ARTICLES

KARSTOLOGY IN MOTORWAY CONSTRUCTION ON CLASSICAL KARST

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ABSTRACT
Karstology in motorway construction on Classical Karst
One of the major ongoing projects in Slovenia was to link the country with modern motorways. Almost half of Slovenia is karst and more than half of its supply of water comes from karst aquifers. Slovenia is the home of the Classical Karst region – Kras. Karstologists have been involved in planning and construction of motorways. We have acquired a great deal of information about surface karst phenomena and the epikarst, and where excavation work has cut deeper in the surface and in tunnels, about the vadose zone and the paleokarst. Development of the karst usually left important traces, above all in the numerous old caves. More than 350 new caves have been opened. During the planning we tried to avoid important karst phenomena as are collapse dolines, large dolines, caves and karst walls and by impermeable construction of a roadway we tried to prevent the pollution flowing from it into underground waters. During the construction works we researched newly discovered karst features and tried to preserve as many as possible.

KEY WORDS
motorway construction, karstological monitoring, karst, karst cave, Classical Karst (Kras), Slovenia

IZVLEČEK
Krasoslovje in gradnja avtocest na matičnem Krasu
Eden večjih projektov, ki potekajo v Sloveniji, je povezati državo s sodobnimi avtocestami. Skoraj polovica Slovenije je kraške in več kot polovica voda, s katerimi se oskrbujemo, je iz kraških vodonosnikov. Krasoslovci smo vključeni v načrtovanje in izgradnjo avtocest. Kjer so zemeljska dela posegla globlje v površje, smo pridobili vrsto spoznanj o površinskih kraških pojavih, epikrasu, v predorih pa o vadozni coni ter paleokrasu. Razvoj krasa pogosto pusti pomembne sledove nad in v številnih jamah. Med gradnjo avtoceste prek Krasa se je odprlo 350 novih jam. Med načrtovanjem se skuša izogniti pomembnim kraškim pojavom, kot so udornice, večje vrtače, jame in kraške stene. Z nepropustnimi cestišči pa skušajo preprečiti onesnaženje podzemne vode. Med gradnjo raziskujemo novo odkrite kraške pojave ter jih skušamo čim več ohraniti.

KLJUČNE BESEDE
gradnja avtocest, krasoslovna spremljava, kras, kraška jama, Kras, Slovenija

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1 Introduction

Over the last fifteen years the construction of modern motorways in Slovenia has been one of the major construction projects aimed at connecting important parts of the country and opening them to Europe. Almost half of Slovenia is karst and more than half of the water for the supply of the population comes from karst aquifers. Slovenia is home to the classical karst region of Kras that gave its name for this unique carbonate rock landscape to numerous world languages and is also the cradle of karstology. We need to better understand this fragile karst landscape and do everything to preserve it since it is an important part of our natural and cultural heritage.

Special attention is devoted to Kras, a karst plateau rising above the northeastern-most part of the Adriatic Sea that is bordered on the southwest by a vast flysch area with elevations exceeding 600 meters. Lying between 200 and 500 meters above sea level, the plateau covers 440 square kilometers and in a broad sense belongs to the External Dinarides. Only Cretaceous and Paleogenic carbonate rocks are found here. They are characterized by exceptionally varied limestone that mostly formed in relatively shallow sedimentation basins with lush fauna and flora. Originally, the plateau was surrounded and covered with flysch and therefore flooded. The role of vertical percolation was minimal. On the Kras plateau there are no sediment remains of the surface waters to explain the development of the plateau. The water table later dropped several hundred meters into the karst (Placer et al. 2010). At the contact between the carbonate rock and flysch, surface waters created characteristic contact karst. Today, all Kras rivers sink where they flow from flysch onto limestone bedrock and flow underground toward the springs of the Timava River in Italy. The largest stream is the Reka River, which sinks in the Škocjan Caves, while 65% percent is precipitation water. From the ecological standpoint, Kras has one of the most vulnerable natural systems in Slovenia.

For a number of years, karstologists have cooperated in construction of motorways in the Kras region (Kogovšek 1993, 1995b; Knez et al. 1994; Šebela and Mihevc 1995; Slabe 1996; 1997a; 1997b; 1998; Mihevc nad Zupan Hajna 1996; Mihevc 1996; 1999; Kogovšek et al. 1997; Mihevc et al. 1998; Šebela et al. 1999; Knez et al. 2003, 2004a; 2004b; Bosák et al. 2000; Knez and Slabe 1999; 2000; 2001; 2002; 2004a; 2004b; 2005; 2006; 2007). In the selection of motorway and railway routes, the main consideration is the integrity of the karst landscape; and therefore the chosen routes avoid the more important surface karst features (dolines, poljes, collapse dolines, karst walls) and already known caves. The removal of soil and vegetation from the karst surface and of course major earthworks such as the excavation of cuts and tunnels reveal karst features. Our task is to study these features as part of the natural heritage, advise on how to preserve them, and of course share our new findings with the builders. These findings are used to overcome construction obstacles.

Special attention is devoted to the impact of the construction and use of motorways on karst waters. Motorways should therefore be impermeable so that runoff water from the road is first gathered in oil collectors and then released clean onto the karst surface.

During the construction of motorways we also perform karstological monitoring. We study newly revealed karst phenomena as an important part of our natural heritage and advise on how to preserve them if the construction work allows it. At the same time our new findings are of great help to the construction companies. We have acquired a number of new findings on the formation and development of the karst surface, epikarst, and the perforation of the aquifer.

2 Exploring the karst surface and new caves during motorway construction

The karst surface is dissected by dolines, cave entrances and unroofed caves (Figure 1). Dolines are a sign of the current shaping of the surface by precipitation water that percolates vertically through it and passes through the vadose part of the aquifer to the underground water. Unroofed caves have a sim-

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Figure 1: Unroofed cave near Povir.

ilar form or are more oblong. These are old caves that appear on the surface due to the lowering of the karst surface and no longer have the upper part of their circumference.

The epikarst is crisscrossed with fissures that are more distinctive in Cretaceous limestone and less so in Paleogene limestone, and many of them open at the bottoms and slopes of dolines. In most cases they are filled with soil and their walls are dissected with subsoil rock relief forms.

More than 350 caves were opened on the 70-kilometer section of motorway built in Kras (Figure 2). Relative to the development of the aquifer, we distinguish between old caves through which watercourses flowed when the karst aquifer was surrounded and covered by flysch and shafts through which water vertically percolates from the permeable karst surface to the underground water. Some old caves are empty, almost two thirds of them are filled with sediments, and one third are unroofed caves. The deepest shaft found measured 109 meters (Figure 3). Due to the lowering of the karst surface, many shafts are now located just below the surface.

We studied all the caves, drew their plans, determined their shape, examined the rock relief, collected samples of sediments for paleomagnetic and pollen analyses, and sampled flowstone for mineralogical analyses and age determination.

Great attention has been devoted to unroofed caves since the occurrence of this phenomena turned out to be considerably higher than previously expected, and numerous articles on unroofed caves and the construction of new motorways are now available (Šebela 1995; Šebela and Mihevc 1995; Mihevc 1996; Mihevc and Zupan Hajna 1996; Slabe 1996; 1997a; 1997b; 1998; Kogovšek et al. 1997; Mihevc et al. 1998; Šebela et al. 1999; Knez and Slabe 2000; 2001; 2002; 2004a; 2004b; 2005; 2006; 2007). The shape of unroofed caves is the consequence of the type and shape of the cave and the development of the karst aquifer and its surface in various geological, geomorphological, climate, and hydrological conditions. The distinctiveness of the surface shape of an unroofed cave is dictated by the speed at which the sediment was washed out of the cave relative to the lowering of the surrounding surface (Knez and Slabe 2002). If the speed was low, we can often see just soil and vegetation or areas of sediments and

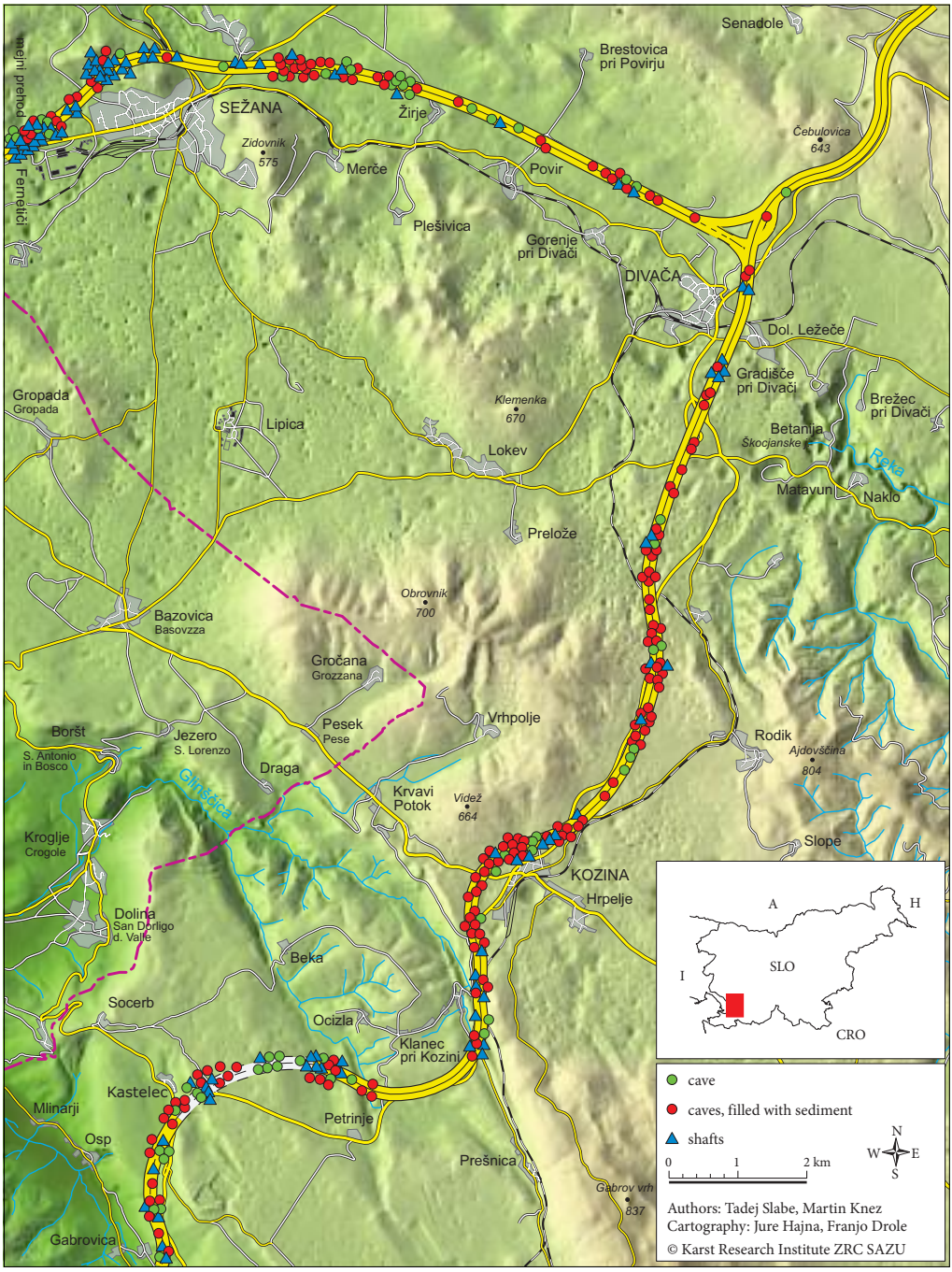

Figure 2: Caves discovered during motorway construction in southwest Slovenia.

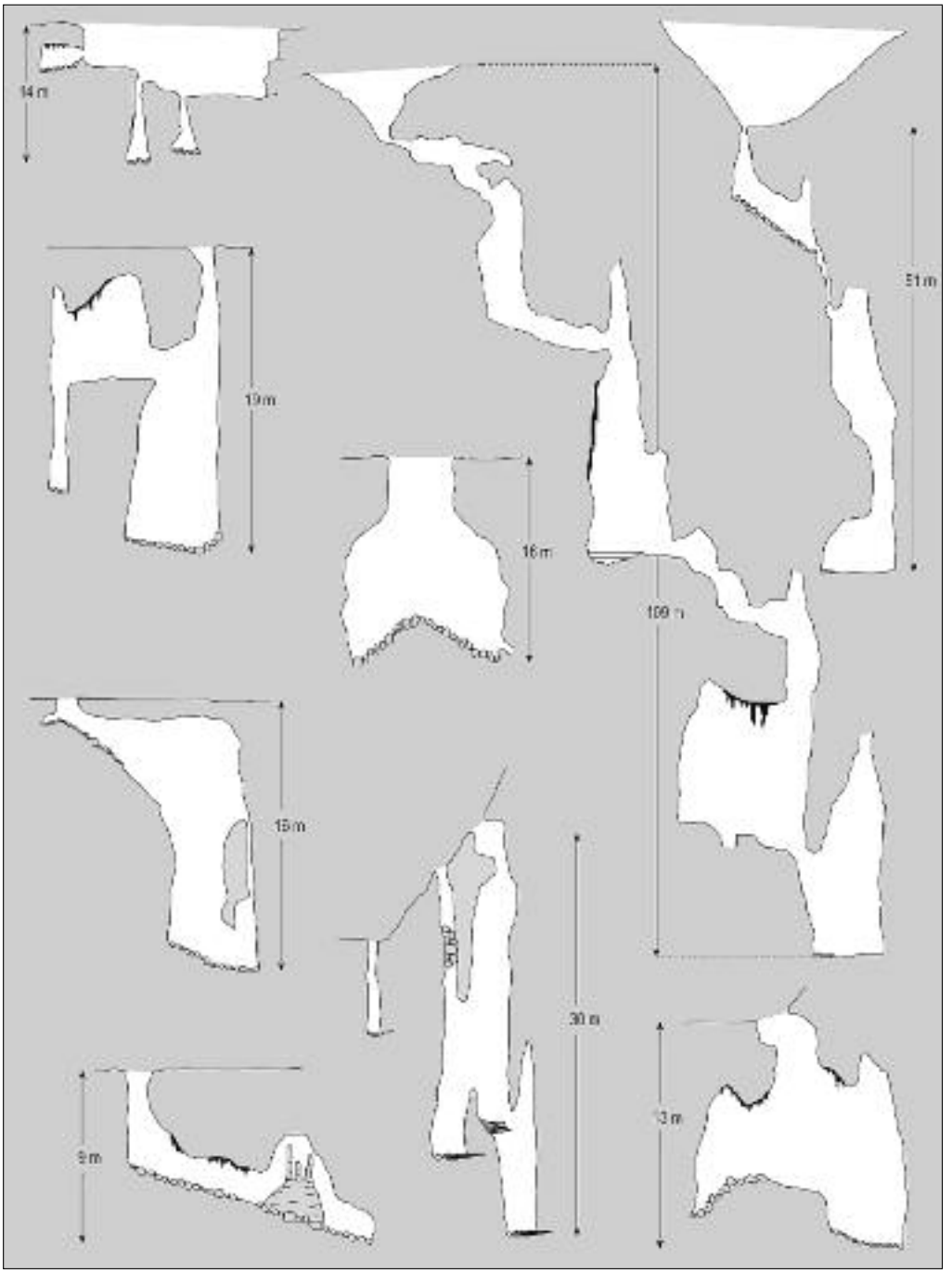

Figure 3: Cross-sections of different caves opened during the construction; their shape and size dictate further appropriate building works.

flowstone on the surface; where it was faster, unroofed caves on the karst surface resemble dolines, a string of dolines, or oblong depressions.

A large proportion of the caves were filled with sediments, in most cases fine-grained flysch sediments with intervening layers of gravel. Bosák et al. (2000) took sediment samples for paleomagnetic research from caves at Kozina and Divača and determined they originated in the Olduvai period. It was therefore concluded that the caves were filled after the Messinian crisis approximately 5.2 million years ago (Bosák et al. 2000).

Determining the age of the sediments (Bosák et al. 2000; Zupan Hajna et al. 2010) helps us understand the oldest periods of karstification and has proven that the oldest caves in Kras are much older than earlier karstologists thought.

3 Planning road construction

Perforation puts a special stamp on the construction of motorways in the Kras region. In addition to its varied development, Slovenia's karst is marked by tectonic and lithostratigraphic diversity and it is therefore difficult to determine in advance where caves will occur. As a rule, caves occur more frequently along the contacts of flysch with limestone. The perforation of the karst aquifer is therefore determined primarily on the basis of good and comprehensive knowledge of the karst and continuous intensive work in planning and constructing the motorways.

When planning motorways, the link between surface and underground karst features requires the karstological evaluation of the karst surface as well as the karst underground, the hydrological situation, and the presented variables. On all the motorway construction sites in Kras we encountered numerous karst phenomena including dolines, filled and empty caves, sections of old and current drainage systems through the karst. We are certain that a quality karstological study of the area where a road is planned enables the better selection of a route and is one of the basic starting points for planning motorway construction in this unique and vulnerable landscape.

We begin by assembling published literature, archives, and various unpublished studies to learn about the surface karst features, and thus identify dolines, collapse dolines, and other morphological features in particular. Through a field survey we establish the starting points for mapping the areas of the selected route. In the field, we evaluate different types of rock from the karstological aspect. On theme maps we present the known entrances to underground caves and supplement them with potential new entrances. We anticipate the branching of underground cave systems on the basis of surface mapping and explanations of the development of morphologically identified unroofed caves visible in the relief. On the basis of surface mapping we also consider possibilities for dumping waste material if necessary.

We know from experience that during construction every route crossing Kras will sooner or later encounter underground caves or parts of cave systems. To a certain degree we can predict the shape and type of caves using our knowledge of surface and underground phenomena. We trace the caves in the wider area of the traffic route, determine their type, position, and role in the aquifer, their shape, rock relief, the sediment and flowstone found in them, and present them on suitable maps. To make the maps easier to read, we present the previous data on the perforation of the aquifer and elaborate predictions with special emphasis on anticipated lithological and tectonic changes in the rock.

When necessary we perform tracing experiments during low and high waters (Kogovšek and Petrič 2007), primarily to determine the direction and velocity of underground flows in the wider area of the traffic route. With the results of field mapping and tracking experiments, we elaborate and upgrade the existing hydrogeological maps, build a database on the state of the environment, and assess the impact of the construction on karst waters.

Experience acquired tracing waters and accidental spillages of various substances on the karst surface drew attention to the great perforation of the karst aquifer, which the number of caves newly

discovered during construction confirmed. Maximum precautions must be employed during both the construction and use of roads. Daily traffic leaves numerous environmentally harmful substances on road surfaces (Kogovšek 1993), and mineral oils were found in stagnant waters in caves located near traffic routes (Knez et al. 1994; Kogovšek 1995a; 1995b; Gabrovšek and Peric 2007). Due to these findings and the persistence of karstologists, motorways are made to be impermeable. Pipes and gutters along the roads lead to wastewater collectors. Untreated water should never reach the permeable karst surface and the specifications for drainage systems must meet this requirement.

The basic guidelines for planning traffic routes include:

- the selection of a route shall be based on a comprehensive assessment of the karst with emphasis on local features;
- the selected traffic route shall avoid specific exceptional karst features;
- the conservation of karst aquifers shall be one of the priority goals of planning.

4 Preserving as many karst caves as possible

Caves are opened when vegetation and soil is removed from the surface, and a large number of caves were opened during the excavation of cuts. Blasting caused their roofs to collapse, and cross sections of passages were preserved in embankments. The most shafts were opened at the bottoms of dolines when the soil and alluvia were removed.

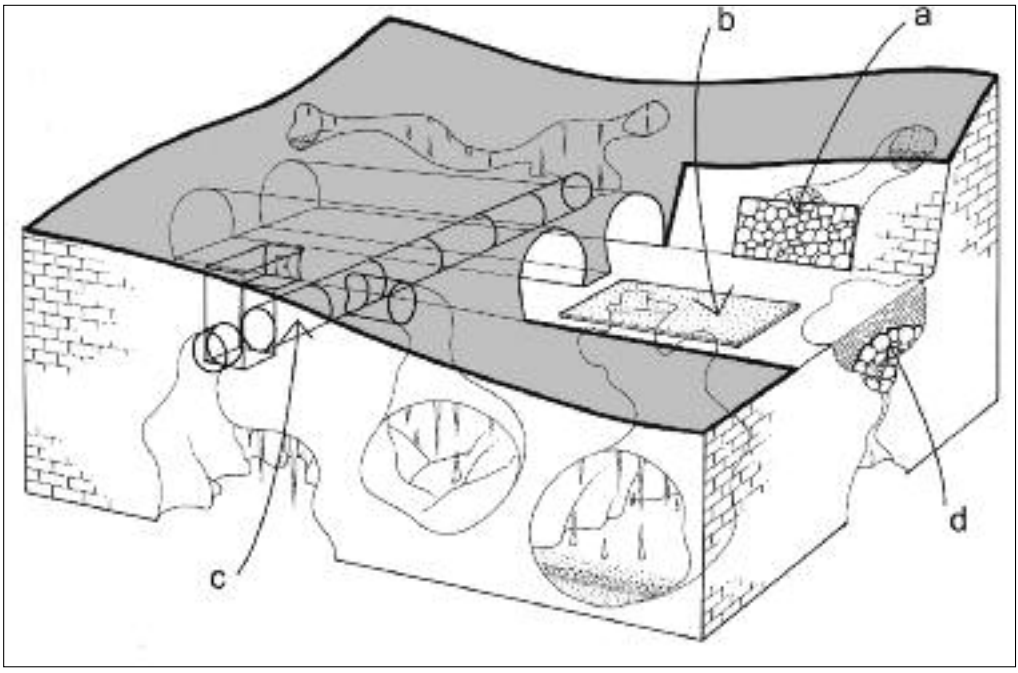

Figure 4: Preservation of caves: a) in road cuts the caves are hidden behind rocky scarps, b) the caves lying below the road with narrow mouth and if their rim is not too much damaged by blasting are covered by concrete lids, c) in the side of the tunnel pipe there is a special door leading to the caves; below traffic belt caves are connected with large concrete pipes, d) karst openings (bottom of dolines, tops of shafts) are often reinforced by arches of big rocks poured over by concrete.

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Figure 5: Preserved cave in Kastelec tunnel.

The shafts were easiest to preserve and concrete plates were used to close the smaller entrances (Figure 4). It was similarly possible to preserve old caves with solid circumferences but caves located in fractured rock or opened during blasting had to be filled. Rock walls were used to close caves crossed by road cuts with entrances on embankments. Their circumferences were fractured to such an extent that they were unsuitable for visiting, and water could wash clay from caves filled with sediments and deposit it on the roads (Figure 4). We extrapolated the further extent of the caves on the basis of their shapes and the geological conditions, which is especially useful for road builders. One well preserved cave was left open for travellers crossing the border with Italy to visit. The most interesting and best preserved caves were completely secured and made accessible for visiting even though they were located under the motorway or even wound around a tunnel as with the Kastelec tunnel (Figures 4, 5). They are accessible via concrete culverts closed at the roadside and in the tunnel with a door.

5 Conclusion

It is clear that the cooperation of karstologists in the construction of motorways in the Kras region has brought positive results. It is important that karstologists participate in the planning and construction of motorways and later that they monitor the impact of the motorways on the environment, that is, throughout the entire process of encroachment on the vulnerable karst landscape. This logical cooperation helps preserve natural heritage and increase our basic knowledge about the formation and development of karst and about the construction of motorways in this unique environment. There are many types of karst and each requires a unique approach, which calls for permanent and continuous cooperation between road builders and karstologists. Over the last fifteen years, the cooperation between

the planners and builders of motorways and karstologists has resulted in rich knowledge used in the planning and implementation of other encroachments in karst areas.

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