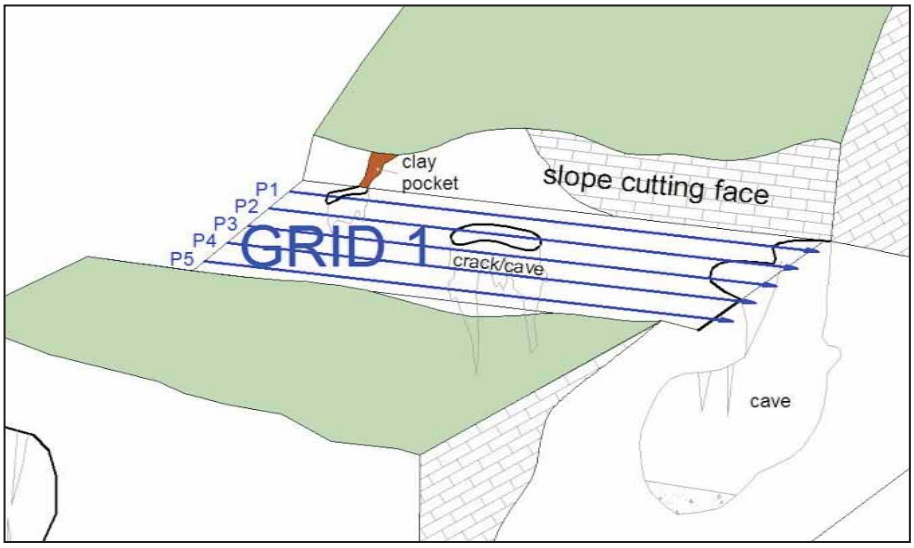

Figure 5. GPR survey in the slope cutting on the planum of highway.

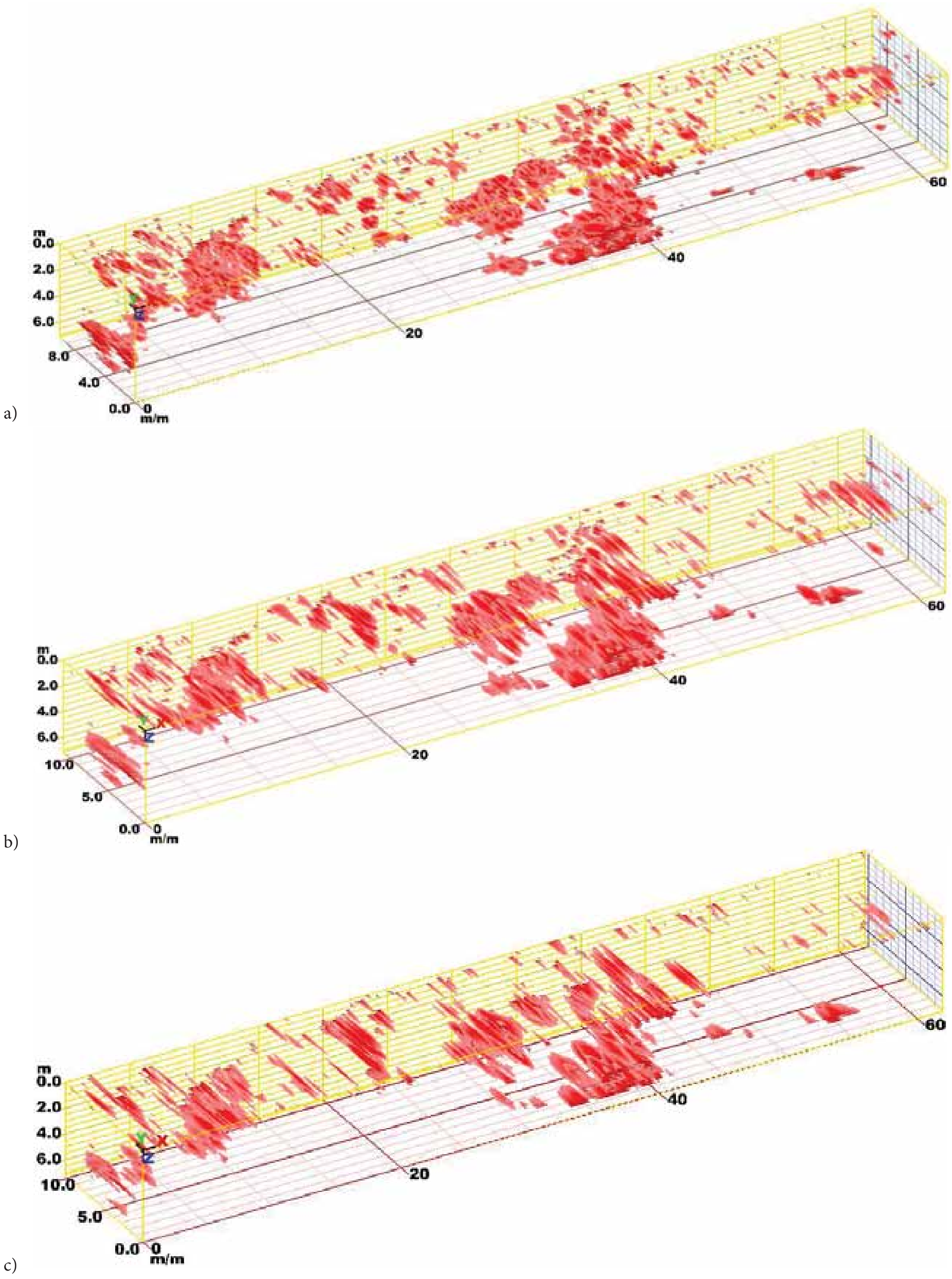

Figure 6. Feature resolution with **a)** 1 meter spacing between 2D profiles, **b)** 2.5 meter spacing between profile lines and **c)** 4 meter spacing between profile lines.

tion in a raster were used in order to sufficiently map all the geotechnical important forms. Figure 6 shows the resolution of 3D models created in the same area with different spacings between the profile lines, where in (a) the spacing between the 2D profile line is 1 meter and in (b) the spacing between the two profile lines is 2.5 meters and in (c) the spacing is 4 meters.

In the conducted survey a 200-MHz antenna was used as a compromise between the resolution and the desired depth for the research. The geotechnical conditions to be met required researching the ground to a depth of around 7 meters under road construction in order to be sure that the stability of the road structure was not compromised. A range of 170 nsec into the subsurface was reached with selected antenna which, with the average dielectric constant of media 12.7, amounted to approximately 7.5 meters of depth. The average dielectric constant was obtained from a hyperbola analysis, which gave a speed for the EM waves of approximately 8.4 cm/nsec. For the distance calibration a GSSI survey wheel was used in order to accurately measure the distance, while simultaneously charging electric pulses into the ground. An electromagnetic pulse was charged every two centimeters in the ground as 50 scans per meter were used. With this set up, a theoretical horizontal resolution by means of the first Fresnel zone gives a value of approximately 1.5 meter [12] [17] at a depth of 6 meters. These values are a mathematical approximation and can vary in real conditions. The horizontal resolution represents the distance at which two different objects with similar electromagnetic properties could be distinguished. The vertical resolution with a 200-MHz antenna used was approximately 10 cm.

As GPR is a contrast method of different reflections between the electromagnetically different media, there is no sure way of knowing that the reflection seen in the radargram is a consequence of dry clay to wet clay or from limestone to wet clay. Assumptions for the type of karstic features below were made based on the analysis of radargrams, “a priori” geological knowledge of the surveyed terrain and the geometrical shapes of the anomalies.

In order to confirm our assumptions, drilling was conducted to confirm whether the recorded reflection occurred on the border between limestone and an empty void or limestone and a clay-filled void. Based on geological knowledge of the terrain and the actual open slope cuttings, different types of media were not expected.

Over 15 boreholes up to 10 meters deep were drilled on several previously decided locations. The data obtained from drilling proved to be very helpful with the calibration since the anomalies found during drilling were almost exclusively (over 95%) a result of the propagation of radar waves from the limestone to an air void or from limestone to a clay pocket.

After the calibration was complete, several more boreholes were drilled in order to confirm our calibrations of the radar reflections. From 18 interpretations (reflection on a radargram later tested with boreholes) 14 were accurate (which means if the interpretation was a clay pocket, a clay pocket was confirmed with drilling). At the other 4 locations where the interpretations were not completely accurate it was the case where voids were partly filled with clay and partly empty (air filled). The reason why our interpretations were not correct is because the dimensions of the clay part and the void part were smaller than the vertical and/or horizontal resolution.

Drilling proved to be a very helpful tool for the calibration of GPR anomalies recorded in 2D radargrams. Over 77 % of the tested reflections were correctly interpreted as voids or clay pockets and others were combinations of partly clay-filled and partly air-filled voids with small dimensions.

The number of test boreholes needed for successful detections can vary significantly from the type of subsurface in the survey. In our case the geology was karstic limestone with more or less repetitive features throughout the surveyed area. For that reason, very low numbers of boreholes were needed for a successful calibration.

GSSI RADAN 6.6 software was used for the processing of the ground-penetrating radar profiles. The processing flow used included a zero time correction, an infinite impulse response filter (band-pass filter for removing high and low frequencies), stacking, stretching, background removal and Kirchhoff migration for the geometry correction and the time-depth conversion. A topographic correction was not applied to any of the acquired profiles because the surveyed area was almost perfectly horizontal. According to Lehman and Green [11], topographic corrections should be considered in regions with surface gradients that are greater than 10% or the slope angle is higher than 6^0.

5 KARSTIC FEATURES REVEALED

During the GPR survey several different karstic and geological features were revealed. Among them, small karstic caves, karstification between sedimentary layers, clayey areas, clay-filled cracks and abysses, water-rinsed (empty) cracks and several different variations of the mentioned forms. The main goal of our survey was to find areas and features that could be potentially hazardous to the stability of the road structure. The different structures found and confirmed with test drilling are shown.

Some examples of different karstic features that were revealed and tested with experimental drilling are shown. After several experimental boreholes, the reflections from the radar signal were better understood. Anomalies where the first reflections were negative were determined as cavities and anomalies, and where the first reflections were positive they were set as clayey and silty areas. These reflections were combined together with a knowledge of the geology of the area to map hazardous areas in each slope cutting.

On the left-hand side of Figure 7, typical anomalies encountered when doing GPR measurements in karst are shown. The anomalies represent two fracture sets oriented at an angle to one another. Because of the stress–strain dynamics, fractures usually evolve in almost perpendicular directions (i.e., a conjugate system). With that and because the fractures are a medium in which water is moving relatively fast, some fractures become wider and partly filled with clay. Areas where both fractures interfere are usually a place where karstic cavities occur. The middle of Figure 7 shows the EM polarities (i.e., the reflection coefficient) diagram of an anomaly where a red vertical line is presented. The first strongest reflection on the diagram is negative, which means that the EM wave progressed from a material with a higher dielectric constant to a material with a lower dielectric constant (as in the case of a limestone-to-air border). The results obtained during the experimental drilling served us as a calibration tool so that we could be certain that the anomaly in question is a cavity. On the right-hand side of Figure 7 we combined the radargram and the 3D anomalies that we obtained from Radan 6.6. The figure shows the propagation of an anomaly through the measured raster.

Figure 8 shows another feature common to karst regions and that is easily identified with GPR prospecting, i.e., delineation due to sedimentary layering. Limestone layers of different thickness are usually karstified on the contacts. Karstification occurs in different ways. In Figure 8 the first anomaly (the red line and the polarity diagram with index 1) shows a small cavity on the part of the sedimentary layer. The dimension of this cavity is small (smaller than 0.5 m). The polarity diagram with index 2 shows layering with crevasses of small dimensions. All the peaks in the polar diagram with index 2 start towards positive, which means that these karstified crevasses between the layers are filled with clay. A 3D view of such an example is shown in the lower part of Figure 8.

Left side of upper part (index 1) on Figure 8 represents a void (cavity) in between layers, the right part (index 2) is clay filled crevasses between layers. The upper part of the figure represents 2D radargram, the lower a 3D view of the measured raster.

Figure 9 shows a typical cavity signature with negative polarity when the signal crosses from the higher to the lower conductive layer. Strong and parallel horizontal reflections indicate the presence of homogenous media (air) with dimensions of approximately 1 x 1.5 m.

Other karstic and geological features can be seen in Figure 10. The left part of the picture shows an unfiltered (un-migrated) radargram with drafted features in it, while the right part of the figure shows filtered data with the time-depth migration of the same area. The karstic cave is seen in both radargrams with the corresponding scan (red vertical line) showing where the polarity of the reflection is negative. The radargram shows a fairly large upside-down funnel-shaped region with many strong horizontal reflections that start with a negative polarity. The experimental drilling showed that the cavities found in the researched area are usually partially filled with clay. The right part of Figure 10 shows migrated (corrected time depth and geometry) data in which we could assess the anomaly's dimensions. At a depth

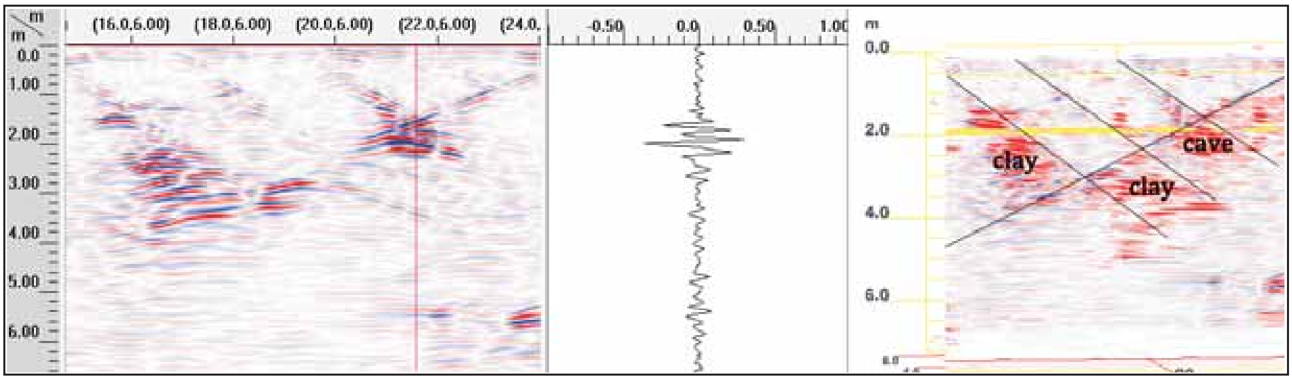

Figure 7. Conjugated system of fractures in limestone with small karstic cavity.

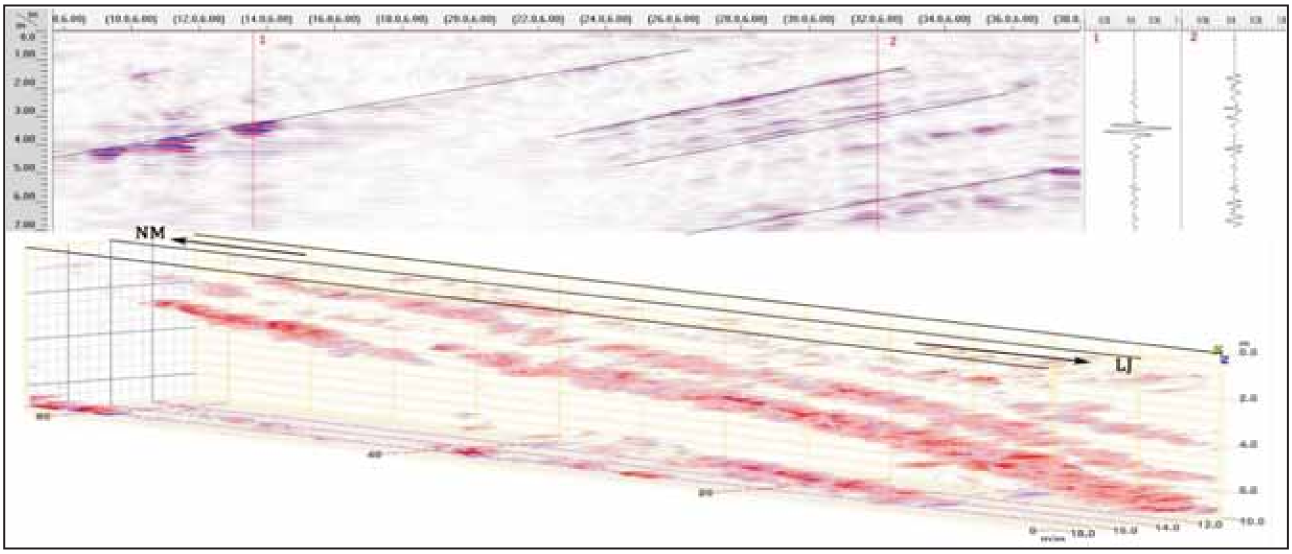

Figure 8. Delineation due to sedimentary layers and karstification of these crevasses.

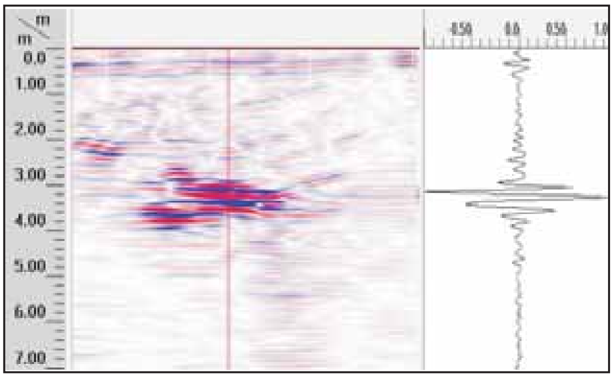

Figure 9. Reflections from a karstic cave of small dimensions at a depth of about 3 meters below the surface.

of approximately 2.2 meters a horizontal anomaly is seen where the water table was recorded (WT). The vertical band on the left side of Figure 10, where strong anomalies occur (electric cable), is due to the ringing effect when the radar signal passes through a highly conductive medium, i.e., an electric cable. The signal gets trapped between two reflectors and is multiplied in the way seen on Figure 10.

Figure 11 shows a strong anomaly where the GPR signal passes from the dry upper gravelly embankment material to the wet karstic clay. This anomaly was confirmed with an on-site excavation to assess the potential danger to the road construction.

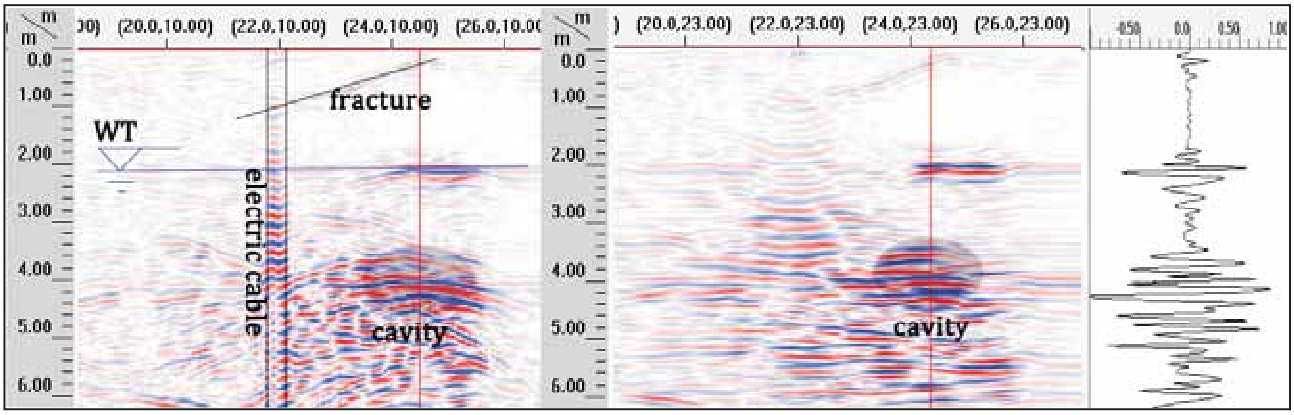

Figure 10. Several karstic and geological features acquired with ground-penetrating radar in the subsurface.

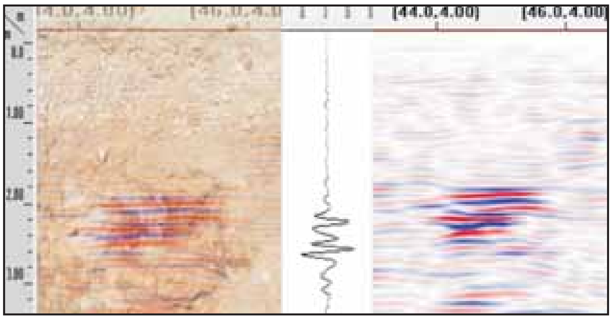

Figure 11. Wet karstic clay reflections.

6 CONCLUSIONS

Ground-penetrating radar proved to be a very effective method for determining the karstic features and other geological phenomena that could undermine the stability of a construction. Nevertheless, a great deal of effort should be made to effectively choose the right equipment and raster for the desired job. The antenna–resolution relation with the electrical properties of the subsurface should be closely studied in order to get the desired results. Also, the distribution of the GPR profiles in the measured raster is very important to effectively map the progression of potentially hazardous karstic features in space.

Initially, the survey was started on a very dense raster (1m between 2D profiles), which was very expensive and time consuming (three hours to record 60 meters of length). After several areas were studied and a study was made using several different distances between the GPR lines, a conclusion was made to increase the distance between the radargrams from 1 meter to 2 meters. This was the optimum distance for a given geology in order to retain the needed resolution and be time effective. Ultimately, the 3D model for each slope cutting was constructed from 2D lines which were geo-referenced to show the GPR anomaly distribution in space.

As GPR is a contrast method of different reflections between the electromagnetically different media, there is no sure way of knowing that a reflection seen in a radargram is a consequence of dry clay to wet clay or from limestone to wet clay. Assumptions for the type of karstic features below were made on the basis of an analysis of radargrams, “a priori” geological knowledge of the surveyed terrain and the geometrical shapes of the anomalies.

Drilling was conducted twice, first to calibrate the radargram reflections and secondly to check and confirm the calibration success. Altogether, over 30 boreholes were drilled at different previously selected locations. The data obtained from drilling proved to be very helpful with a calibration since the anomalies found during drilling were almost exclusively (over 95%) a result of the propagation of radar waves from limestone to an air void or limestone to a clay pocket.

Drilling proved to be a very helpful tool for the calibration of GPR anomalies recorded in 2D radargrams. Over 77 % of the tested reflections were correctly interpreted as voids or clay pockets and others were combinations of partly clay-filled and partly air-filled voids of small dimensions.

GPR has proven to be a very cost-effective and reliable method for determining karstic features that could compromise the stability of the road. Taking in consideration that almost 100,000 m^2 of area was surveyed, it is also very time effective as it is almost impossible to survey an area this big with any other field method (boreholes, DPSH, SPT, etc.) to an accuracy obtained with GPR. A quick estimate is: in order to get roughly the same research coverage that a GPR survey offers, around 700 meters of boreholes should be drilled per 60 meters length of highway lane (60 meters in length x 9 meters width). Taking this into account the price ratio is around 1:5 to 1:10 for the GPR survey.

While the GPR method is very effective and it is in some cases possible to accurately predict the type of anomaly, on the other hand, this is not necessarily true in others cases, where the presence of changes in EM anomalies and the GPR reflections in the subsoil can be related to the variation of other physical properties (porosity, density, saturation, etc.).

In the presented article GPR prospecting was used side-by-side with the construction of the road. Even though in such an approach some logistical and operational problems occur, it is the most economical way to research the area. GPR surveying was done together with experimental drilling and excavations to calibrate the obtained reflections. With the side-by-side approach all heavy machinery is available so that experimental drillings or excavations are easily done and affordable.

Even though GPR is a very efficient method for karst surveying, there are some restrictions. One of the biggest restraints is that usually there is a considerable amount of clay soil, which greatly attenuates the GPR waves. One other thing that is common to the karstic world and poses a problem for a successful GPR survey is an uneven surface. In order for a GPR survey to be successful, all these restrictions have to be closely examined and studied so that the optimal equipment and measurement plan can be chosen.

ACKNOWLEDGMENTS

The authors would like to thank the investors DARS and the contractor SCT d.d. for their good cooperation in conducting a survey and helping with all the logistical problems.

REFERENCES

[1] Daniels, D. J., Ground Penetrating Radar (2nd Edition). Institution of Engineering and Technology. On-line (2010), http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1244&VerticalID=0

[2] Gherig M. D., Morris D. V., Bryant J. T., (2004). Ground penetrating radar for concrete evaluation studies, on-line (2010). http://www.foundation-performance.org/pastpresentations/gehrig_paper_march2004.pdf.

[3] Kathnage A., (2008)+., SIR 3000 Training notes, Internal reference.

[4] Knez M., Slabe T. (2004a). Karstology and the opening of caves during motorways construction in the karst region of Slovenia. Int. J. Speleology, 31(1/4), p. 159 – 168.

[5] Knez M., Šebela S. (1994). Novo odkriti kraški pojavi na trasi avtomobilske ceste pri Divači, Naše jame, 36/102.

[6] Knez M., Slabe T. (2001). Karstology and expressway construction. Proceedings of 14th IRF Road World Congress, Paris.

[7] Knez M., Slabe T. (2004b). Highways on karst. In: Gunn J. (ed): Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, London, p. 419-420.

[8] Knez M., Slabe T. (2005). Caves and sinkholes in motorway construction, Slovenia. In: Waltham T F, Bell M, Cullshaw (eds); Sinkholes and subsidence: karst and cavernous rocks in engineering and construction. Springer, Berlin, p. 283 – 288.

[9] Knez M., Slabe T., Šebela S., Grabrovšek F. (2007). The largest cave discovered in a tunnel during motorway construction in Slovenia's classical Karst, Environmental Geology, vol. 54, p. 711-718, SpringerLink.

[10] Komel P., Pavlič M. U., (2008). Uporaba georadarja v geotehniki, geologiji in gradbeništvu ob praktičnih primerih - Ground penetrating radar use in geotechnics, geology and civil engineering on case studies. V: LOGAR, Janko (ur.), PETKOVŠEK, Ana (ur.). *Razprave petega posvetovanja slovenskih geotehnikov, Nova Gorica 2008, Nova Gorica, 12. do 14. junij 2008*. Ljubljana: Slovensko geotehniško društvo, 2008, p. 143-153.

[11] Lehmann F., Green A. G., (2000). Topographic migration of georadar data: Implications for acquisition and processing. Geophysics 65(3): p. 836–848.

[12] Reynolds J. M. (1997). An introduction to applied and environmental geophysics. Wiley, Chichester.

[13] Šebela S., Mihevc A., (1999). The vulnerability map of karst along highways in Slovenia. In: Beck B F, Petit A J, Herring J G (eds): Hydrogeology and engineering geology of dolines and karst – 1999. Proceedings of the 7th multidisciplinary conference on dolines and the engineering and environmental impacts on Karst. A A Balkena, Rotterdam, p. 419 – 422.

[14] Živanovič M., (2003a). Poročilo o georadarskih meritvah na območju vdorov vozišča na AC odseku Unec – Postojna, internal report GI ZRMK d.o.o.

[15] Živanović M., (2003b). Primeri uporabe georadarskih raziskav v različnih kamninah: *Geološki zbornik-razprave, poročila. 16. posvetovanje slovenskih geologov*. Ljubljana: Naravoslovnotehniška fakulteta, Oddelek za geologijo, 2003, p. 181-186.

[16] Daniels J. D., (2004), Ground penetrating radar, 2nd edition, 726p.

[17] Wikipedia on-line, (2010), http://en.wikipedia.org/wiki/Fresnel_zone

[18] Knez, M. (ed), Slabe, T. (ed), (2007). Kraški pojavi razkriti med gradnjo slovenskih avtocest, (Carsologica, 7), Ljubljana: Založba ZRC SAZU, p. 250.