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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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THE APPLICATION OF ELECTRICAL RESISTIVITY IMAGING IN COLLAPSE DOLINE FLOORS: DIVAČA KARST, SLOVENIA

Abstract: Electrical Resistivity Imaging (ERI) is a widely used tool in geophysical surveys for investigation of various subsurface structures. In this study an ERI was conducted in collapse doline floors located in Divača karst, Slovenia. This group of collapse dolines in hinterland of River Reka ponors have floors inundated and flattened with loamy sediment. Collapse doline development and transformation processes are discussed, and various characteristics and potential formation mechanisms of flat and loamy doline floors are considered. The loamy fills might reflect sedimentation of suspended material from floodwaters that inundated the lower parts of the collapse dolines, or could have originated in now-demolished cave passages on the slopes that were filled with finer material.

Key words: karst, collapse doline, loamy sediment, Electrical Resistivity Imaging (ERI), Slovenia

INTRODUCTION

Karst surface in Slovenia covers an area of about 44% or 9,000 km^2 (N o v a k 1993). It developed mainly in limestone and dolomite bedrock. The Slovenian karst includes at least 330 major collapse dolines with volumes ranging from 0.03 Mm^3 up to 12.6 Mm^3. The larger collapse dolines are usually situated in areas of karst through flow, mainly in the hinterland of the larger ponors and in the catchments of major karst springs. Collapse dolines are more common in the hinterland of the ponors of the Matarsko podolje area, in the Ljubljanica River catchment and on the Kras (Karst, Carso) plateau.

The article discusses collapse dolines in the southeast part of the Kras plateau which will be referred to as the Divača karst. Detailed geomorphic analysis of several collapse doline floors in the area is discussed in this article. The subsurface structure of the doline floors was established using Electrical Resistivity Imaging (ERI) techniques, with subsequent interpretation of the ERI data. A SuperSting R1/IP earth resistivity meter, developed by Advanced Geosciences, Inc., was used for data collection. The data were processed to generate two-dimensional resistivity models using EarthImager 2D resistivity inversion software.

This method has been confirmed to be appropriate for providing a robust visualization of the epikarst structure and the subsurface structure of the collapse dolines (Stepišnik and Mihevc 2008). The research included geomorphological mapping of several collapse dolines and granulometrical and petrological analyses of loamy sediment from the collapse doline floors.

ELECTRICAL RESISTIVITY IMAGING

Although Electrical Resistivity Imaging has been successfully utilised for characterising the subsurface for many years, it has certain limitations. The method was labour-intensive, interpretation of data was time-consuming and the method itself based on individual subjective interpretation (Roman 1951; Zhou et al. 2002). Development of computer controlled multielectrode resistivity survey systems and the development of resistivity modelling software have allowed more cost-effective resistivity surveys and better interpretation of the subsurface (Locke and Barker 1996). These surveys are usually referred to as Electrical Resistivity Imaging (ERI) or Electrical resistivity tomography (ERT) (Zhou et al. 2002). These facts allow data to be collected and processed quickly so the electrical Resistivity Imaging surveys become a valuable tool in subsurface investigations (Zhou et al. 2000).

Electrical Resistivity Imaging surveys are typically conducted to determine the resistivity of the subsurface. Resistivity data can be used to determine the location of various geologic and soil strata, bedrock fractures, faults and voids. Fundamental to all resistivity methods is the concept that the current is impressed into the ground and the effect of this current within the ground can be measured. The effect of potential or differences of potential, ratio of potential differences, or some other parameter that is directly related to these variables are the most commonly measured effect of the impressed current. The principal differences among various methods of electrical resistivity lie in the number and spacing of the current and potential electrodes, the variable quantity determined and the manner of presenting the results (EarthImager 2003; Zhou et al. 2000).

Generally, carbonate rock has a significantly higher resistivity than loamy material because of its considerably smaller primary porosity and fewer interconnected pore spaces. Its resistivity value is about 1000 ohm · m (Telford et al. 1990). Loamy materials can hold more moisture and have higher ion concentration to conduct electricity; therefore, their resistivity values are below 250 ohm · m (Telford et al. 1990). The high contrast in resistivity values between carbonate rock and loamy material favours the use of Electrical resistivity method to determine the boundary between bedrock and overburden or loamy sediment (Zhou et al. 2000).

A frequently occurring problem with Electrical Resistivity Imaging is the determination which electrode configuration will respond best to the material changes in karst features. Each array has distinctive advantages and disadvantages in terms of sensitivity to the material variations, depth of investigation and signal strength. The most typical arrays are dipole-dipole array, Wenner array and Schlumberger array. The dipole-dipole array gives good horizontal resolution of data while Wenner and Schlumberger arrays are more directed in vertical resolution. In the application to karst surveys, the dipole-dipole array has provided highest precision of ground changes sensitivity and had greatest sensitivity to vertical resistivity boundaries (Zhou et al. 2002).

COLLAPSE DOLINES

Collapse dolines are surface karst depressions of varied shape and size. Volumes of larger collapse dolines exceed the volumes of the largest known cave chambers in the area, so collapse doline formation cannot be related solely to a series of collapse processes within cave chambers and eventually on the surface (Habič 1963; Šušteršič 1973; Stepišnik 2004; Waltham et al. 2005; Stepišnik 2007). Their origin is related to the concentric removal of material, with associated collapse of underground chambers, or with gradual removal of tectonically fractured carbonate bedrock above active cave passages (Habič 1963; Mihevc 2001; Stepišnik 2004). Although collapse dolines have commonly been defined as depressions that are formed above cave chambers (Cramer 1941; Gams 1983; Šušteršič 1973; Ford and Williams 1989), a variety of speleogenetic mass removal processes contribute to their development.

Formation of smaller collapse dolines is related to cave chamber collapse. At the instant of collapse, a qualitative modification takes place as a subsurface karst feature becomes a surface karst feature. From this moment onward a combination of speleogenetic processes and a variety of exogenic geomorphic processes begin to operate. Development of larger collapse dolines involves gradual removal of material above the active cave passages. Duration of the process defines the volume of the collapse dolines and the dynamics of the process defines the inclination and morphology of the slopes. Dominance of material removal over the rate of weathering of bedrock on the doline margins results in the formation of steep slopes and walls (Stepišnik 2007).

Many morphological classifications of collapse dolines have appeared in published karstological literature. The most common is a simple subdivision of collapse dolines into "immature" and "mature" or "degraded" (Habič 1963; Šušteršič 1984; Summerfield 1996; Waltham et al. 2005; Waltham 2006). However, collapse doline morphology is a result of the establishment of a balance between various geomorphic processes, whose dynamics, extent and duration inside the collapse dolines influence their size and shape. Changes involved depend upon the rates of underground removal of the rock, on slope angles and mechanical properties of the bedrock, which are not uniform even within a single collapse doline (Stepišnik 2007). Consequently, the published, classical, view of collapse dolines, which estimates their age on the basis of their general morphology, is not appropriate.

Collapse doline floors are subjected to a number of processes that result in the development of a variety of floor morphologies. In collapse dolines undergoing continuous removal of material above active cave passages, the floors are rocky with funnel-shaped depressions in accumulated talus. If the process of material removal is negligible or absent, concave floors occur, and these are filled with the finer fractions of weathered bedrock, commonly covered with soil. Smaller patches of loamy material are not uncommon on the floors of collapse dolines. If their floors lay tens or hundreds of meters above piezometric level and there is no soil on the karst surface, it must be concluded that the soil originated in now-demolished cave passages on the slopes that were completely filled with finer material. If weathered material has been completely removed or if the floor lies near the level of the piezometric surface, the lower parts of the collapse dolines are permanently or periodically filled with water or active water flow is present. In most cases the floors of such collapse dolines are flooded only occasionally, during periods of higher piezometric levels. If floodwaters contain a significant suspended load, sediment will eventually be deposited from a stagnant water body. Each ensuing flood will result in the deposition of additional loamy sediment layers on the floor. The ultimate outcome of such sedimentation is the establishment of flat, loamy floors in collapse dolines (Stepišnik 2003; Stepišnik 2007). The occurrence of flat collapse doline floors at similar elevations might be a result of sedimentation of suspended material from floodwaters that inundated the lower parts of several neighbouring collapse dolines approximately at the same flooding event (Stepišnik 2004; Stepišnik 2007).

DIVAČA KARST

Kras is a limestone plateau situated above Trieste Bay in the northern Adriatic Sea. Stretching in the Dinaric (northwest–southeast) direction, it is 40 km long and 14 km wide and covers about 440 km^2. With regard to the surrounding regions, it is physiographically well individualised. Lower flysch regions and the Adriatic Sea bound it from the southwest and the northeast, to the northwest it is surrounded by the alluvial Isonzo (River Soča/Isonzo) plain. Towards southeast, the border of Kras can be well defined by the flysch Brkini Hills and the River Reka valley.

Divača karst is situated in the south-eastern part of the Kras between the hinterland of the River Reka ponor and the town of Divača. The bedrock in the area comprises thickly bedded Cretaceous limestone, dipping approximately 20 degrees towards the south, bounded in the south and north by Paleogene thin-bedded limestone. The Divača karst is positioned northwest of the contact with the Eocene flysch bedrock. At the end of extensive blind valley on the eastern flank, the River Reka sinks into the cave system of — Škocjanske jame (5,800 m of passages; Central Cave..., 2008) at the elevation 317 m. This large sinking river causes substantial oscillations of the water level in the caves and neighbouring karst surface. In Škocjanske jame water rises up to 90 m (Mihevc 1984). After the terminal sump River Reka reappears in the Kačna jama (12,750 m of passages; Central Cave 2008) which is situated south of Divača.

Surface of the Divača karst is mainly planated at the elevation of 430 m and is dissected by numerous dissolution dolines, collapse dolines and roofless caves. Dissolution dolines are up to 100 m in diameter and about 10 m deep. Their density can be higher than 200 dolines per km^2. The volumes vary between some thousands to several tens of thousand cubic meters (Mihevc 1997). On the planated surface it is possible to recognise several roofless caves which are denuded sections of horizontal or subhorizontal epiphreatic cave passages. The largest section is about 30 m wide and can be recognised for a length of about 600 m (Mihevc 1997). Several authors have investigated the development of collapse dolines and caves on the Divača karst (Radinja 1967; Gams 1983; Gospodarič 1984, 1985), classifying collapse dolines by shape and position and according

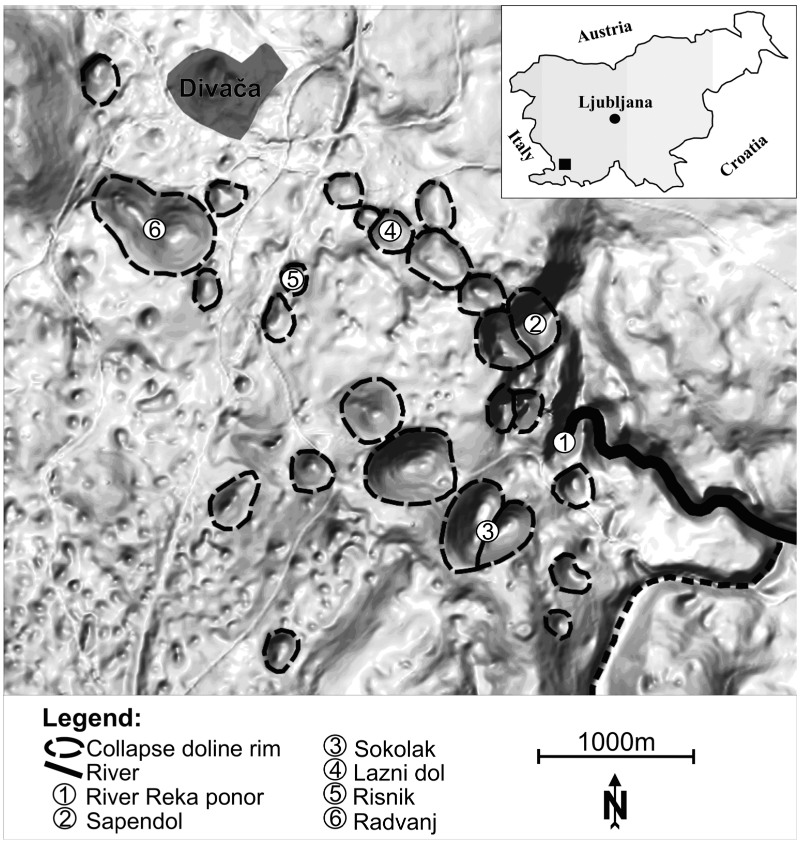

Fig. 1. DEM of the Divača karst

to this division indirectly interpreting the development of the cave system in the area. A. Mihevc (1997) associated the position and morphological elongation of collapse dolines with their geological structure. The development and origin of collapse doline floors has not yet been interpreted in detail.

On the surface there are also 27 large collapse dolines with an overall volume of more than 41 Mm^3. Their mean depth is about 45 m and mean diameter is 135 m. These collapse dolines cover an area of 1.5 km^2 and differ in terms of morphology. Most of their slopes are balanced, but extensive rocky walls and scree also occur. With the exception of Velika dolina and Mala dolina, situated directly above — Škocjanske jame where underground flow of the River Reka reappears on the surface, all collapse dolines have floors inundated and leveled by deposits of loamy sediment. Petrological analysis of the sandy fraction in the sediment revealed that the loam contains particles of flysch origin. Grain-size analysis of the sediment showed that the loam comprises mainly clay and silt size particles. The elevations of the floors vary between 270 m and 430 m above mean sea level.

Several neighbouring large collapse dolines have floors at the same elevation, and the floors are flat due to the presence of loam deposits. In the Divača karst, some of the collapse doline floors fall into groupings at two general levels. Those in the southern side near Sokolak lie at the elevations between 350 and 360 m. The floors in the northern group of collapse dolines, between Sapendol and Lazni dol, are at elevations between 415 and 433 m (Fig. 1).

USE OF ELECTRICAL RESISTIVITY IMAGING IN COLLAPSE DOLINES

Electrical resistivity data were collected in five different collapse dolines with floors inundated with loamy material. The SuperSting R1/IP earth resistivity meter developed by Advanced Geosciences, Inc. was used for data collection. The survey was conducted with dipole-dipole array. In most cases 20 electrodes were used simultaneously with alternation of two current and two potential electrodes. For longer profiles roll-along survey was used. The data was processed to generate two-dimensional resistivity models using Earthimager 2D resistivity inversion software developed by Advanced Geosciences, Inc. The Root-Mean-Square (RMS) error quantifies the difference between the measured resistivity values and those calculated from the true resistivity model. A small RMS value indicates small differences. The minimum RMS error in the survey was 2.59%, and the maximum error was 8.2%.

Previous application of this method in various karst surface features on Slovenian karst revealed that the resistivity value for carbonate rock exceeds 1,000 ohm · m. For soil and weathered bedrock, the resistivity values are approximately between 200 and 1,000 ohm · m. Loamy material has resistivity values lower than 150 ohm · m (Stepišnik 2007; Stepišnik and Mihevc 2008).

The doline slopes are rocky walls with scree below them. Lower parts of the slopes are mostly balanced and modified by human activity. Northern part of the collapse doline is open towards inactive section of the River Reka steephead valley. Loamy sediment fill in the floor is completely flattened at the elevation of 336 m. The diameter of the flattened floor is 230 m (Fig. 2).

Results of Electrical Resistivity Imaging with 6 m electrode spacing shows that inside the doline there is an extensive fill of less resistive loamy material with resistivity value up to 150 ohm · m. Depth of the fill is more than 35 m. Only in the north-

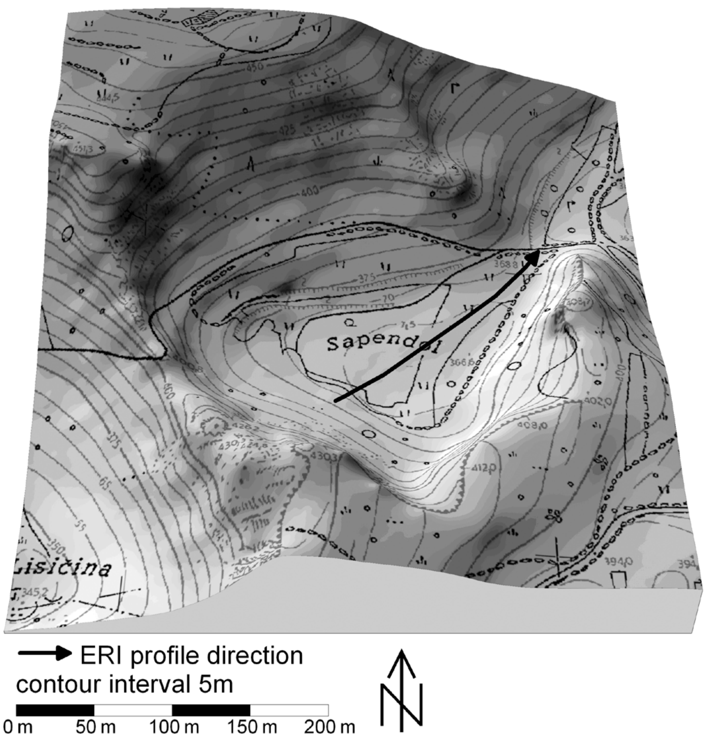

Fig. 2. DEM of Sapendol with ERI profile direction

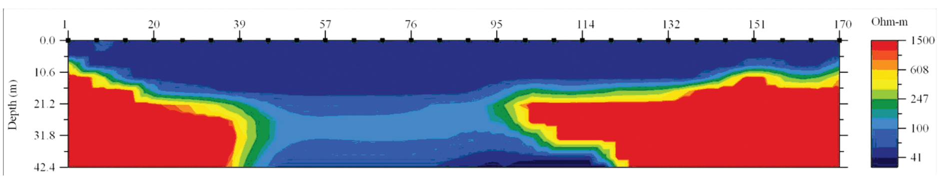

Fig. 3. Inverted ERI profile of Sapendol

ern part where slopes are interrupted and the collapse doline floor elongates towards steephead valley, depth of the loamy material, overlaying carbonate bedrock with resistivity values more than 1000 ohm · m, is less than 10 m (Fig. 3).

SOKOLAK

Sokolak consists of two collapse dolines elongated in the north–south direction. The collapse doline slopes in the southern part are steep rocky walls with extensive scree at their foot. Other slopes are mostly balanced and are covered with grikes and slope breccia. Floors of the dolines are flattened with loamy material. The western side of the doline is flattened at the elevation of 350 m and the eastern side is at 357 m. Elevation of their floors corresponds to the elevation of the floors in several surrounding collapse dolines (between 350 and 360 m) (Fig. 4).

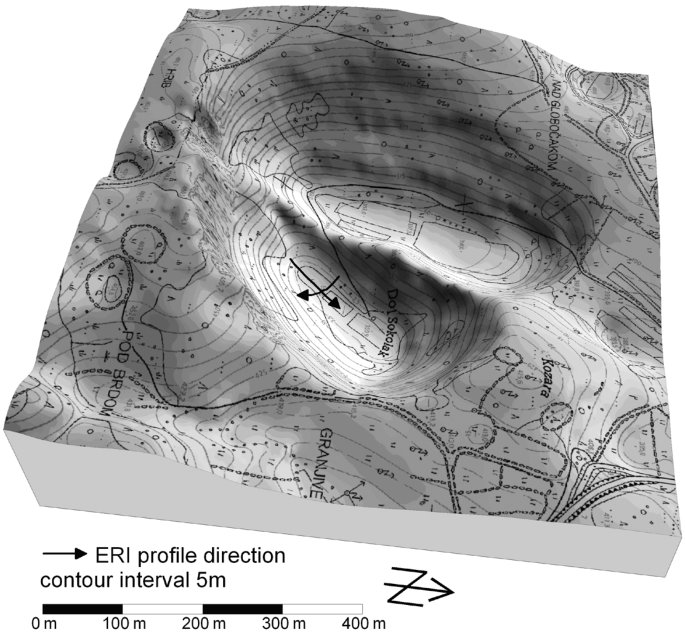

Fig. 4. DEM of Sokolak with ERI profile directions

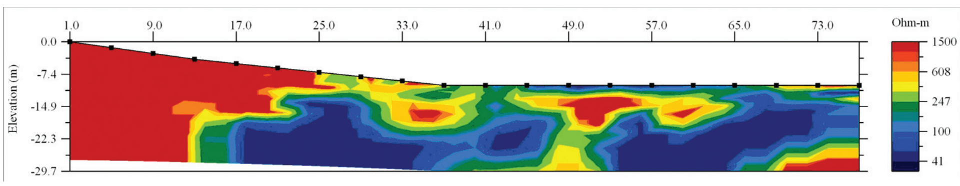

Fig. 5. Inverted ERI profile of Sokolak in direction of 30 degrees

Both ERI surveys were conducted in the western part of the collapse doline. First ERI profile at the foot of the southern slope in the direction of 30 degrees with 5 m electrode spacing showed that its limestone scree slopes, which are not covered by soil or vegetation, have resistivity values higher than 1,000 ohm · m. Extensive loamy fill at the foot of the slope has resistivity value lower than 150 ohm · m and is covered with limestone rubble with resistivity value between 150 and 1,000 ohm · m (Fig. 5).

Second ERI profile was conducted transversely to the elongated collapse doline floor in the direction of 120 degrees with 5 m electrode spacing. It revealed that bedrock slopes with resistivity values higher than 1,000 ohm · m are covered with a thin layer of less resistive soil and weathered rock with resistivity values up to 500 ohm · m. In the central part of the profile the floor is flattened with loamy sediment that inundates collapse doline at the depth of approximately 23 m with resistivity value lower than 150 ohm · m (Fig. 6).

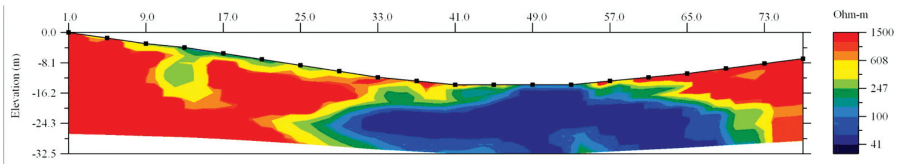

Fig. 6. Inverted ERI profile of Sokolak in direction of 120 degrees

LAZNI DOL

The slopes of the collapse doline are balanced, covered with grikes with the inclination up to 17 degrees. The floor of the doline is an extensive flat surface filled with loamy material with a longer diameter of about 220 m. Lowest section of the floor is at the elevation of 424 m. Elevation of the floor corresponds to the elevation of several surrounding collapse dolines in the northern part of the Divača karst which have floors situated between 415 and 433 m (Fig. 7).

Two ERI surveys were conducted in the Lazni dol. First ERI survey of the doline floor, in the direction of 135 degrees with 5 m electrode spacing, indicated that the lower section of its bedrock slopes are covered by a thin layer of soil and weathered rock with resistivity values ranging between 200 and 1,000 ohm · m. The infill of loamy material in the doline floor has resistivity values up to 150 ohm · m. Limestone bedrock underlying the slope material and parts of the loamy sediment floor infill has resistivity values higher than 1,000 ohm · m. In the central part of the doline, the thickness of the more conductive material exceeds 25 m (Fig. 8).

Second ERI profile in the direction of 225 degrees was conducted with 5 m electrode spacing. It revealed that the floor of the doline is inundated with loamy material with resistivity value lower than 150 ohm · m at the depth of more than 28 m (Fig. 9).

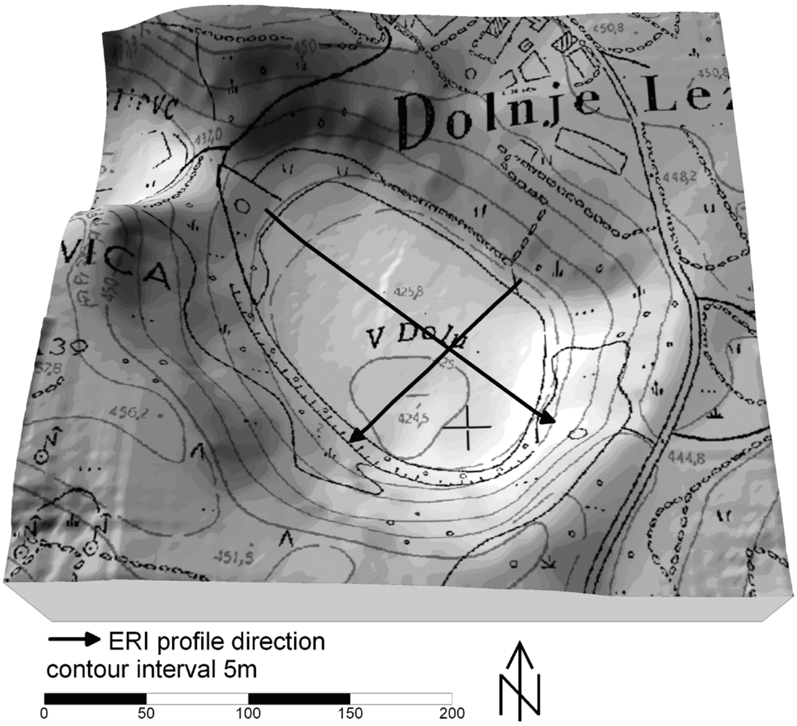

Fig. 7. DEM of Lazni dol with ERI profile directions

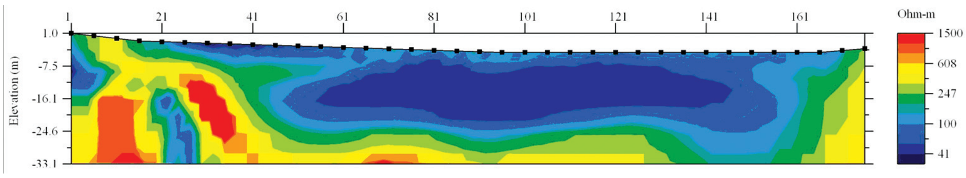

Fig. 8. Inverted ERI profile of Lazni dol in direction of 120 degrees

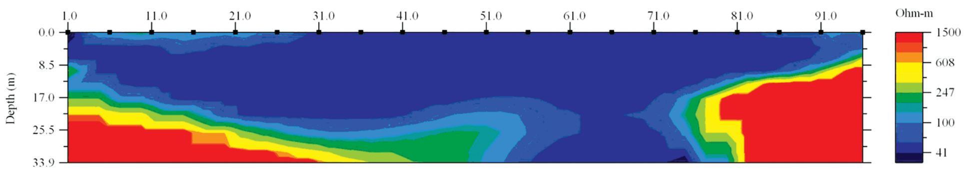

Fig. 9. Inverted ERI profile of Lazni dol in direction of 225 degrees

RISNIK

Risnik is a collapse doline situated above a sump which divides — Škocjanske jame from Kačna jama. All of the collapse doline slopes are steep rocky walls with scree at their foot which covers the slopes to the floor. The floor is filled with loamy alluvial fan 40 m in diameter. Its apex is at the mouth of a distinctive erosion gully filled with loamy material and flowstone. The dip of the alluvial fan is 2 to 4 degrees with the lowest point at the elevation of 366 m. The elevation of its floor does not correspond to any adjacent collapse doline (Fig. 10).

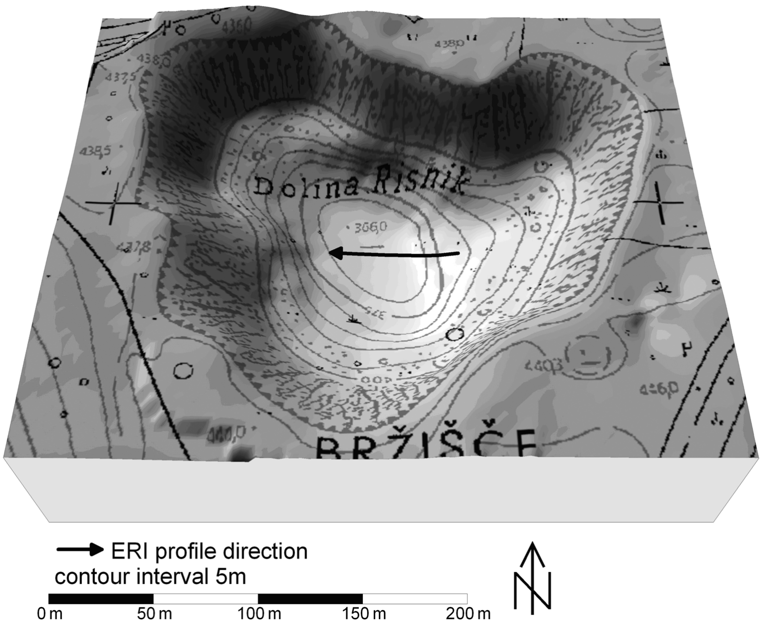

Fig. 10. DEM of Risnik with ERI profile direction

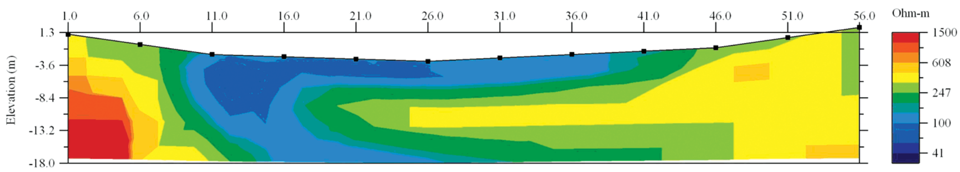

Fig. 11. Inverted ERI profile of Risnik in direction of 280 degrees

ERI profile in the direction of 280 degrees with 5 m electrode spacing shows that inside the doline there is a 5-metre deep pocket of less resistive loamy material with resistivity value up to 150 ohm · m, overlying a structure with resistivity value of approximately 500 ohm · m. It corresponds to the resistivity values of carbonate rubble or scree. In the western part of the floor the depth of loamy sediment exceeds 12 m. The eastern slope of the collapse doline is composed of scree, covered with a thin layer of soil and vegetation, with resistivity values up to 600 ohm · m. Lower section of the western slope is covered with soil and vegetation on top of 5 m thick scree, (resistivity value up to 600 ohm · m), overlying carbonate bedrock with resistivity value higher than 1,000 ohm · m (Fig. 11).

RADVANJ

Radvanj consists of two collapse dolines: Divaški Radvanj in the west and Gorenjski Radvanj in the east. The ridge between both dolines is located 10 m higher than the floor of a shallower Gorenjski Radvanj collapse doline. Slopes of the Divaški Radvanj are balanced in the north and partly covered with grikes. Southern part of the doline has steeper slopes with some sections covered with scree. On the northern slope there are two erosional gullies filled with loamy material including pieces of flowstone. Two smaller alluvial fans are formed at their mouth in the floor of the collapse doline. Other section of the floor is flattened with loamy material at the elevation of 365 m.

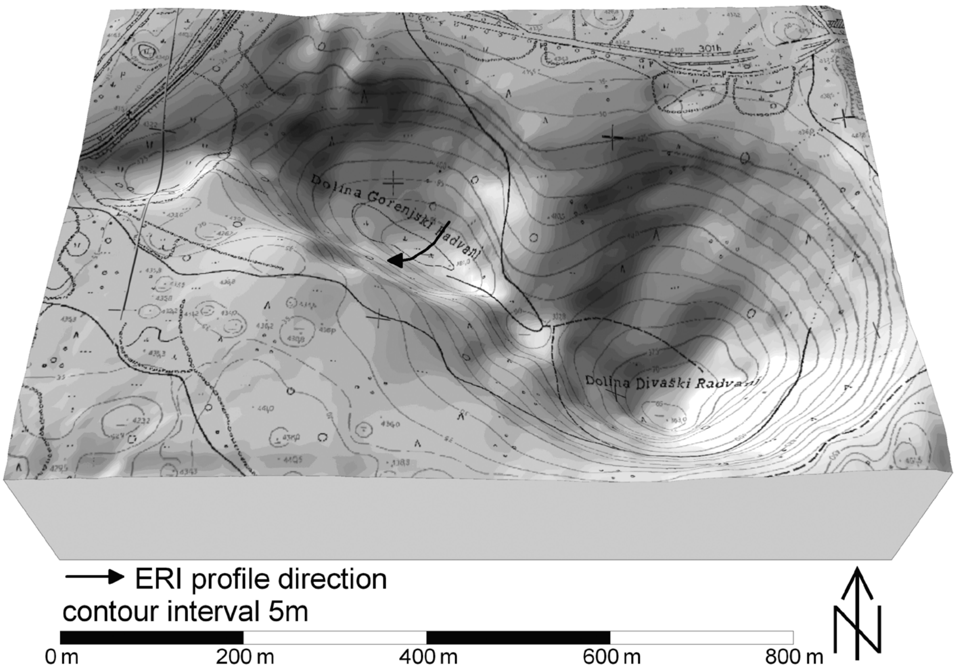

Fig. 12. DEM of Radvanj with ERI profile direction

The slopes of the Gorenjski Radvanj are mostly balanced. Lower sections of the slopes are covered with loamy material. On the western slopes there are two erosional gullies filled with loamy material and flowstone. At the mouth of the gullies, on the floor of the collapse doline two small alluvial fans are formed. The floor of the doline is flattened with loamy material which is inclined from 1 to 3 degrees towards the eastern, lowest part of the doline at the elevation of 381 m. Elevation of the floor is not identical to any nearby collapse doline (Fig. 12).

ERI survey of the Gorenjski Radvanj floor in direction of 210 degrees with 5 m electrode spacing that the bedrock slopes of the collapse doline with resistivity value more than 1,000 ohm · m are covered with thin layers of electrically less resistive soil, mechanically weathered rock or loamy material with resistivity value about 500 ohm · m. Thickness of the weathered material is greater in the lower part of the slope. The doline floor itself is filled with over 22 m of loamy sediment (resistivity value up to 150 ohm · m), overlying carbonate bedrock with resistivity value exceeding 1,000 ohm · m. In the central part of the loam-covered bedrock floor there is an electrically less resistive vertical structure with resistivity values up to 150 ohm · m, possibly a fault or a shaft, now filled with loamy sediment, which guided doline development (Fig. 13).

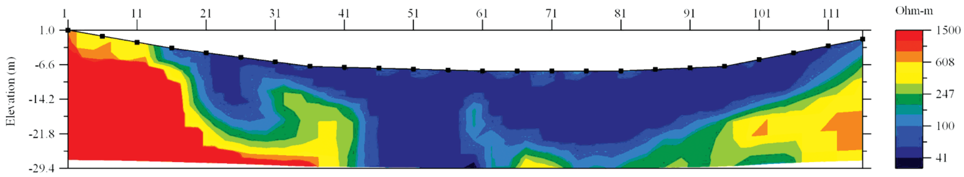

Fig. 13. Inverted ERI profile of Radvanj in direction of 210 degrees

CONCLUSIONS

The results of ERI profiling in collapse doline floors show zones with important differences in electrical resistivity. The resistivity of the subsurface depends mainly on water saturation and chemical properties of pore water. The bottoms of collapse dolines show smaller resistivity as a result of retention of water by the sediment. On the slopes there are zones with more resistive carbonate bedrock due to lower porosity. The application of ERI revealed that the resistivity value for carbonate bedrock exceeds 1,000 ohm · m. Loamy material has resistivity values lower than 150 ohm · m. For soil, weathered bedrock and scree the resistivity values are between 250 and 1,000 ohm · m. Due to the lack of moisture active scree slopes without soil cover and vegetation have resistivity values higher than 1000 ohm · m. If scree is covered with a layer of soil and vegetation, resistivity values are approximately 500 to 600 ohm · m.

In all investigated collapse dolines we can clearly see the difference between slopes and floors. The slopes show highly resistive rock, which is limestone or scree, possibly covered with weathered bedrock or a layer of soil or loamy sediment which display lower resistivity values. At the floors there are thick infills of loamy sediment and patches of slope material at the foot of the active slopes. Loamy sediment completely inundates original collapse doline floors to the depths greater than 30 m.

The origins of loamy material are not clear. Some collapse doline slopes show traces of demolished cave passages filled with finer sediment and flowstone. It implies that loamy material originates from cave infill that appeared on the slope surface during or after the collapse dolines were formed. Similar floor level elevations inside many collapse dolines also suggest that the process that led to the sedimentation of the fine allochtonous particles from stagnant water was active, not only locally inside isolated collapse dolines but across a wide area. It is likely that the deposition of the loamy sediment fills inside the collapse dolines resulted from the River Reka oscillations and subsequent flooding inside the Divača karst. The original floors of the affected collapse dolines extended below the upper limits reached by floodwaters supplying the loamy sediment that formed the new flat floors.

The results of the study presented in this paper show that the method of Electrical Resistivity Imaging is a valuable tool for investigation of robust subsurface structures of collapse doline floors filled with loamy material. It is useful if there is a considerable difference in electrical conductivity between carbonate bedrock and loamy sediment.

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STRESZCZENIE

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ZASTOSOWANIE OBRAZOWANIA ELEKTROOPOROWEGO W BADANIACH DOLIN KRASOWYCH Z ZAPADANIA, OBSZAR KRASOWY DIVAČA, SŁOWENIA

Obrazy elektrooporowe są szeroko stosowane w badaniach geofizycznych dla określania struktur podłoża. W tym przypadku użyto metody ERI dla określenia morfologii podłoża ślepych dolin krasowych, powstałych na skutek osiadania den dolin na obszarze krasowym Divača. Zespół ponorów zapadliskowych w dorzeczu rzeki Reka posiada płaskie dna, wypełnione materiałem ilastym. W pracy omówiono rozwój zapadniętych dolin oraz są analizowane procesy przekształcające te formy. Wypełnienia ilaste są interpretowane jako produkt sedymentacji materiału zawiesinowego wód powierzchniowych, które zalewały dolne części zapadających się dolin, lub mogły pochodzić ze zniszczonych korytarzy jaskiniowych. Autor pokazuje, że metody elektrooporowe pozwalają odróżnić podłoże skał węglanowych od osadów ilastych, przy zastosowaniu dwuwymiarowego modelu Earth Imager 2D. Analizowane formy są ukazane w świetle istniejących w literaturze klasyfikacji.