Surface Geophysical Methods used to Verify the Karst Geological Structure in the Built-up Area: A Case Study of Specific Engineering-Geological Conditions

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Abstract: This article presents a research study of complex limestone karst engineering-geological conditions in the municipality Valaská near Banská Bystrica in Slovakia. The aim of the study is to demonstrate the impossibility of spatial identification of cave spaces using surface geophysical methods due to the specific engineering-geological conditions of a thick surface layer of anthropogenic fill containing highly heterogeneous anthropogenic material. Its maximum thickness is 3 m. Another specificific condition of the study area is its location in the built-up area, due to which the applicability of geophysical methods was limited. The article contains methodological recommendations to be used in analogous geological conditions with karst structures topped with anthropogenic fill, which complicates the identification of cave spaces. The recommended solution herein is the identification of the cave system using underground mapping of the karst and its projection onto the surface for which surface geophysical methods have been combined.

Key words: karst, engineering geology, limestone, dolomite, anthropogenic fill, complicated engineering-geological conditions, geophysical study

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1 Introduction

The engineering-geological environment of karst is connected with a number of geohazards that cause different engineering problems (Karacan and Yilmaz, 1997; Yilmaz, 2007, Parise, 2010; Parise et al., 2015; Yilmaz et al., 2011, 2015; Gutiérrez et al., 2014; Keskin and Yilmaz, 2016). These are influenced by specific hydrological (White, 2002) and hydrogeological conditions of karst areas, which subsequently affect the environmental situation (LaMoreaux et al., 1997; Guo et al., 2013). Karst is very sensitive to anthropogenic interference (Milanovic, 2002), which often changes its character. Among others, the anthropogenic interference may be related to urban development, construction of dams (Li and Zhou, 1999; Chen and Wu, 2008), and mining (De Waele, 2008).

The most important goal of engineering-geological research and investigations in karsts is the spatial identification of karst underground space in order to assess its stability (Yang and Drumm, 2002) and reduce the risk of collapse. In the karst area, which is the subject of this case study, there are specific engineering-geological conditions. This meant that specific solutions and methods were needed to identify the underground space. In the case study presented herein this paper, there is the playground for children on the ground surface. It was assumed that the human lives of the present on the children's playground, situated on limestone karst in the contact with dolomite rock massif, were endangered.

In 2014 subsidence of ~30 cm appeared on the children's playground and it was necessary to verify the engineering-geological conditions, including the geometrical determination of the karst environment. In the past, a horse-drawn cart disappeared underground. Meanwhile, several houses had to be demolished for safety reasons, and made-up ground as thick as 3 m in places was formed there. The made-up ground contains anthropogenic fill of highly heterogeneous physical-mechanical properties of the rock materials.

A great deal of attention is paid to engineering-geological research and investigations of karst. However, this case study presents a unique environment of the karst system topped with anthropogenic sediments. Another

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specificity of the engineering-geological conditions is the fact that a built-up area is located in the vicinity of the endangered site. Investigations of karst in the built-up area has been reported by Sevil et al. (2017), and it is clear that geophysical research and investigations in such localities have their limits arising from the necessity to investigate the deeper karst geological structures. This is especially complicated because of the need of longer geophysical cross-sections for the application of geoelectric methods, in particular.

The geophysical investigations of karst areas are very specific (Margiotta et al., 2012) due to the physical-mechanical properties of the karst rocks and the specific hydrogeological conditions in the karst (Barner, 1999; Wang et al., 2001; Parise, 2003) in dependence on the karst permeability (Galvão et al., 2016) and sudden changes in the karst water regimes. Next, there is the influence of large underground spaces that may be void or filled with secondary sediments. All the environments may be free of water, may be permanently submerged in water, or both situations may alternate, which poses another complication for the stability of the rock massif. The last situation is characteristic for the area of interest presented in the article.

The aim of the study is to demonstrate the impossibility of spatial identification of cave spaces using surface geophysical methods due to the specific engineering-geological conditions. The study recommends a solution lying in the identification of the cave system using underground mapping of the karst and its projection onto the surface, and a combination of surface geophysical methods. The recommendation may be useful in analogous conditions.

2 Specific Conditions of Different Engineering-Geological Environments of Karst and Engineering-Geological Investigation Methods

Engineering-geological research and investigations of karst areas are highly specific for the limiting conditions to be considered. For the stability of rock massif in the karst, the most important is the geometry and shape of the karst space, disruptions of the rock massif, failure mechanisms (Parise and Lollino, 2011), thickness and character of the rock mantle, hydrogeological conditions and their changes, petrographic, physical-mechanical properties of carbonate rocks (Eroskay, 1982), karst permeability, the karst character, its age and its various natural or anthropogenic impacts. An important aspect of the karst geological environment is its susceptibility to subsidence problems (Lamont-Black et al., 2002; He et al., 2003; Wu, 2006), which lead to changes in the rock massif stability. The specific karst geohazards (Farrant and Cooper, 2008) cause problems in foundation engineering (Yu, 2001; Cooper and Saunders, 2002). Due to a high variability in the conditions, engineering classification of karst is crucial (Waltham and Fookes, 2003).

In engineering-geological investigations using geophysical methods, the overlying geological structure is very important. For illustration, four simplified forms of the structure as it is crucial for the results of the engineering-geological research and investigations are presented in Fig. 1. In the first case the karst outcrops onto the ground surface (Fig. 1a). In the second case (Fig. 1b) the karst is roofed with the Quaternary geological structure of various character. In the third case the karst is topped with anthropogenic sediments, mostly in the form of made-up ground (Fig. 1c). In the fourth case (Fig. 1d) the bottom of the anthropogenic made-up ground contains Quaternary geological cover that passes into the karst geological structure.

The aim of the article is to point at the different approaches to engineering-geological research and investigations in the above mentioned situations, but in the first place to emphasize the particularities of the third (Fig. 1c) and fourth case (Fig. 1d; subject of the case study, see the next section). The first and second situations are well feasible and rather easy to interpret during an engineering-geological investigation using geophysical methods. However, the third and fourth situations (the case study) are completely different and they need a specific methodological approach arising from the limited possibility to well distinguish the physical fields in the bedrock of the heterogeneous anthropogenic made-up ground, especially if its thickness is higher (as much as 3 m in this case study).

3 Case Study

Three different methodological approaches were used in the study.

The first approach aimed to verify the karst situation using surface geophysical measurements as the drilling and penetration operations were excluded. Drilling operations (Fig. 2a) were excluded because of the risk of cave formation top collapse due to drilling equipment

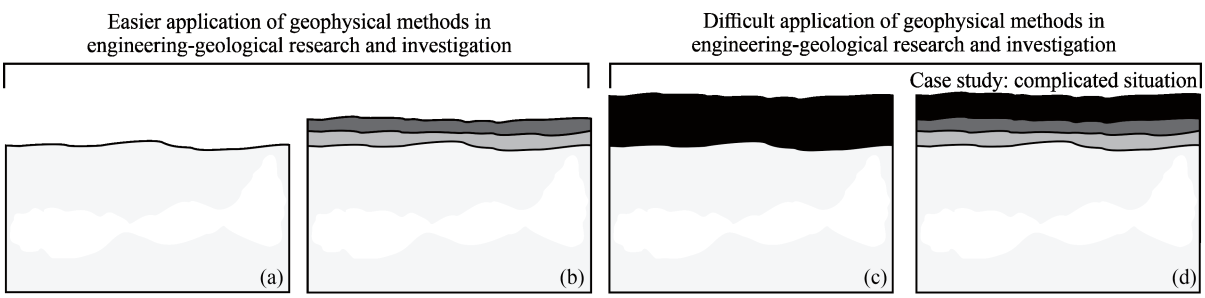


Fig. 1. Four different situations in terms of applying geophysical methods in engineering-geological research and investigation. (a) Karst without an overlying geological stratum in the formation top; (b) karst with the Quaternary geological structure in the formation top; (c) karst with a heterogeneous made-up ground; (d) karst with the Quaternary geological cover in the bottom of an anthropogenic ground.

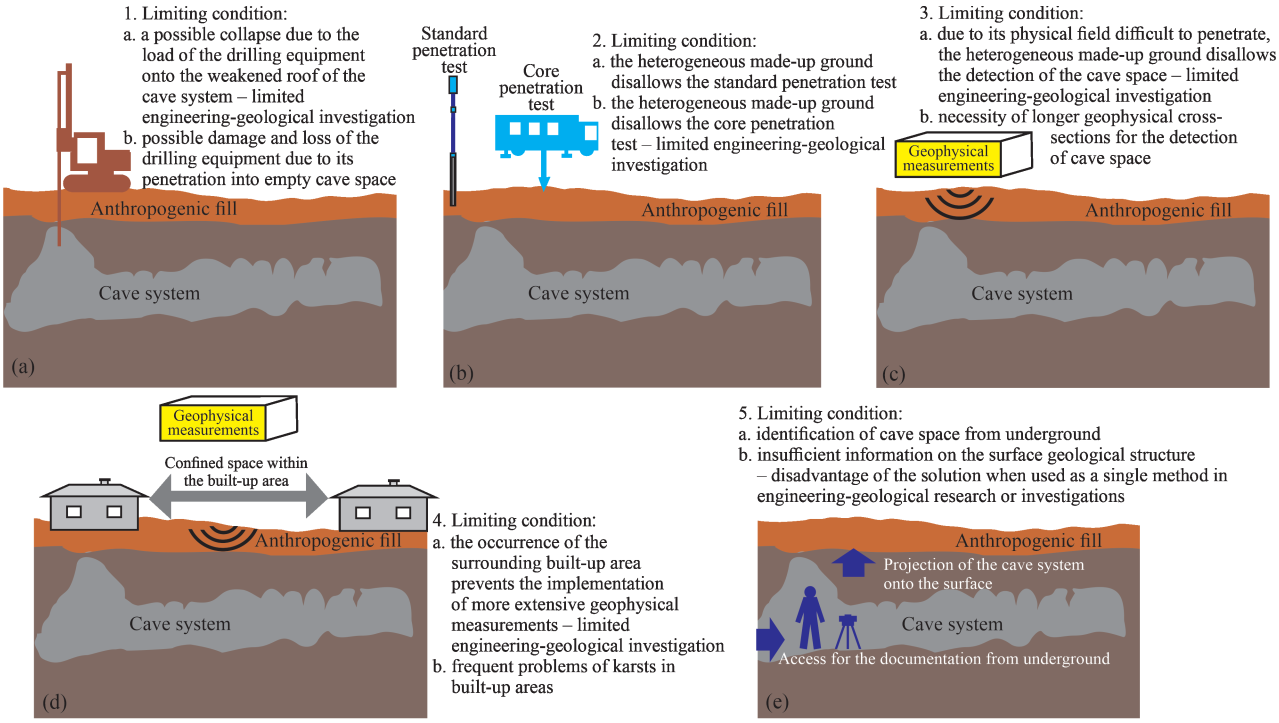


Fig. 2. Limiting conditions in the case study presenting the difficulties of engineering-geological investigation of a possible collapse of karst topped with heterogeneous made-up ground.

excess load and possible damage of the drilling equipment in the cave system. Penetration methods (Fig. 2b) were not used as the passage through the heterogeneous made-up ground constituting of debris was not possible. Using a core penetration test the hazard is even higher than in case of standard penetration test due to the risk of collapse because of the weight of the equipment needed.

As a result, a geophysical approach was selected as the geological structure of many karst areas. However, the possible hazards of geophysical methods can't be studied from the underground, and the geophysical research within the case study concluded that the application of such methods in the locality is limited due to the made-up ground position (Fig. 2c) and the surrounding built-up area (Fig. 2d). The applied geophysical methods are discussed in Section 4.

The second approach to verify the karst situation was the identification of cave spaces from underground (Fig. 2e). However, this approach showed to have provided insufficient information on the surface geological structure, which is vital for the optimum proposal of safety measures in the locality. There is children's playground located on the surface and the stabilization measures had to take the character of the surface material into account. At the same time, the upper space of the karst system had to be investigated too.

The third approach (the case study discussed in Section 4) combined the access from the surface and the access from underground. Finally, it showed as the most optimum solution for the geological conditions of the case study (see Fig. 2c, e).

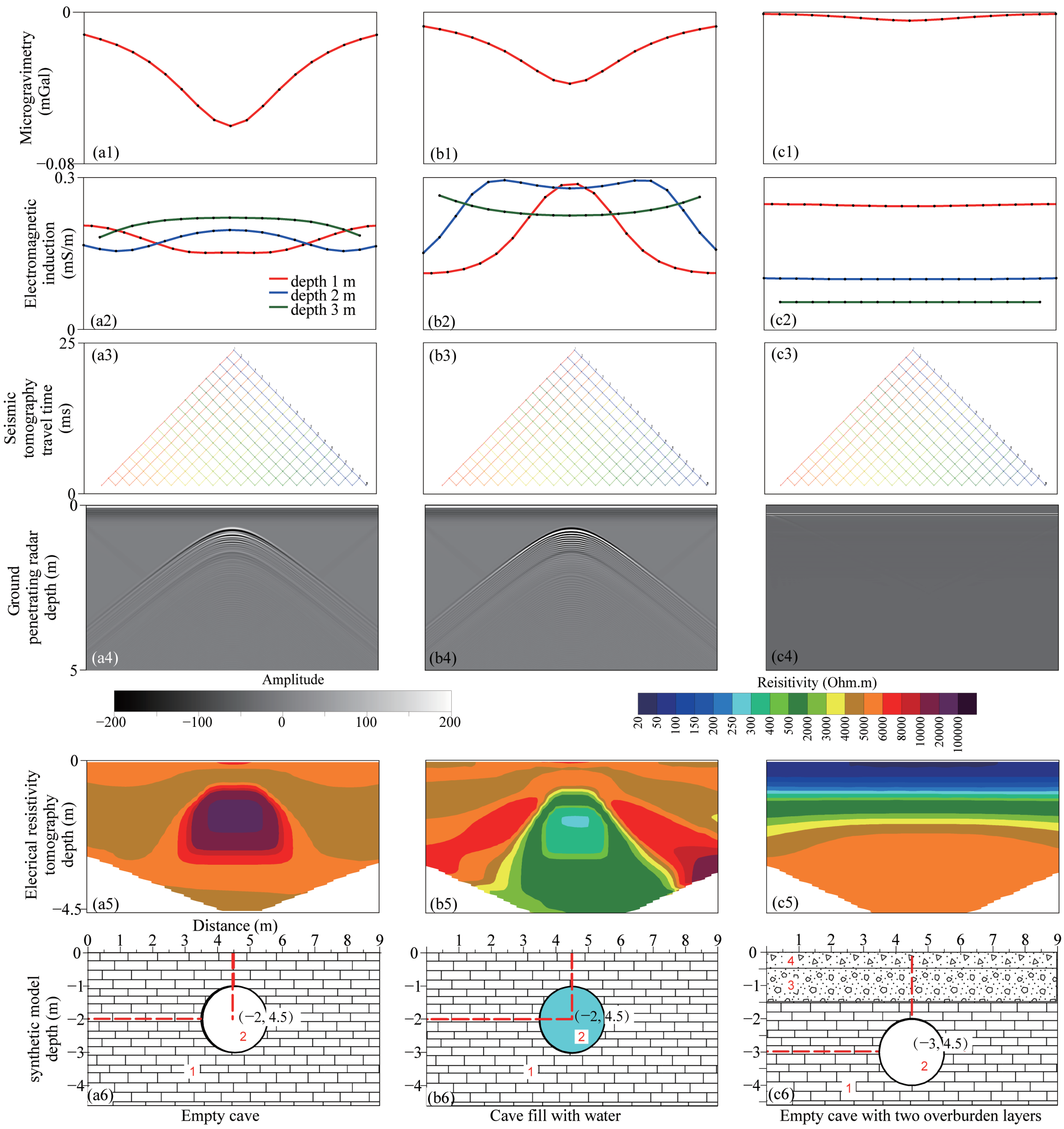
4 A Combination of the Applied Geophysical Methods and Identification of the Cave Space via the Underground Access

Selected geophysical methods applied in the conditions of karst, which were applied in the case study: microgravimetry (Beres et al., 2001; Leucci and De Giorgi, 2010), electromagnetic induction (Zhang et al., 2011; Gondwe et al., 2012), seismic tomography (Cardarelli et al., 2010; Galibert et al., 2014), ground penetrating radar (Carrière et al., 2013; Rodríguez et al., 2014), and electrical tomography (Roth et al., 2002; Metwaly and AlFouzan, 2013). Within the case study, we identified different effects of physical fields in the karst, which have been influenced by the heterogeneous fill containing debris.

It is important for the methods applied in geophysical investigations of karst areas to have a sufficient physical contrast between the structure of interest (cave) and its surroundings. We present two model cases when ideal situations may be expected (Fig. 3).

In the first case (Fig. 3a6, model A6), when the karst area is empty and there is no anthropogenic fill on the top, the physical effects are sufficient to reliably identify the spatial dimensions. There is a clear resistivity (high resistivity values; Fig. 3a5), ground penetrating radar record – a significant hyperbola of indirect waves (Fig. 3a4), and the gravitational effects in microgravimetry (Fig. 3a1) (significant minimum). There is an unclear effect using electromagnetic induction (Fig. 3a2) and no effect in seismic tomography (Fig. 3a3).

In the second case (Fig. 3, model B6), when the karst



Model/parameter		Reisitivity (Ohm.m)	Permitivity	Conductivity (mS/m)	Seismic velocity (m/s)	Density (kg/m³)
Model A	1	5000	6	0.2	4000	2700
	2	1000000	0	0	0	0
Model B	1	5000	6	0.2	4000	2700
	2	100	80	10	1500	1000
Model C	1	5000	6	0.2	4000	2700
	2	1000000	0	0	0	0
	3	300	4	0.0001	1500	2000
	4	50	9	0.1	2000	1500

Fig. 3. Three synthetic models A6: empty cave, B6: cave filled with water, C6: empty cave with two overburden layers, and their effects in 5 geophysical methods (microgravimetry a1, b1, c1; electromagnetic induction a2, b2, c2; seismic tomography a3, b3, c3; ground penetrating radar a4, b4, c4; electrical resistivity tomography a5, b5, c5). The physical parameters of modelled geological environments are shown in the table.

area is filled with water and there is no anthropogenic fill on the top, the physical effects obtained from certain methods are well interpretable. There is a clear resistance Fig. 3b5 (low resistivity values), ground penetrating radar – a significant hyperbola of indirect waves (Fig. 3b4), the electromagnetic induction curves have sufficient contrasts in the different depths (Fig. 3b2) as opposed to the previous model of karst without water - A6. In the gravitational field in microgravimetry (Fig. 3b1) the local minimum is smaller due the combination of the larger depth of the cave and contribution of a negative effect of the anthropogenic fill on the top. In seismic tomography there was no clear physical effect (Fig. 3b3), similarly to the model of karst without water - A6.

Substantial complications for the geophysical investigation of karst areas are the Quaternary and anthropogenic covers, which are discussed in this article. The thickness of overlying strata is directly related to the depth of karst cave position from the surface (model in Fig. 3c6). The effect of karst cave in the geophysical fields decreases along with the increase in depth. Another important aspect are different physical properties of the overburden of the Quaternary sediments and anthropogenic fill in relation to the immediate surroundings of the karst cave. In such situations, the physical effect of the karst caves may be shadowed as the physical effect of fill and sediments dominate (Fig. 3c1–5).

Within a complex geophysical investigation of the area of interest, the article presents the results of cross-section measurements above the known karst cavity (Fig. 4), from which the underground space had been mapped in the past (Fig. 1e, 4). In this study, measurements of gravimetry (GG-5-Scintrex), electromagnetics (CMD Explorer-Multidepth Electromagnetic Conductivity Meters-GF Instruments), refraction seismics (A6000-MAE, 36 channels), GPR with 100 MHz antenna (SIR 3000-GSSI) and electric resistance tomography (ARESII-Automatic resistivity system-GF Instruments) were used.

The results of the geophysical investigation in the presented cross-section show a prominent impact of the anthropogenic fill and Quaternary sediments on the measured physical fields and thus the effect of the karst space is difficult to interpret (Fig. 4a–e). The situation is further complicated by the presence of the built-up area and steep slopes, which represent important limiting conditions of engineering-geological research and investigation of karst areas. As a result, using the method of electric resistivity tomography (Fig. 4e) it was possible to reach only the upper part of the karst space. Their effect is shadowed by the effect of Quaternary sediments and anthropogenic fill (Fig. 4f). The measurement results correspond to the model situation in Fig. 3c5, where the effect of the karst cave disappeared under the layer of fill and sediments.

The fill and Quaternary sediments may also be interpreted from the records of the ground penetrating radar (Fig. 4d). Due to the overburden layers, the signal from lower depths is not sufficient to record other structures. This result is also confirmed by the results of modelling (Fig. 3c4), where it is possible to observe only an interface between the conducting anthropogenic fill and Quaternary sediments. Deeper interfaces did not show there.

Seismic tomography (Fig. 4c) managed to distinguish only the interface of the fill and Quaternary sediments from the bedrock limestone. The identification of deeper interfaces was excluded by the limited length of cross-section due to the surrounding built-up area.

The method of electromagnetic induction (Fig. 4b) only rendered information on the character of the fill and Quaternary sediments, but did not provide any information on karst cave space that is clearly present there. The depth level of 2.2 m is solely made up by anthropogenic fill. The

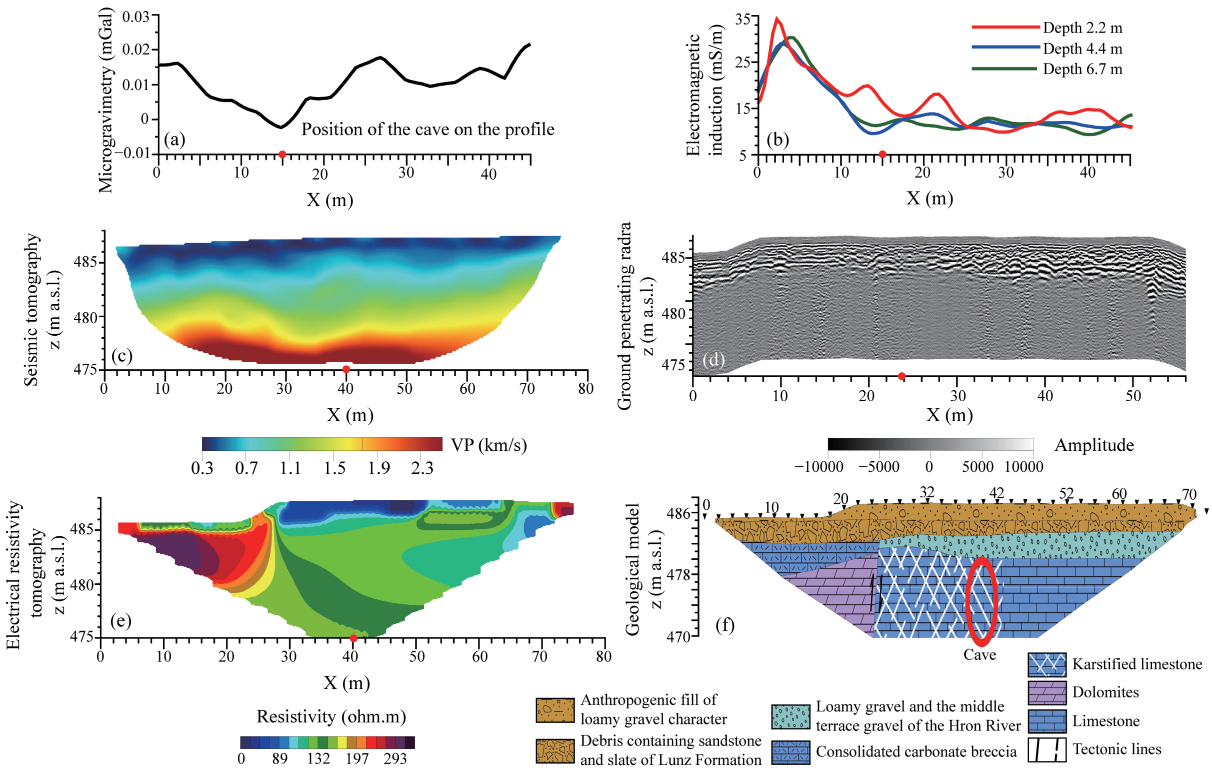


Fig. 4. Geophysical measurements in the area of interest.

depth level of 4.4 and 6.7 m reflect the relative homogeneity of Quaternary gravel sediments constituted by the Hron River terrace. As clear from the model in Fig. 3c2, the character and thickness of the anthropogenic fill directly influences the measurement results, i.e. the karst cave space is not visible.

The local gravitational minimum from microgravimetry (Fig. 4a) had a very small amplitude. It may be attributed to the low degree of compaction of the anthropogenic fill. Based on the microgravimetry results, the effect of the anthropogenic fill and sediments corresponds to the results of modelling (Fig. 3c1), where the effect of caves in the gravitational field almost disappeared under the overburden layers.

The location of the cave in Fig. 4f is given by a red circle. The actual geometry of the cave mapped by divers is shown in Fig. 5. There is an air pocket in the upper part of the cave system. The water level changes based on the current climatic, hydrological and hydrogeological conditions of the cave system.

5 Conclusions

The research results of the case study point at the necessity to distinguish the methodological approaches to the determination of geological structure in the karst environment, in the overburden of which there are anthropogenic heterogeneous sediments. This represents a significant limiting condition which hinders the effectiveness of verification of karst geometry as the physical fields change to such an extent that the spatial dimensions of the cave system cannot be clearly determined.

Another limiting condition that influences the application of geophysical methods in this case study is the location of the site in the built-up area, which limits and influences the application of geophysical methods

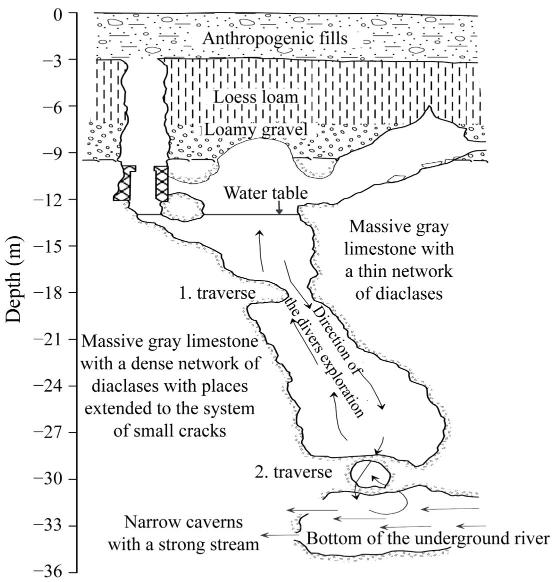


Fig. 5. Mapped karst space accessed above the cavity from underground; it is topped with anthropogenic heterogeneous fill.

during the identification of karst geological structure. The application is especially impossible because of insufficient lengths of geophysical cross-sections used for the methods of electrical resistivity tomography (ERT), the presence of utility lines when using the methods of electromagnetic induction (EMI) and ground-penetrating radar (GPR), and last but not least, the presence of transport which influences the measurements of seismic tomography and gravimetry.

In case of problematic identification of karst using surface geophysical methods, it is possible to use drilling and penetration operations. In this case, drilling operations are not recommended because of possible risk of collapse due to the equipment weight and possible damage or loss of the equipment in the empty karst space. The limitations are of a safety, technical and financial character. As for the penetration methods, the complications lie in the impassability of the heterogeneous debris materials and there is also a risk of collapse of the penetration equipment due to its weight.

Therefore, the solution may be found in the identification of karst space and their mapping accessed from underground. The access from underground may be ensured in several different ways. The first option is to access the investigated site posing hazard on the surface from a more remote karst outcrop on the ground surface. The second option is to access the karst via an artificial adit, which is the safest and less expensive way to make the karst accessible. The third option is to exploit the karst cavity in the site of overburden collapse.

However, the information obtained via the access from underground may be limited due to the passability of karst and impossibility to obtain spatial information on the cave space geometry using the geophysical methods. Therefore, in the given conditions, we decided to combine the access from the ground surface using geophysical methods and the access from underground cave system related to the site under hazard on the ground surface. Direct engineering-geological and speleological mapping were used.

The case study determined the geometry of the cave space. The karst system is approximately 35 m deep and 15 m wide (Fig. 5). It consists of partial cave spaces, in which the vertical orientation dominates. We also found that the upper part of the cave space is located 8 m below the ground surface. Originally, the thickness was only 5 m, but a 3-meter layer of anthropogenic fill had been placed there. The stability of the site is endangered by high water tables of as high as 10 m below the ground surface and the occurrence of permanent underground river. This is remediated via a drainage system of three horizontal drainage boreholes. These get clogged and need to be cleaned on a regular basis. As it is mentioned on page 3 that in the past, a horse-drawn cart had disappeared underground. The place of the overflow was opened, mapped and drawn by a diver and a geologist. Based on this and overlap of archival information, Fig. 5 was constructed.

There are three model situations in the article. The realized study deals with the third model situation, where the cave system is covered with heterogeneous anthropogenic made-up ground with a thickness of 3 m. The identification of the cave was made on the basis of an overlap with historical data (fall of the horse into the cave system and diving survey and mapping of the cave system). For the inversion the RMS error statistics was set to 5%.

The geometry of the overburden was verified by geophysical and geodetical measurements (in the old reports, the original terrain height was stated). The cave itself was verified by a study of archival data associated with the fall of the horse-drawn carriage and the subsequent diving focus of the cave system (Fig. 5). The spatial error is determined by the errors of the measuring instruments used, random errors and external disturbances.

This article also draw attention to the relatively high risk of not discovering the karst system using a set of geophysical methods in certain specific conditions. In this case, we have a combination of high heterogeneous anthropogenic made-up ground over the karst system and at the same time geophysical survey is carried out in an area where there is dense construction. In these cases, it is necessary to combine the results of the measurements with the available information and with the review so far.

The results of the case study are applicable in analogous geological conditions. The problem of heterogeneous anthropogenic fill above karst systems needs larger attention as this engineering-geological problem completely alters the application of so far used investigation methods. The solution is relevant also for other engineering-geological environments, but is highly significant for karst environments, in particular.

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