COBISS: 1.01

ANALYSIS OF THE CAPABILITIES OF LOW FREQUENCY GROUND PENETRATING RADAR FOR CAVITIES DETECTION IN ROUGH TERRAIN CONDITIONS: THE CASE OF DIVAČA CAVE, SLOVENIA

ANALIZA ZMOŽNOSTI NIZKOFREKVENČNEGA GEORADARJA ZA ZAZNAVANJE JAM NA TEŽKO PREHODNEM POVRŠJU: PRIMER DIVAŠKE JAME, SLOVENIJA

Andrej GOSAR[1]

Abstract UDC 550.837.7:551.435.84(497.4)

Andrej Gosar: Analysis of the capabilities of low frequency ground penetrating radar for cavities detection in rough terrain conditions: The case of Divača cave, Slovenia

High frequency ground penetrating radar (GPR) is usually applied for cavities detection in a shallow subsurface of karst areas to prevent geotechnical hazards. For specific projects, such as tunnel construction, it is important to detect also larger voids at medium depth range. However, dimensions of classical rigid low frequency antennas seriously limit their applicability in a rough terrain with dense vegetation commonly encountered in a karst. In this study recently developed 50 MHz antennas designed in a tube form were tested to detect cave gallery at the depth between 12 m and 60 m. The Divača cave was selected because of a wide range of depths under the surface, possibility of unknown galleries in the vicinity and a rough terrain surface typical for Slovenian karst. Seven GPR profiles were measured across the main gallery of the cave and additional four profiles NE of the cave entrance where no galleries are known. Different acquisition and processing parameters were analysed together with the data resolution issues. The main gallery of the cave was clearly imaged in the part where the roof of the gallery is located at the depth from 10 m to 30 m. The width of the open space is mainly around 10 m. Applied system was not able to detect the gallery in the part where it is located deeper than 40 m, but several shallower cavities were discovered which were unknown before. The most important result is that the profiles acquired NE of the cave entrance revealed very clearly the existence of an unknown gallery which is located at the depth between 15 m and 22 m and represents the continuation of the Divača cave. Access to this gallery is blocked by the sediment fill in the entrance shaft of the cave. The results of the study are important also for future infrastructure projects which will involve construction of tunnels through karstified limestone and for speleological investigations to direct the research efforts.

Keywords: ground penetrating radar, cavity detection, spatial resolution, limestone, Divača cave.

Izvleček UDK 550.837.7:551.435.84(497.4)

Andrej Gosar: Analiza zmožnosti nizkofrekvenčnega georadarja za zaznavanje jam na težko prehodnem površju: primer Divaške jame, Slovenija

Za zaznavanje jam plitvo pod površjem se pri preprečevanju geotehničnih nevarnosti na kraških območjih navadno uporablja visokofrekvenčni georadar. Pri posebnih gradnjah kot so predori, pa je pomembno zaznati tudi večje praznine v srednje velikih globinah. Velikost klasičnih nizkofrekvenčnih georadarskih anten pa močno omejuje njihovo uporabnost na težko prehodnih območjih z gosto vegetacijo, ki so zelo pogosta na krasu. V tej študiji je bila preizkušena novo-razvita 50 MHz antena cevaste oblike za zaznavanje jamskega rova na globini med 12 m in 60 m. Izbrana je bila Divaška jama, in sicer zaradi širokega razpona globin rova pod površjem, možnostjo za obstoj še neodkritih rovov in težko prehodnega površja, značilnega za slovenski kras. Izmerjeno je bilo sedem georadarskih profilov prek glavnega jamskega rova in dodatni štirje profili SV od vhoda v jamo, kjer še ni znanih rovov. Analizirani so različni parametri terenskih meritev in obdelave podatkov, skupaj z njihovo ločljivostjo. Glavni jamski rov se zelo jasno odraža na georadarskih profilih na območju, kjer se strop nahaja v globini med 10 m in 30 m, širina rova pa je okoli 10 m. Uporabljen georadarski sistem pa ni bil zmožen zaznati jamskega rova tam, kjer se ta nahaja globlje od 40 m. Zaznane pa so bile številne plitvejše kaverne ali rovi, ki pred tem niso bili znani. Najpomembnejši rezultat raziskave je, da je bil odkrit še neznan rov SV od jamskega vhoda. Rov se nahaja v globini med 15 m in 22 m in predstavlja nadaljevanje Divaške jame. Dostop do rova preprečujejo sedimenti na dnu vhodnega brezna. Rezultati imajo pomen tudi za prihodnje infrastrukturne projekte, ki bodo vključevali izgradnjo predorov skozi zakrasel apnenec in za speleološke raziskave pri njihovem usmerjanju.

Ključne besede: georadar, zaznavanje jam, prostorska ločljivost, apnenec, Divaška jama.

[1] University of Ljubljana, Faculty of Natural Sciences and Engineering; Environment Agency of Slovenia, Seismology and Geology Office, Dunajska cesta 47, SI-1000 Ljubljana, Slovenia, e-mail: andrej.gosar@gov.si

Received/Prejeto: 5.12.2011

INTRODUCTION

Cavity detection is one of primary objectives of geophysical investigations in karst regions. Commonly applied geophysical techniques for this purpose include gravity method, electrical resistivity imaging, seismic refraction and ground penetrating radar (GPR) (Mareš *et al.* 1997; Reynolds 1997). Especially GPR has become in the last 15 years the most important method for shallow investigations, because different conditions for its successful application are usually favourable in karst. Some applications described in literature are related to shallow depth penetration which rarely exceeds 5–8 m using GPR systems with high frequency antennas, usually between 200 MHz and 500 MHz (Chamberlain *et al.* 2000; Knez & Slabe 2005; Pavlič & Praznik 2011). There are at least two reasons for this. The first is that most investigations are aimed to assess geotechnical hazards for different constructions on the surface, which are in karst related to the danger of the sudden collapse of the ground or to the activation of a sinkhole, both related to shallow hidden cavities. Second reason is that karst surface is usually very rough and measurements using small high frequency systems in which both transmitting and receiving antenna are integrated in a common case, are much easier.

However, sometimes there is a need to detect also larger cavities at greater depths in karst areas. This is especially important for projects which involve tunnel constructions or for speleological purposes when we want to discover a continuation of a known cave, but the access to new galleries is blocked by a collapsed material or other sediment fill, flowstone or too narrow passages. Low frequency antennas in the range from 25 MHz to 100 MHz should be applied for this purpose to achieve the depth penetration down to 20–30 m or even 40–50 m. The dimensions (length) of classical unshielded antennas are from 1 m for 100 MHz to 4 m for 25 MHz and the weight of each 50 MHz antenna for instance is close to 3 kg. During the acquisition, transmitting and receiving antenna should be spaced from 2 m to 6 m, which requires a system of rigid handles and horizontal connection bars. Therefore, it is very difficult to move a rigid system of two properly spaced large antennas across a rough terrain and impossible through the dense vegetation common in karst, or extensive clearing of the profile route is necessary prior to the survey. The additional problem is to assure a good contact of long rigid antennas with the ground on a rough terrain. These are all reasons why there are only few reports on low frequency GPR applications in karst areas. Recent development of special rough terrain antennas (RTA) has only enabled application of low frequency GPR measurements in realistic conditions.

The purpose of this study is to analyse the capabilities of low frequency GPR with RTA for cavities detection in a medium depth range and rough terrain conditions. The main issue to be tested is the penetration depth, since rather different values between 25 m and 40 m are reported by different authors for different geological conditions (Reynolds 1997; Daniels 2004; Jol 2009). The second important issue is the horizontal resolution, as it is well known that resolution in realistic conditions can be significantly different from the theoretical estimations. For testing we selected the Divača cave in SW Slovenia (Fig. 1) which has accessible galleries in the length of 610 m. They extend from 12 m to 60 m below the surface. A series of GPR profiles was measured across the known galleries of the cave as well as across the extension of the main axis of the cave towards the NE where no galleries are known. Different aspects of the data acquisition and processing were analysed and results compared with speleological data. Verification of the methodology for cavities detection in medium depth range is important for the future infrastructure projects in Slovenian karst, such as a new railway Divača–Koper, where several long tunnels through karstified limestone are planned. Several examples are known where even large cavities were discovered during tunnel constructions. In the case of Učka tunnel (Istra, Croatia) the discovered cave required to build even a special construction which supports the tunnel tube (Božičević 1995).

Fig. 1: Location of the Divača cave.

THE DIVAČA CAVE

The Divača cave is an important cave in the Divača karst (Mihevc 2001). It was in details surveyed and investigated from speleological and geological point of view by Gospodarič (1985). Its entrance is 1 km SW from Divača at the elevation of 427 m (Fig. 1). Its main gallery is 610 m long and extends between elevation 360 m and 390 m in NE–SW direction (Figs. 2 & 3). This is 200 m above the actual flow of the underground Reka River in nearby Kačna cave and in Škocjanske cave. The total length of the surveyed polygon is 707 m and the maximum depth 75 m. The main gallery is from 5 m to 15 m wide and the roof of a cave reach a maximum height of 20 m. The main gallery is located from 12 m to 60 m below the surface. The surface above the cave is generally flat, but contains several dolines. It is covered by a quite dense forest and bushes.

The area of Divača cave is built of Late Cretaceous micrite and sparite bedded limestone of Turonian age. The strata are dipping in the first half of the cave (NE part) for 15–20° towards the south-west and in the second half (SW part) for 15–20° towards the south. The rock in the area is tectonically fractured but not crushed (Gospodarič 1985). The largest tectonic feature in vicinity is a NW–SE trending right-lateral strike slip Divača fault which runs approximately 1 km to the NE from the cave (Placer 1981).

Divača cave is characterized by extensive infill of sediments which completely cover the cave floor. Prevailing is flowstone in forms of different speleothems, but there are also several fluvial sediments (red loam and sand) and rockfall boulders. In the SW the cave ends in Žiberna hall, close to Trhlovca cave which is located above this hall (Fig. 3). In the NE where the entrance to the cave is located (Fig. 3) the floor in the entrance hall is covered manly by collapsed blocks and rubble (Gospodarič 1985). Extension of the cave gallery towards NE is very probable, but blocked by sediments and collapse material at the entrance shaft.

Electrical resistivity imaging was recently conducted above the Divača cave and its continuation in denuded cave located to the NE on slopes of Radvanj collapse doline (Mihevc & Stepišnik 2011). Empty cave passages were not detected, presumably as electric resistivity contrast between voids and high resistant carbonate is too small. On the other hand, denuded caves and cave sections filled with loam can be clearly distinguished.

THE GROUND PENETRATING METHOD AND CAVITY DETECTION

After earlier applications of ground penetrating radar (GPR) method in specific conditions of permafrost and ice covered areas, the method has started to develop rapidly for investigations of the shallow subsurface around 25 years ago (Davis & Annan 1989). The method has been successfully applied to solve various geological, geotechnical, engineering and archaeological problems in a depth range from few centimetres to several tens of meters or even hundred of meters in case of penetrating the ice. Among geological problems the most common applications are related to the investigations of the bedrock depth, stratigraphy and sedimentology of sediments, faults and fracture zones, delineation of rock fabric, determination of water table depth, identification of karst features and detection of voids (Reynolds 1997; Daniels 2004; Jol 2009).

The principle of GPR method is that a short pulse of high frequency (25–2,000 MHz) electromagnetic (EM) energy is transmitted into the ground where it is reflected from the interfaces which separates layers with different electrical properties. The reflected signal is detected by the receiver antenna, amplified, digitized and stored for later data processing. The GPR is normally used in a common-offset reflection mode using pair of properly spaced antennas which are moved along the straight measuring profile.

Propagation of EM waves trough the rocks is controlled by dielectric and conductivity properties of the material. The velocity of wave propagation V in low-loss geologic materials depends on the relative dielectric permittivity (dielectric constant) ε by equation

$$V = \frac{c}{\sqrt{\varepsilon}} \qquad (1)$$

where

$c = 3 \cdot 10^8$ m/s or 30 cm/ns, the propagation velocity of EM waves in vacuum.

On the other hand, the attenuation of EM waves depends mainly on the conductivity of material. Since the presence of water in rocks is the main factor which controls the conductivity, GPR method is most suitable for dry rocks where greatest depth of penetration can be achieved. Second factor which contrails the depth of penetration and data resolution is the frequency of the EM signal. Antennas which transmits and receives signals with different central frequencies should be therefore used for different purposes.

Detection of underground voids is quite a typical application of the GPR method. It can be used to assess geotechnical hazards related to the sudden collapse of natural or artificial cavities like abandoned mines or other underground excavations (Benson 1995). It is widely used also in archaeology to detect underground chambers which can have a significant archaeological meaning such as vaults, culverts and crypts (Reynolds 1997; Daniels 2004). Natural cavities and sinkholes which pose potential hazards can be related to the dissolution of various materials like salt and anhydrite (Frumkin *et al.* 2011), but most frequently they are characteristically for karstified limestone (Sharma 1997; McMechan *et al.* 1998; Chamberlain *et al.* 2000; Pueyo-Anchuela *et al.* 2009). Cavities can be formed also inside man maid structures like dikes and dams by dissolution and erosion where they can also be detected by GPR (Xu *et al.* 2010) and thus prevent the related hazards.

Most frequently detection of shallow cavities (depth smaller then 10 m or even smaller then 5 m) is described in literature. This is understandable, because shallow features pose the main hazard for any surface construction or are interesting from the archaeological point of view. High frequency GPR systems in the range from 200 MHz to 500 MHz are therefore usually applied, because they have appropriate depth penetration, but retain a good spatial resolution needed to detect also small cavities. But for specific projects, such as a tunnel construction through karstified rock, it is important to detect also larger cavities at greater depths. For medium depth range of up to 40 m, this can be accomplished by application of low frequency (25–100 MHz) GPR systems. However, classical rigid low frequency antennas are quite large and their application is thus very difficult or even impossible in a rough terrain with dense vegetation which is usually encountered in karst areas. Application of low frequency GPR for cavities detection in a medium depth range is therefore a challenge, which is analysed in this study.

DATA AQUISITION

To asses the capabilities of low frequency GPR and to investigate the possible existence of unknown cave galleries NE of the Divača cave entrance, we planned 16 profiles oriented in NW–SE direction, which is in general perpendicular to the axis of the main cave gallery. First of all start and end point of planned profiles were marked in the field with the help of a portable GPS receiver. Secondly all the profile locations were carefully inspected to assess the possibility to traverse the field with GPR in approximately straight direction. This field inspection has shown that measurement along some profiles is not possible, mainly due to very dense bushes. At the end we decided to measure seven profiles across the known cave gallery and four profiles NE to the entrance where no cave passages are known yet (Fig. 2). The length of the each profile is between 150 m and 190 m. The surface above the cave is relatively flat although there are some dolines. On the other hand, microtopography is quite rough because of several rocks in the ground, some rock fences and dense vegetation. We decided not to perform a topographic survey of elevation changes along the profiles, because detailed survey would take much more time than GPR acquisition itself, and because it is difficult to correct the profile for small topographic features when spacing between antennas is 4 m. On the other hand, single receiver GPS applied for position does not provide elevation data of sufficient accuracy. Our aim was therefore to asses the capability of the method without performing topographic correction.

Data were acquired using Mala ProEx GPR recording unit with 50 MHz antennas using common offset technique. Special rough terrain antennas (RTA) recently developed by Mala were used. Specific to these antennas with respect to normal unshielded antennas which should be oriented perpendicular to the profile direction and are rigid, is that RTA are flexible, in-line oriented, all-in-one antennas (Mala 2010). The flexible "snake" like design in form of a long tube allows the antenna to be manoeuvred easily and efficiently through the dense vegetation or uneven terrain without affecting ground contact, providing optimum results also in difficult environment. The most important benefit is that it isn't necessary to clear the profile route prior to the survey. The total length of 50 MHz RTA is 9.25 m and the spacing between antennas 4 m. A nominal penetration depth of 50 MHz acquisition system is according to different authors between 25 m and 40 m (Reynolds 1997; Daniels 2004; Jol 2009; Mala 2010).

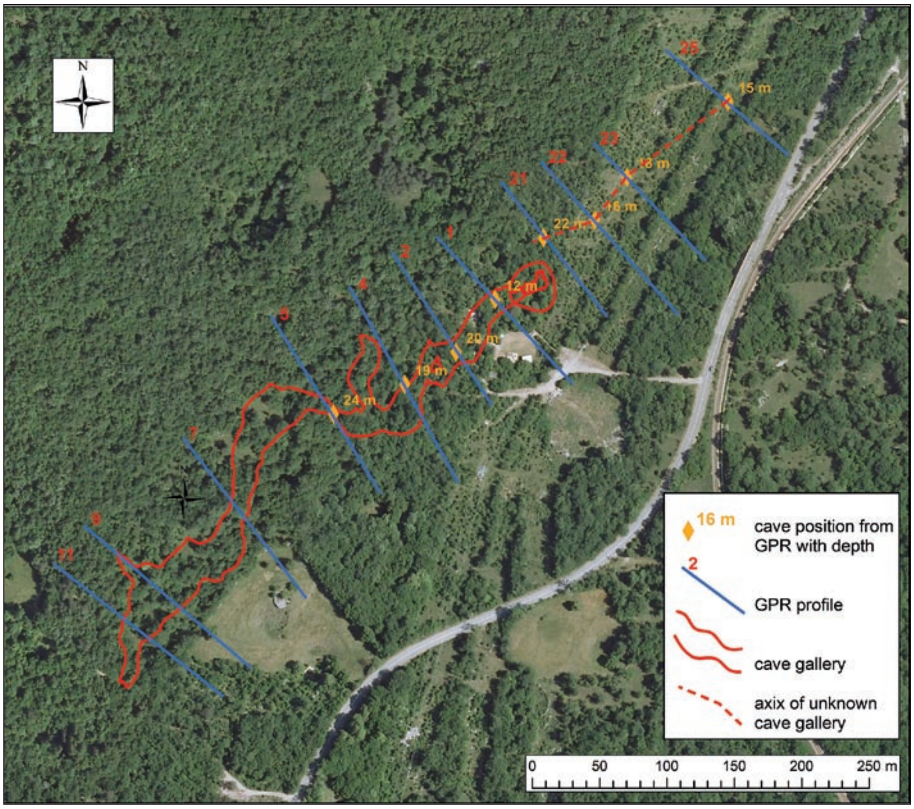

Fig. 2: Position map of GPR profiles and schematic presentation of Divača cave ground plan. Locations where the main cave gallery was revealed by GPR are indicated. Aerial image after Surveying and mapping authority of Slovenia (GURS).

To trigger acquisition in regular intervals two different systems are used in common GPR systems. First is a distance-measuring wheel which is used with high-frequency all-in-one antennas that are towed or pushed along the profile. Second is a chain (leash) profile encoder composed of a leash and a wheel which is rotated by unwrapping of the leash and triggers the acquisition in regular distance intervals. Unfortunately, this system is also not suitable for rough terrain with dense vegetation. Therefore we decided to use time interval trigger and GPS receiver attached to the acquisition unit. The profile is measured at as much constant velocity of movement along the profile as possible, and the data recorded at fixed time interval, 0.2 s in our case. As GPS receiver marks

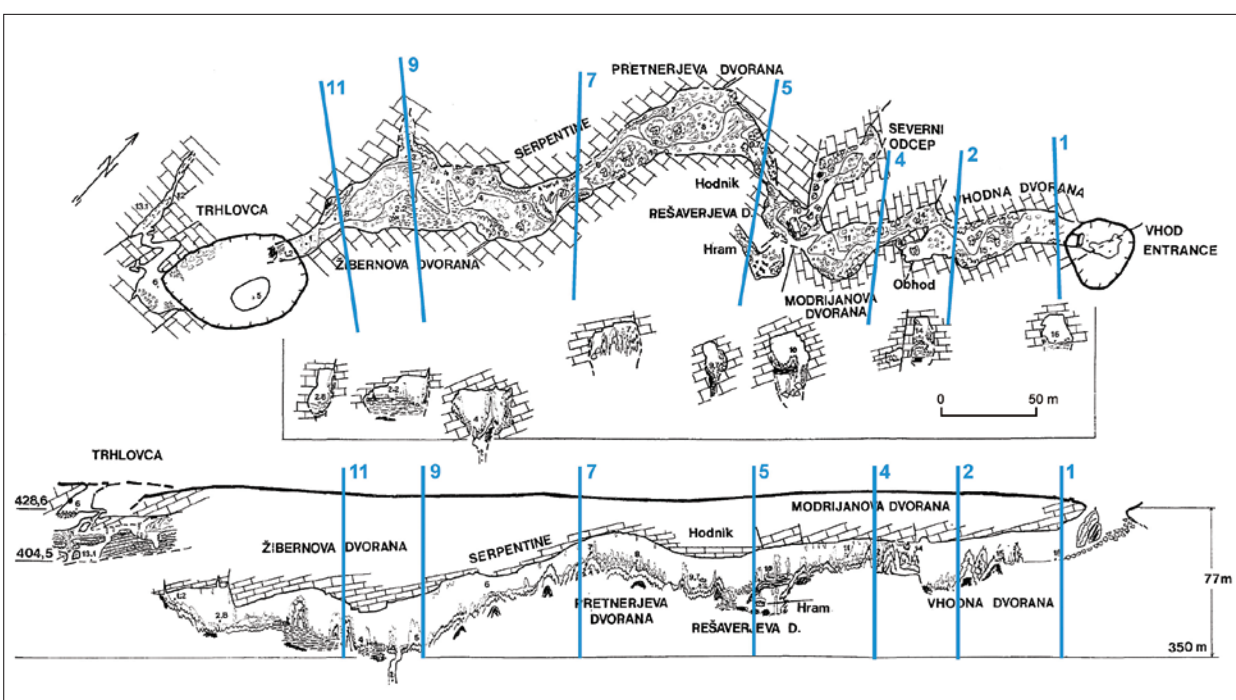

Fig. 3: Divača cave ground plan and longitudinal section with some cross sections (after Gospodarič 1985). Blue lines indicate locations of GPR profiles.

each recorded trace with coordinates, it is possible to later adjust any uneven progress along the profile during measurement by trace interpolation. We succeeded to perform measurements quite smoothly, since trace interpolation has given average spacing between traces from 0.19 m to 0.22 m for different profiles, which is a rather small scatter. Marking traces with GPS coordinates was very important also to exactly determine the locations of interpreted features in processed profiles.

Acquisition parameters are summarized in Tab. 1. Sampling interval was 1 ns and the acquisition window length 1024 ns. Data were acquired after a longer period (two weeks) without precipitations. The surface soil layer and limestone beneath were therefore relatively dry. All the profiles presented in continuation (Figs. 4–14) are shown in direction NW on the left side and SE on the right side, independent of the actual direction of acquisition.

Tab. 1: GPR acquisition parameters.

Antennas:	50 MHz unshielded rough terrain antennas (RTA)
Antenna separation:	4 m
Sampling frequency:	1000 MHz
Sampling interval:	1 ns
Acquisition window length:	1024 samples = 1024 ns
Stacks:	16
Trig interval:	0.2 s
Average trace spacing:	0.19 – 0.22 m

DATA PROCESSING

Data were processed using a processing sequence shown in Tab. 2. Spatial interpolation of traces which follows DC correction and time zero adjustment was based on the GPS signal recorded together with traces and enabled equal distance presentation of results as explained in the previous section. Clear diffractions observed in profiles, which correspond to the cave locations, were used for velocity determination by hyperbola fitting (e.g. Fig. 4b). Average value of velocities from different profiles has given the value of 11.3 cm/s which corresponds to the dielectric constant $\varepsilon=7$. This figure corresponds well to the central value for a dry limestone from the literature where the ε span from 4 to 9 (Reynolds 1997; Daniels 2004; Jol 2009). Predictive deconvolution was used only optionally and for comparison, since it did not contribute to the better image of the subsurface. Stolt F-K migration using established velocity of 11.3 cm/s was also used only for comparison and not for interpretation. Example in Fig. 4c clearly shows its effect on the diffraction hyperbola caused by a cave. Time to depth conversion was performed using constant velocity of 11.3 cm/s since no lithological changes are expected along the investigated depth of penetration.

Tab. 2: GPR profiles processing sequence.

DC removal
Time zero adjustment
Spatial interpolation
Background removal
Amplitude correction (AGC)
Bandpass filtering
Hyperbola fitting for velocity determination
Time to depth conversion

VERTICAL AND HORIZONTAL RESOLUTION

It is well known that there is a trade off between the desired depth of GPR penetration and spatial resolution of the data. A compromise is thus always needed.

Vertical resolution (*Vr*) is normally better understood, since it is directly related only to the wavelength. It is given by

$$Vr = \frac{Tpulse\ c}{2\sqrt{\varepsilon}} \qquad (2)$$

where

Tpulse – transmitted pulse duration; inversion of antenna centre frequency,

$c = 3 \cdot 10^8$ m/s or 30 cm/ns, the propagation velocity of EM waves in vacuum,

ε – relative dielectric permittivity (dielectric constant).

Horizontal resolution (*Hr*) is a topic of much debate and different authors give different opinion on what should be the right way of calculating the horizontal resolution. Basically it depends on the following parameters:

- the number of traces per unit distance,
- the beam width of the antenna,
- the spacing between transmitting and receiving antenna,
- the depth of the object.

Following is the relation which according to Alvarez-Cabrera (2011) fits best the results in real conditions

$$Hr = \frac{c}{4\ f\ \sqrt{\varepsilon}} + \frac{D}{\sqrt{\varepsilon + 1}} \qquad (3)$$

where

f – central frequency of the antenna,

D – depth to the plane where the two objects to be distinguished are located.

$c = 3\cdot10^8$ m/s or 30 cm/ns, the propagation velocity of EM waves in vacuum,

ε – relative dielectric permittivity (dielectric constant).

Tab. 3: Vertical and horizontal resolution of 50 MHz acquisition system in limestone.

Centre frequency:	50 MHz
Wavelength (λ) in air:	6 m
Dielectric constant (ε) of limestone:	7
EM velocity in limestone:	11.3 cm/ns
Wavelength in limestone:	2.3 m

Depth (m)	*Vertical resolution (m)*	*Horizontal resolution (m)*
10	1.1	4.1
20	1.1	7.6
30	1.1	11.2
40	1.1	14.7

Although this relation is not exact and due to all the factors influencing the horizontal resolution, it gives only a good approximation on what to expect.

For the 50 MHz antennas used and limestone with ε=7, vertical and horizontal resolutions according to equations (2) and (3) for four different depths are given in Tab. 3. Considering the dimensions of the Divača cave main gallery (Fig. 3) it seems that the horizontal resolution of applied system is sufficient at least down to the depth of 30 m where it is still around 11 m

RESULTS AND INTERPRETATION

Processed GPR profiles acquired across the known cave gallery are shown in Figs. 4–10 and profiles acquired NE of the cave entrance in Figs. 11–14. The locations of the profiles are shown in Figs. 2 & 3. All the profiles were processed using processing sequence listed in Tab. 2. For some of the profiles velocity analysis using hyperbola fitting to the diffraction caused by a cave is also shown. Only for profile 1 results of Stolt F-K migration are also shown (Fig. 4c). All the profiles are shown down to the 700 ns two-way-traveltime which corresponds to the depth of 40 m. Although the data were recorded in 1000 ms long window, no interpretable features are visible in the lower most part between 700 ms and 1000 ms.

In profile 1 (Fig. 4) recorded close to the entrance of the cave the gallery is very clearly visible with its roof at the depth of 12 m. Some reverberations (Kofman *et al.* 2006) inside the open space are visible both on unmigrated (Fig. 4a) and migrated (Fig. 4c) profile. Another distinct feature is a doline characterized by a low-frequency signal due to red loam and soil infill at its bottom. By four small arrows locations of four additional unknown cavities are shown. They are located at the depth from 10 m to 20 m. The cave gallery with its roof at 20 m depth is also clearly visible in profile 2 (Fig. 5). It corresponds to the entrance hall of the cave and the established depth is in agreement with the cave longitudinal section (Fig. 3). The width of the gallery is around 10 m. Additional smaller cavities indicated by arrows are located at the depth between 8 m and 16 m. In profile 4 (Fig. 6) the cave gallery is less clear. Its roof is at 19 m depth. According to the ground plan and cross-sections (Fig. 3) the gallery is here very narrow (less then 10 m) which is presumably the main reason for a weaker response. Interesting feature is a dipping horizon in the NW part of the profile. It is most probably related to the side gallery called Severni odcep (Fig. 3). Several cavities located relatively deep are visible in profile 5 (Fig. 7). The main gallery has a roof at the depth of 24 m. NW of its location there are at least three additional cavities at the depth between 19 m and 25 m. Also a clear deep feature at the NW end of the profile is most probably a cave located at the depth of 32 m. The response of GPR is less clear in profile 7 (Fig. 8) and the main gallery can not be interpreted with confidence although three marked features are most probably caused by cavities. According to the ground plan (Fig. 3) the gallery is here very narrow,

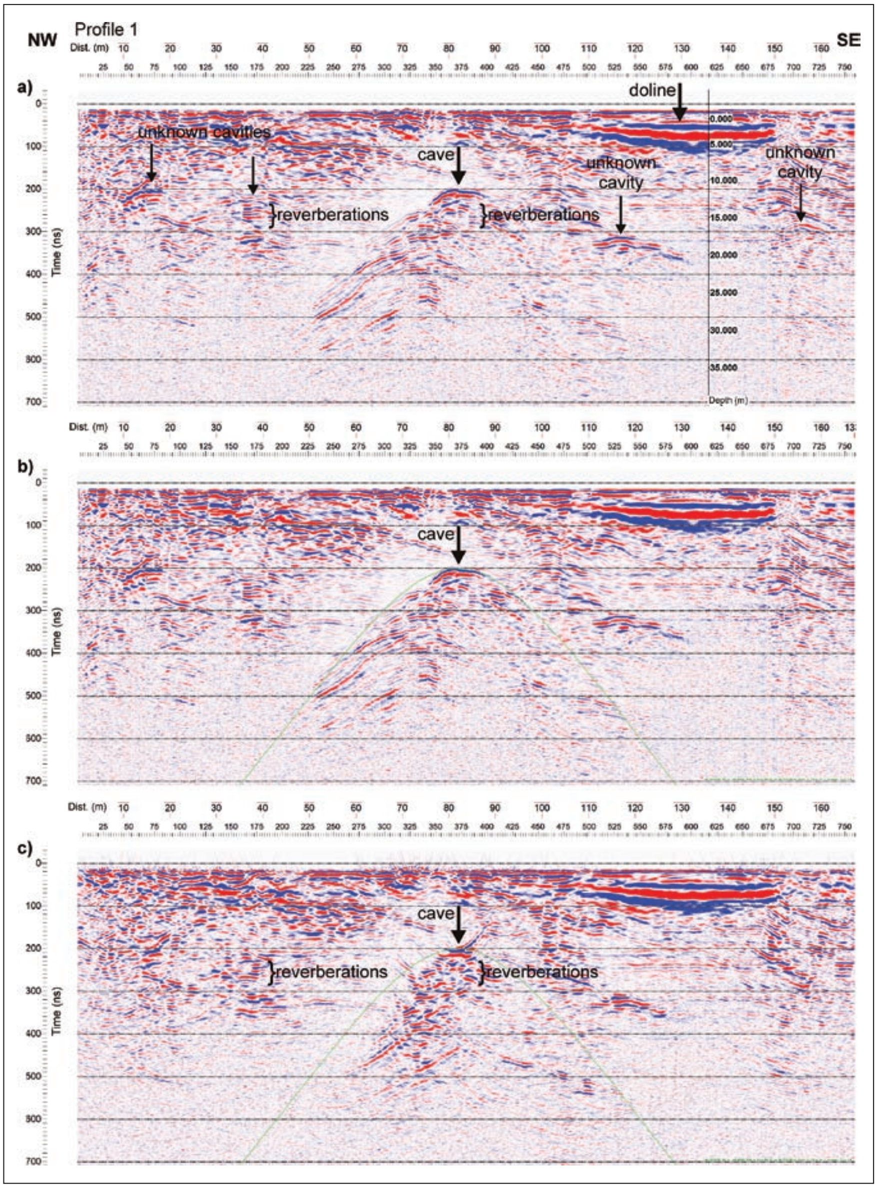

Fig. 4: GPR Profile 1 a) with time and depth scale, b) with hyperbola fitted to the diffraction caused by a cave, c) after Stolt F-K migration.

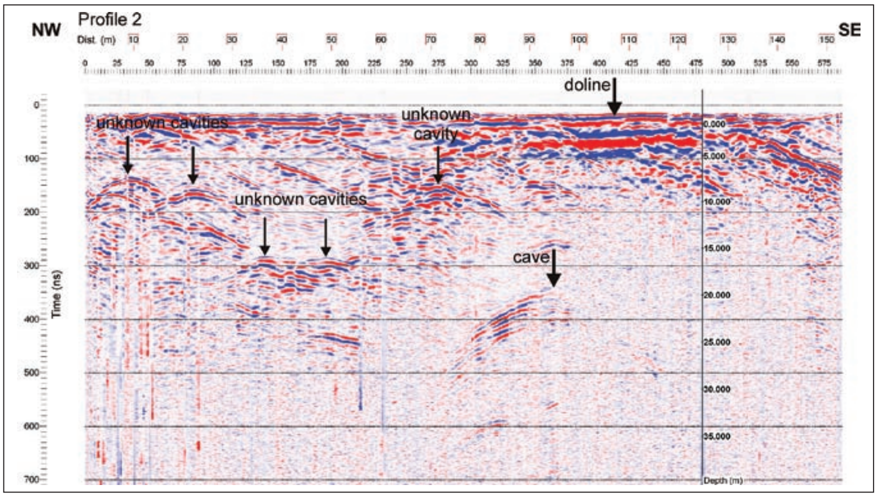

Fig. 5: GPR Profile 2 with time and depth scale.

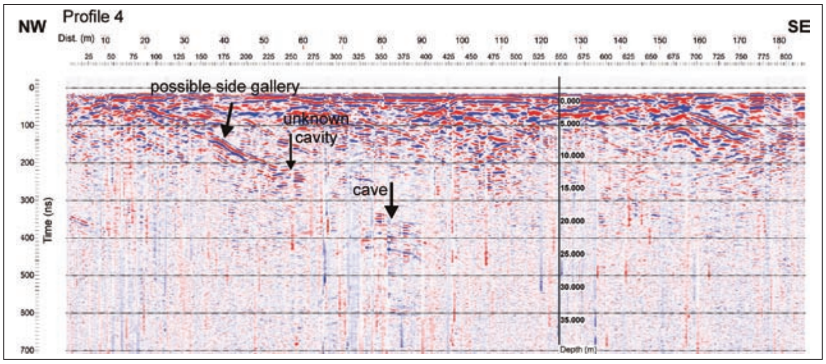

Fig. 6: GPR Profile 4 with time and depth scale.

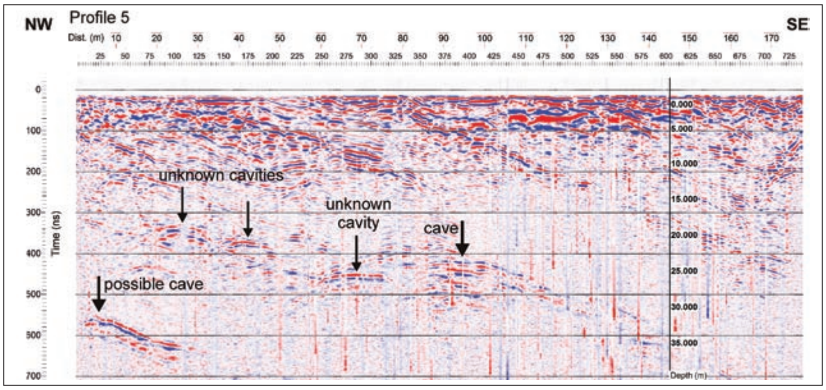

Fig. 7: GPR Profile 5 with time and depth scale.

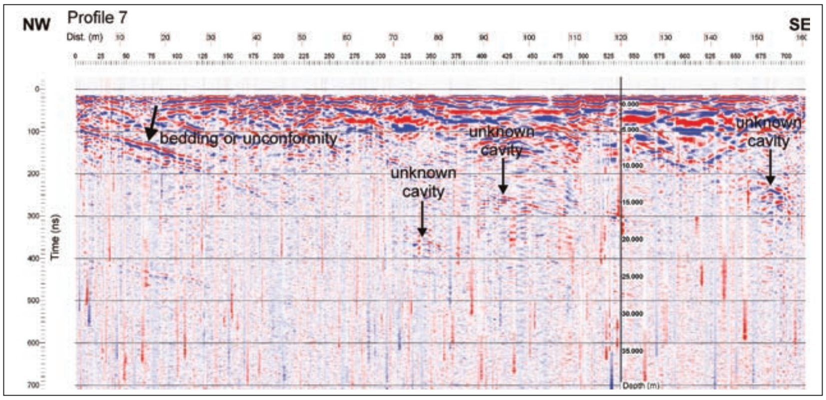

Fig. 8: GPR Profile 7 with time and depth scale.

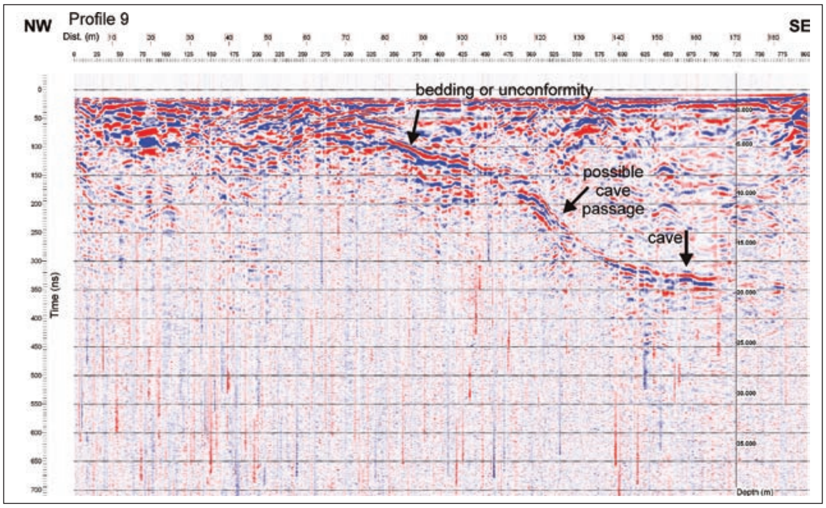

Fig. 9: GPR Profile 9 with time and depth scale.

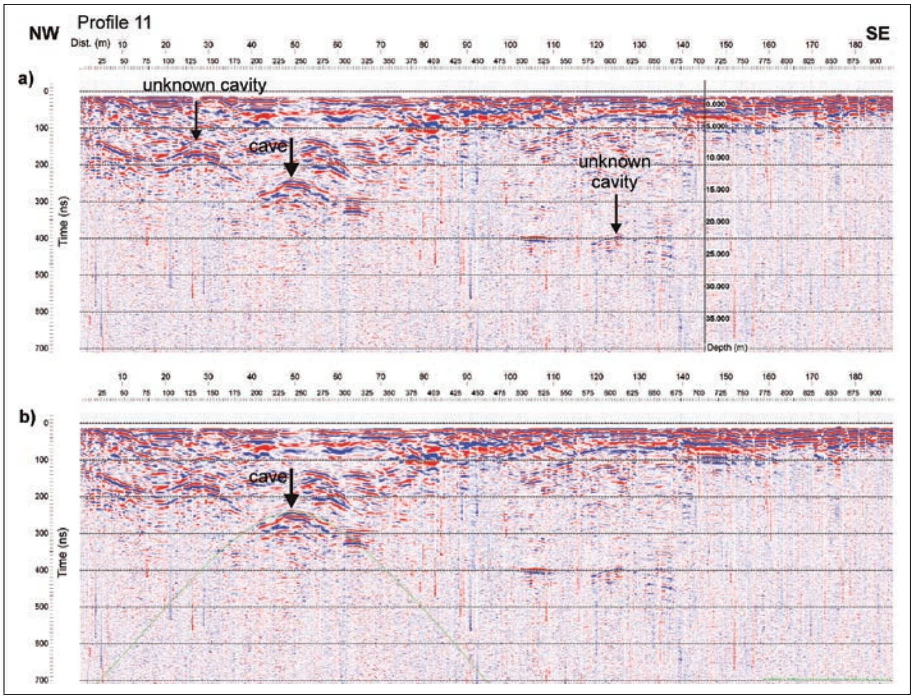

Fig. 10: GPR Profile 11 a) with time and depth scale, b) with hyperbola fitted to the diffraction caused by a cave.

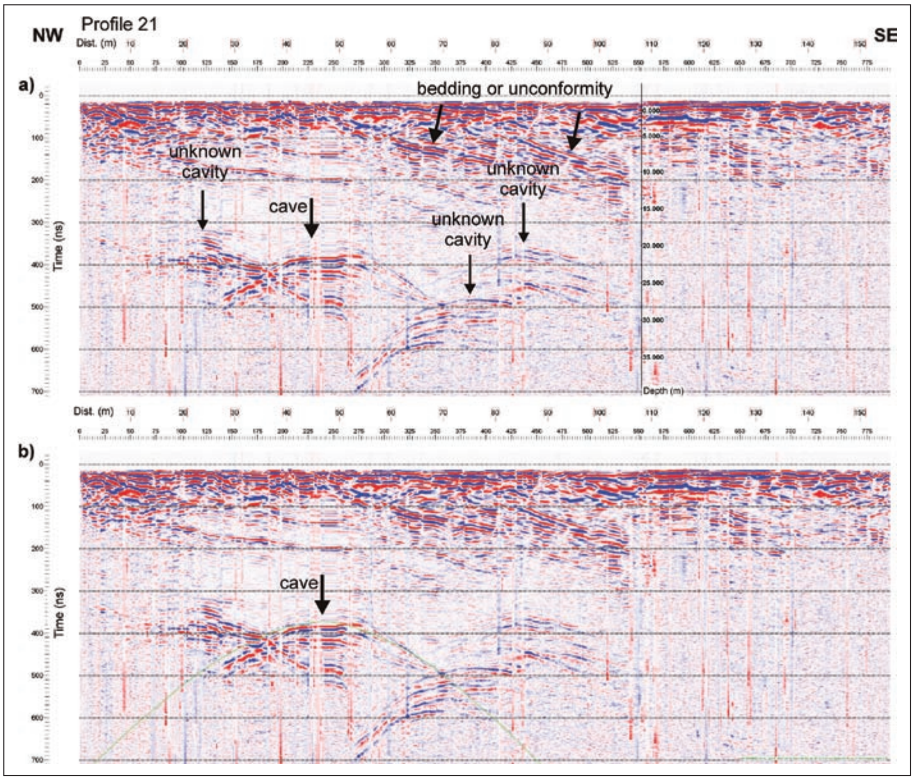

Fig. 11: GPR Profile 21 a) with time and depth scale, b) with hyperbola fitted to the diffraction caused by a cave.

less than 10 m wide. A dipping horizon at the NW end of the profile is perhaps caused by bedding or unconformity inside the limestone. Profile 9 (Fig. 9) was acquired across the widest part of the Žiberna hall. According to GPR data the gallery roof is at the depth of 18 m which is too shallow with respect to longitudinal cave section. It is possible that an unknown cave was detected and that the main gallery which should be at the depth of around 40 m remains unrevealed. There are also two horizons dipping in SE direction. The first one in the shallow part is most probably related to the bedding or unconformity and the second more steep one to the unknown cave

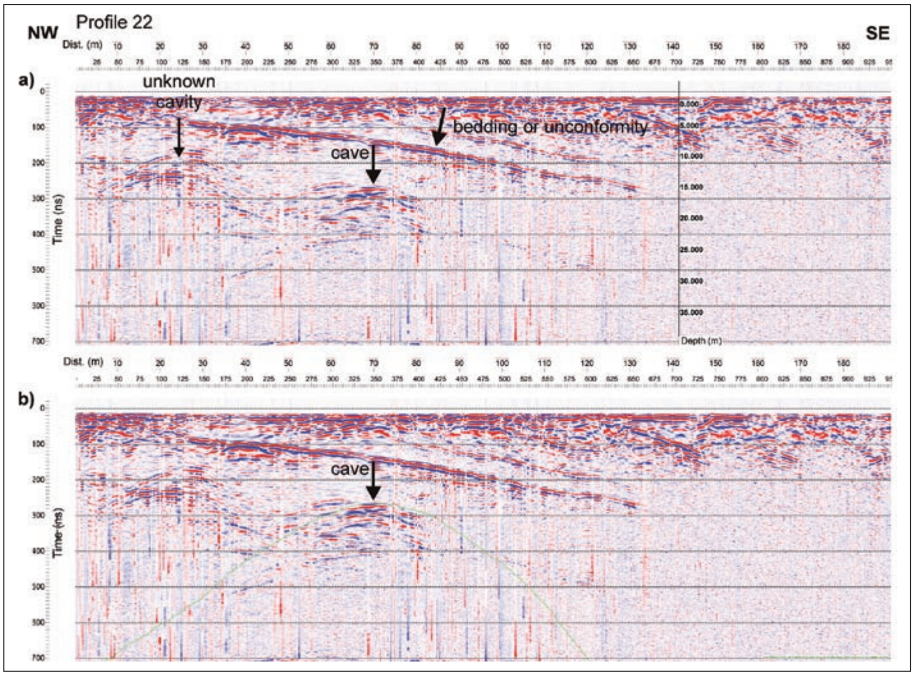

Fig. 12: GPR Profile 22. a) with time and depth scale, b) with hyperbola fitted to the diffraction caused by a cave.

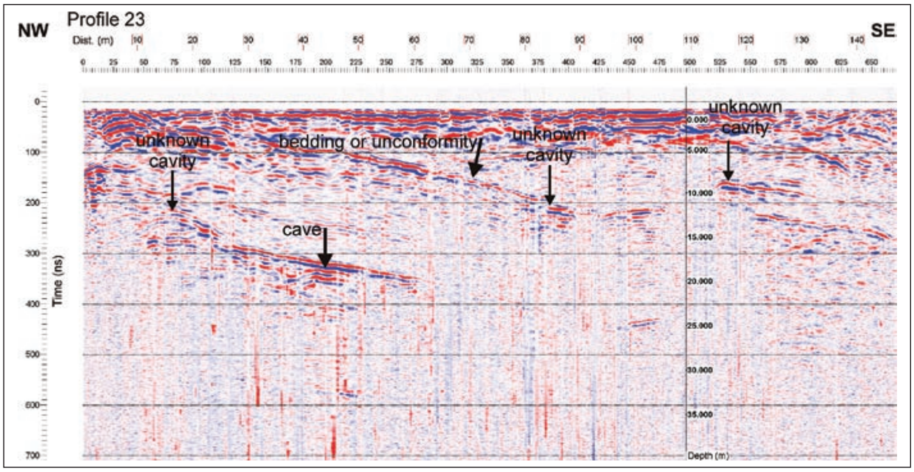

Fig. 13: GPR Profile 23 with time and depth scale.

passage, because underneath there is according to the ground plan a side gallery. Two shallow caves are clearly visible at the depth between 10 m and 15 m in profile 11 (Fig. 10), as well as a feature most probably related to the cavity at the depth of 22 m. At larger depths no cavities were imaged, but the profile is located near the SW end of the cave where the gallery is less than 10 m wide. Locations where the main cave gallery was revealed in all recorded profiles are shown in Fig. 2 and coincide very well with the actual location of the cave gallery.

Profiles 21–25 were recorded NE of the cave entrance across the prolongation of the axis of the main cave gallery when no accessible cavities are known. In profile 21 (Fig. 11), there are four clear diffractions visible which are interpreted as unknown cavities. The most prominent feature is interpreted as a continuation of the main gallery at the profile distance of 45 m and at the depth of 22 m. In the shallow part two horizons dipping to the SE are visible which can be interpreted as beddings or unconformities in the limestone. Profile 22 (Fig. 12) also reveals a clear cavity at the profile distance of 70 m and at the depth of 16 m. Additional cavity is very probable at the profile distance of 25 m and at the depth of 11 m. Clear bedding or unconformity horizon dipping toward SE is also visible. In profile 23 (Fig. 13) the main cavity is most probably located at the profile distance of 45 m and the depth of 18 m, but it is slightly masked by onlaping horizon. It is not impossible that also this horizon is related to larger underground chamber, because it is limited in space, in contrast to the more shallow dipping horizon which is much longer. Additional smaller cavities are probable at marked locations. Profile 25

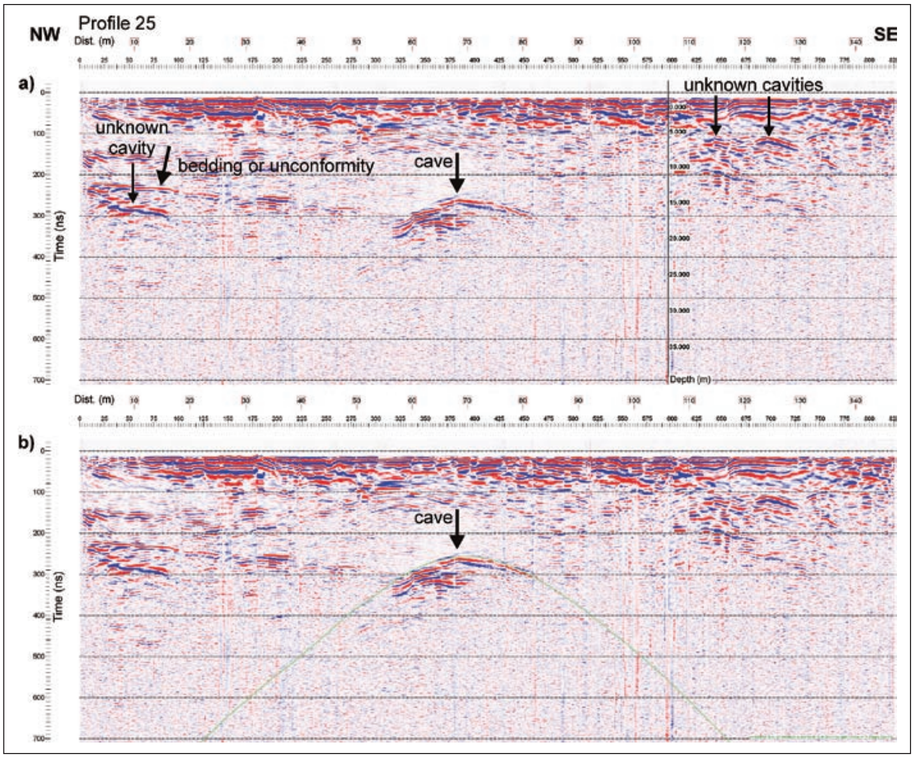

Fig. 14: GPR Profile 25 a) with time and depth scale, b) with hyperbola fitted to the diffraction caused by a cave.

(Fig. 14) reveals very clearly a cavity at the profile distance of 70 m and at the depth of 15 m. Some smaller cavities indicated by diffractions are probable at both ends of the profile.

The extent of unknown gallery can be clearly deduced by the interpolation between the markers shown in Fig. 2. In this area an anomaly with low resistivity was obtained by electric resistivity imaging which was interpreted as a cave gallery filled with loam (Mihevc & Stepišnik 2011). From georadar data alone it is not possible to deduce with confidence whether or not the detected galley is filled with sediments. However, since diffractions are very clear and similar to the features observed across the known cave, and include also prominent reverberations, it is more probable that we are dealing with open gallery. Therefore, the single resistivity profile from this part should be supplemented by additional profiles measured along existing georadar profiles to provide additional insight into this question.

CONCLUSIONS

Low frequency GPR have proved to be a very effective tool to detect larger cavities located at medium depths. The known main gallery of the Divača cave was clearly imaged in the NE part of the cave where the roof of the gallery is located at the depth from 10 m to 30 m and the width of the open space is mainly around 10 m. In the SW part of the cave the gallery is located deeper than 30 m, reaching the maximum depth of 60 m. In this part the performed measurements were not able to image the main cave gallery. This is most probably related to the limit of the depth penetration of 50 MHz system although the conditions were favourable, because it is expected that the limestone above the cave was relatively dry during measurements. Since the main cave gallery has a width between 5 and 15 m, the horizontal resolution should generally not be a problem at the depth of down to 40 m, but can limit the system capabilities at larger depth, especially where the gallery is less then 10 m wide. Although the main gallery was not imaged in this part, several shallower cavities were detected which were previously unknown. Testing of 25 MHz antennas, currently not available to us, is recommended as a next step to increase the depth penetration, but the spatial resolution at greater depths can limit the success in detection of a gallery in this case.

The most important result of this study is that the profiles acquired NE of the cave entrance revealed very clearly the existence of an unknown gallery which is located at the depth between 15 m and 22 m (Fig. 2). From the speleogenetic point of view (Gospodarič 1985; Mihevc 2001; Mihevc & Stepišnik 2011) continuation of the cave in this direction is expected. Access to unknown galleries is blocked by a collapsed material and other sediments at the entrance shaft. In addition to the main gallery which is visible in all profiles, some additional smaller cavities are also imaged. Additional speleological investigations are recommended to see if it is possible to reach the unknown galleries from either new entrances at the surface or from the entrance hall of the Divača cave, or to assess the feasibility if digging could result in a research progress.

High frequency GPR was already successfully applied in Slovenian karst in the past (Brezigar *et al.* 1995; Trček *et al.* 2000; Knez & Slabe 2005; Pavlič & Praznik 2011). On the other hand, some important infrastructural projects will be realized in the next decade, which will enclose also the construction of several long tunnels in karstified limestone. Therefore, it would be very important to supplement other geophysical investigations in the future also with the low frequency GPR profiling for detection of cavities in medium depth range which represent a serious hazard for such projects (Šebela 2009). In addition to surface GPR investigations, it is recommended to apply also GPR measurements inside boreholes drilled vertically from the surface or horizontally ahead of the tunnel front for more detailed in-situ information which will secure a safe realization of a project. Low frequency GPR investigations are recommended also in a basic speleological research to direct the research efforts when searching for continuation of existing caves, especially to assess if digging is feasible.

ACKNOWLEDGMENTS

The project was realized with the support of research program P1-0011 financed by Slovenian Research Agency. The author is indebted to Jure Hajna for a digital version of Divača cave ground plan.

REFERENCES

Alvarez-Cabrera, R., 2011: GPR Antenna Resolution. Geoscanners AB.- [Online] Available from: http://www.geoscanners.com/pdf/antres.pdf [Accessed 2nd December 2011].

Benson, A.K., 1995: Application of ground penetrating radar in assessing some geological hazards: examples of groundwater contamination, faults, cavities.- J. of Applied Geophysics, 33, 177–193.

Božičević, S., 1995: Kaptaža u kaverni ispod tunela Učka.- In: Vlahović, I., Velić, I. & M. Šparica (ed.) *Vodič po ekskurziji na 1. hrvatskom geološkom kongresu*, 18th–21th October 1995, Opatija, Croatia. Hrvatsko geološko društvo, 3–15, Zagreb.

Brezigar, A., Tomšič, B., Štern, J. & G. Rašković, 1995: Georadar – visokoločljiva geofizikalna elektromagnetna naprava (Georadar – high resolution geophysical electromagnetic device).- Geologija, 37–38, 437–458.

Chamberlain, A.T., Sellers, W., Proctor, C. & R. Coard, 2000: Cave detection in limestone using Ground Penetrating Radar.- J. of Archaeological Science, 27, 957–964.

Daniels, D.J., 2004: *Ground Penetrating Radar*.- The Institution for Electrical Engineers, pp. 726, London.

Davis, J.L. & A.P. Annan, 1989: Ground-Penetrating radar for high-resolution mapping of soil and rock stratigraphy.- Geophysical Prospecting, 37, 5, 531–551.

Frumkin, A., Ezerssky, M., Al-Zoubi, A., Akkawi, E. & A.R. Abueladas, 2011: The Dead Sea sinkhole hazard: Geophysical assessment of salt dissolution and collapse.- Engineering Geology, 134, 102–117.

Gospodarič, R., 1985: O speleogenezi Divaške jame in Trhlovice (On the speleogenesis of Divaška jama and Trhlovca cave).- Acta Carsologica, 13, 5–32.

Jol, H.M., 2009: *Ground Penetratig Radar: Theory and applications*.- Elsevier, pp. 524, Amsterdam.

Knez, M. & T. Slabe, 2005: Non-destructive georadar researches in the area of road subsidence of motorway near Postojna, classical Karst, Slovenia.- Geophysical Research Abstracts, 7.

Kofman, L., Ronen, A. & S. Frydman, 2006: Detection of model voids by identifying reverberation phenomena in GPR records.- J. of Applied Geophysics, 59, 284–299.

Mala, 2010: *ProEx – Professional Explorer control unit, Operating manual*.- Mala, pp. 60, Mala.

Mareš, S., Kelly, W.E. & O. Mazač, 1997: *Applied Geophysics in Environmental Engineering and Science*.- Universita Karlova, pp. 98, Prague.

McMechan, G.A., Loucks, R.G., Zeng, X. & P. Mescher, 1998: Ground Penetrating Radar imaging of a collapsed paleocave system in the Ellenburber dolomite, central Texas.- J. of Applied Geophysics, 39, 1–10.

Mihevc, A., 2001: *Speleogenesis of Divača karst (Speleogeneza Divaškega krasa)*.- Založba ZRC, 27, pp. 180, Ljubljana.

Mihevc, A. & U. Stepišnik, 2011: Uporaba metode električne upornosti tal na primeru Divaške jame. Dela, 35, 45–54.

Placer, L., 1981: Geološka zgradba jugozahodne Slovenije (Geological structure of southwestern Slovenia).- Geologija, 24, 1, 27–60.

Pavlič, M.U. & B. Praznik, 2011: Detecting karstic zones during highway construction using ground-penetrating radar.- Acta Geotech. Slovenica, 8, 1, 17–27.

Pueyo-Anchuela, O., Pocovi-Juan, A., Soriano, M.A. & A.M. Casas-Sainz, 2009: Characterization of karst hazards from the perspective of the doline triangle using GPR –Examples from Central Ebro Basin (Spain).- Engineering Geology, 108, 225–236.

Reynolds, J.M., 1997: *An Introduction to Applied and Environmental Geophysics*.- Wiley, pp. 796, Chichester.

Sharma, P.V., 1997: *Environmental and engineering geophysics*.- Cambridge University Press, pp. 475, Cambridge.

Šebela, S., 2009: Caves as potential karst geohazards on highways in SW Slovenia.- Annales Ser. hist. nat., 19, 177–184.

Trček, B., Car, M. & M. Veselič, 2000: The use of isotopic, hydrogeochemical and ground-penetrating radar investigations in the study of the unsaturated zone of the karst aquifer.- RMZ – Materials and geoenvironment, 47, 335–344.

Xu, X., Zeng, Q., Li, D., Wu, J. & J. Shen, 2010: GPR detection of several subsurface voids inside dikes and dams.- Engineering Geology, 111, 31–42.