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CAVES AS POTENTIAL KARST GEOHAZARDS ON HIGHWAYS IN SW SLOVENIA

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ABSTRACT

Highways construction across the karst areas of SW Slovenia uncovered at least three times more caves than had been known prior to their construction. Sudden collapses during highways construction were documented, with some practical solutions discussed and proposed by karstologists and constructors. Beside denuded caves, many other new caves (mostly shafts) were discovered during the construction of highways in SW Slovenia. We have only few documented examples of sudden collapses along highways that have been opened to traffic for almost 40 years. In this sense, the highways in SW Slovenia are stable and have posed no great risk for karst geohazards so far. However, regular monitoring of highway stability, especially in supposed weaker places (remediated shafts directly under highway), is recommended.

Key words: highway construction, cave, karst, geohazard, Slovenia

GROTTE QUALI POTENZIALI GEO-PERICOLI PER LE AUTOSTRADE DELLA SLOVENIA SUD-OCCIDENTALE

SINTESI

Con la costruzione di autostrade nell'area carsica della Slovenia sud-occidentale il numero di grotte scoperte si è almeno triplicato. Improvvisi collassi avvenuti durante la costruzione sono stati documentati ed alcune soluzioni pratiche sono state applicate da carsologi e costruttori. Durante la costruzione di autostrade nella Slovenia sud-occidentale sono stati ritrovati, oltre alle grotte denudate, anche altri tipi di grotte, soprattutto a strapiombo. Visto che il numero dei casi di collassi improvvisi di autostrade (in uso da quasi 40 anni) è minimo, gli autori concludono che le autostrade della Slovenia sud-occidentale sono stabili e sicure e non rappresentano grandi rischi per i geo-pericoli carsici. In ogni caso è consigliabile che la stabilità delle autostrade venga monitorata regolarmente, soprattutto nelle aree instabili, quali pozzi risanati sottostanti le autostrade.

Parole chiave: costruzione autostrade, grotte, carso, geo-pericolo, Slovenia

INTRODUCTION

Few decades of highway construction in the Slovene karst areas is useful not only for a better traffic solution, but for new scientific data on karstology and speleology as well. Besides technical solutions for applied karst problems in highway construction, a big step in theoretical approach in karst geomorphology was also made. Many denuded caves were discovered (Fig. 1) representing old horizontal cave passages filled with cave sediments (Knez & Šebela, 1994; Mihevc, 1996; Mihevc *et al.,* 1998; Šebela, 1999; Mihevc, 2001; Knez & Slabe, 2002). Due to the processes of tectonic uplifting, erosion and corrosion, they have lost their roofs. In the past, such karst features were described as dolines or karst depressions filled with remains of old surface stream sediments. But many dolines are in fact remains of old denuded caves. One third of all dolines in Slovene Kras are supposed to be remains of old caves (Mihevc, 2001).

A horizontal karst depression filled with sandstone pebbles and cave sediments that were discovered during the construction of Divača–Dane highway was the first denuded cave studied in detail (Knez & Šebela, 1994; Šebela & Mihevc, 1995; Mihevc, 1996, 2001). Flowstone depositions on original cave passage wall and over cave sediments proved that this was an old karst cave, and not a surface stream valley.

Besides denuded caves, many new caves were opened during the highway construction in SW Slovenia. Since 1994, more than 350 new caves have been discovered in the course of building some 60 km of new highways (Knez *et al.*, 2008; Knez & Slabe, 2009). Some of them opened as collapses during the construction. In this sense, the question about caves as possible karst geohazards on Slovene highways was unveiled. A geohazard can be defined as a geological state that represents or has the potential to develop further into a situation leading to damage or uncontrolled risk (http://en.wikipedia.org/wiki/Geohazard).

In the Slovene karst areas generally, not only on highways, there are some examples of collapses, but not as many as on gypsum karst (Cooper, 1995; Fuleihan *et al.*, 1997) or karst areas where ground-water pumping is causing sudden subsidences, such as in southern and southeastern USA (Leake, 2004). Gospodarič (1962) described a sudden sinkhole collapse at Tomaj in Kras, which caused destruction of the house as it was founded on karst cavity filled by the sediments. Frequent are the collapses due to human interventions on the karst surface. While blasting the cess-pool for a house at Kozina, 2 m thick roof of a big underground chamber (Habič, 1984) suddenly collapsed. During the road construction between Divača and Koper, three major potholes appeared. The deepest pothole was 50 m deep. Huge caves were met at the construction of the road near Sežana (Habič, 1984).

Fig. 1: Denuded cave with partly removed sediments on Divača–Kozina highway, August 1997. (Photo: S. Šebela)
Sl. 1: Denudirana jama z delno odstranjenimi sediment na avtocesti Divača–Kozina, avgust 1997. (Foto: S. Šebela)

While building about 500 km of highways (1991–2008) in the Croatian karst region, over 945 caverns were discovered. Most of them (85.5%) are vertical speleological structures, while 14.5% are horizontal speleological structures. The deepest cave reaches -196 m, whereas the longest cave is known to have 1,490 m of passages (cavern in the Učka tunnel). "Kaverna u tunelu Sveti Rok" was discovered in the left-side Sveti Rok tunnel, and has 1,137 m of channels. The cave was subjected to speleological investigations and topographic surveys. The preparation of cavern remediation design solutions was greatly facilitated by speleological investigations. At some points, the roadway route had to be partly modified, but the groundwater flow patterns, discovered during speleological investigations, have in no case been altered (Garašić, 2009). In November 2004, an access to a very big cave (almost 4 km long and about 220 m deep) named "Grotta Impossibile" was found near Trieste (Cattinara) in Italy during tunnel construction (Torelli & Guidi, 2006). The cave is preserved and tunnel construction works considered all safety requirements.

Highway construction across karst areas in SW Slovenia as well as in Croatia and Italy opened many new unknown caves. When the upper part of the karst surface (1–10 m) is removed, epikarst shows it uppermost characteristics with significant increase of entrances to unknown caves. In this paper, selected caves situated below highways in SW Slovenia are presented as potential karst geohazards. There are only few examples of sudden collapses along highways when they have already been used for traffic. In this sense, highways in SW Slovenia are very stable so far.

The study was performed as part of the projects sponsored by DARS d.d. (Motorway Company in the Republic of Slovenia) and DDC svetovanje inženiring d.o.o. (DDC Consulting & Engineering Ltd.) and as collaboration with The Institute of the Republic of Slovenia for Nature Conservation, regional unit Nova Gorica and the Ministry of the Environment and Spatial Planning.

METHODS

To understand caves as potential karst geohazards, detailed topographic maps of previously known and newly discovered caves are necessary, as well as determination of the precise position of cave entrances regarding the highway lines. Some karstologic and geomorphologic research had been carried out prior to highway construction and during the construction itself. In this sense, the idea of what could be found some meters below the karst surface before and during the construction became clearer. The fact is that highway construction across the karst areas of SW Slovenia uncovered at least three times more caves as known before the construction (example from the Divača–Kozina highway). Sudden collapses during highway construction were documented and some practical solutions discussed between karstologists and constructors. For constructors the main objectives are safe and stable mechanical properties of highways. Karstologists are looking to protect caves and other karst features as much as possible. In such a manner, technical solutions suitable for both partners were realized (Knez *et al.*, 2008).

In the event of new cavities being discovered during highway construction, drilling has to determine hazards for eventual collapses. Here, georadar research (Knez & Slabe, 2005a) can be an important method for identification of road subsidence.

RESULTS AND DISCUSSION

In SW Slovenia, there are some roads (Divača–Koper) and highways (Vrhnika–Postojna) that have been opened to traffic for few decades. Even though used for 30 or 50 years, only few collapses have been reported. The roads across the karst in SW Slovenia are in fact very stable. More collapses occur during highway construction, when mostly associated with blasting of strongly karstified areas. In this way, many new unknown caves have been discovered. But with correct remediation decisions, the problems are solved and so far the new highways across the karst in SW Slovenia show very good stability.

Vrhnika–Postojna highway section

During the highway construction between Vrhnika and Postojna, 22 cavities (7 cavities/km^2 on average) without natural entrances were discovered (Kranjc, 1983). The area is built of limestone, dolomite and dolomitic breccia. While building the three viaducts on the Vrhnika–Postojna highway, the planner had to change the projects and replace the foundations due to the fact that karst caves were situated just below (Habič, 1984).

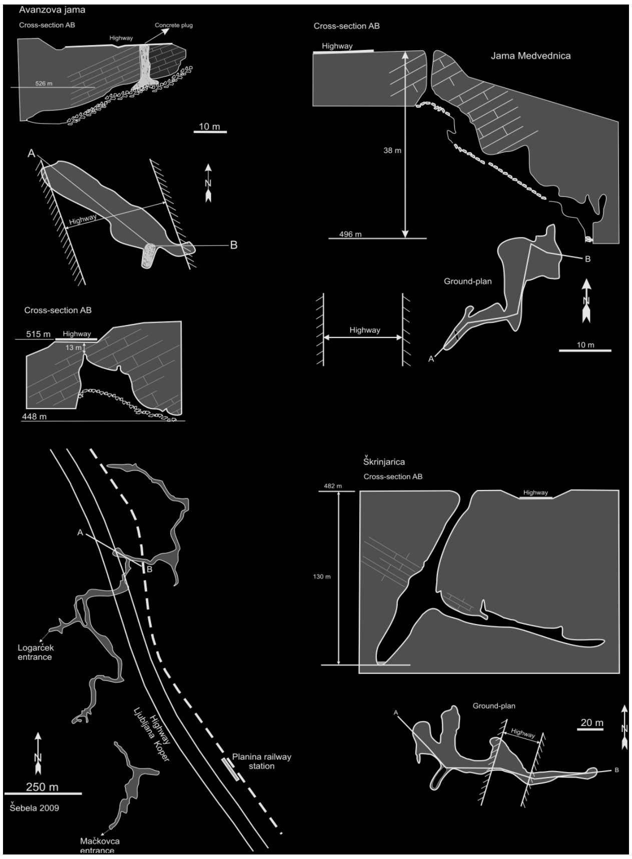

Fig. 2: Position of some caves situated below or near highways.
Sl. 2: Položaj nekaterih jam, ki ležijo pod avtocestami ali v njihovi bližini.

Near Postojna, at the contact of limestone and non-carbonate rocks, not all the debris that partly filled up the karst cave was removed during the highway construction. This fact later caused the subsidence of the roadway. After a decade, the road was in need of repair as a part of the roadway collapsed. In 1993, twenty-one years after the road was completed, the cavity of about 10 m^3 occurred at Verd near Vrhnika. The cave entrance opened in-between two highway lines due to the lower layer of gravel falling into the unfilled cave below.

Directly under the Vrhnika–Postojna highway (29 km long, constructed in 1972), some very deep shafts were included in the highway construction. Many shafts are no longer accessible, as the highway runs over them ("Brezno II pod železniško postajo Planina" (13 m deep), Avanzova Jama (28 m deep), Škantlovo Brezno (10 m deep)). The cave passage of Avanzova Jama is situated directly under the highway (Fig. 2). The cave is 47 m long and 28 m deep. Roof thickness between the cave passage and the highway ranges from 10 to 20 m. During the construction, the original entrance shaft was filled with material and covered with concrete plug. The entrance to Jama Medvednica (Fig. 2) is situated only some meters to the east from the Vrhnika–Postojna highway.

Just under the Vrhnika–Postojna highway and the railroad near Planina railway station, the 2,285 m long and 83 m deep karst cave Logarček is situated (Gams, 1963) (Fig. 2). One of its collapse chambers called Podorna Dvorana is directly under the eastern edge of the highway (Fig. 2). The roof thickness between the cave and the surface is 13 m. The Logarček cave is often affected by high waters. Part of the cave can sometimes be flooded and inaccessible. The Podorna Dvorana, however, is never affected by high floods. Cavers claim that sounds of highway and railway traffic can be heard in the cave. But we do not have any solid evidence that some collapse blocks in the Podorna Dvorana have fallen down due to highway traffic.

Dane–Fernetiči highway section

Two tunnels (240 and 260 m long) were constructed in the 4.8 km long Dane–Fernetiči highway (Fig. 3). Just at the exit of the southern tunnel, a bigger (5x10 m) cave opened with collapse due to blasting. The cave was filled with block material and protected by concrete plate. Just between both tunnels, two vertical shafts of up to 30 m deep were discovered. One of them had been formed along a well-expressed fault (Fig. 3).

Near the highway, a 109 m deep shaft was discovered. The entrance to the cave was in a doline, which is used as catchment area for waste waters from the highway. Special arrangements for the protection against leakage into the cave were carried out (Slabe, 1997a).

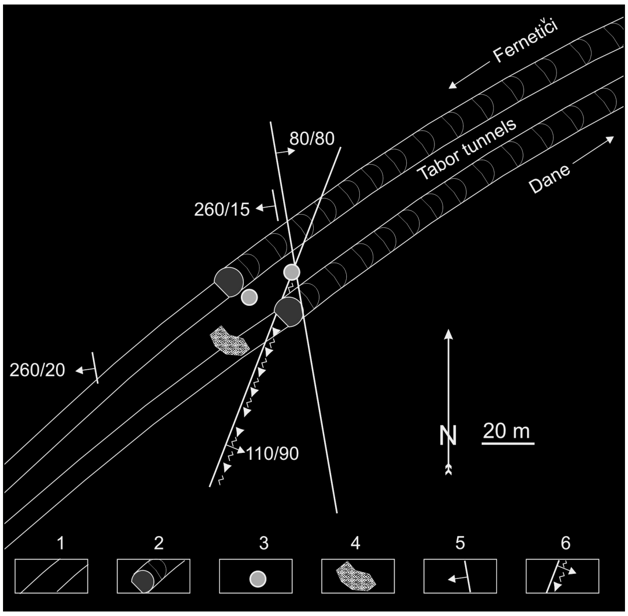

Fig. 3: Tabor tunnel. Legend: 1 = highway; 2 = Tabor tunnel; 3 = shaft opened during highway construction; 4 = cave opened during highway construction; 5 = strike and dip direction of bedding-planes; 6 = strike and dip direction of fault zone.
Sl. 3: Predor Tabor. Legenda: 1 = avtocesta; 2 = predor Tabor; 3 = brezno, odprto med graditvijo avtoceste; 4 = jama, odprta med graditvijo avtoceste; 5 = smer vpada in vpadni kot plasti; 6 = smer vpada in vpadni kot prelomne cone.

Divača–Kozina highway section

With preliminary karstologic and geologic field studies on the 6.7 km long planned highway, 4 denuded caves were determined (Šebela, 1996). This was the proof that denuded or roofless caves can be determined primarily from original morphological shape of depressions and dolines. During highway construction, 2 more denuded caves were opened by construction works.

Besides denuded caves, other unknown smaller or bigger caves were also detected during preliminary studies. On the 6.7 km long highway, 9 new caves were found apart from the 6 already known caves (Kataster jam IZRK ZRC SAZU). This means that with the preliminary karst studies carried out before highway construction, 2.2 caves per 1 km of the road were determined (Šebela, 1996, 2000).

Later on, during the Divača–Kozina highway construction, 50 caves were discovered along the 7.5 km long highway (Slabe, 1998) or 6.6 caves per 1 km, which is three times more than during the preliminary karstologic studies. The entrance to Jama nad Škrinjarico (Fig. 2) is situated 35 m W from the Divača–Kozina highway (Šebela, 1996). The cave is 270 m long and

130 m deep. The thickness of the cave roof under the highway is 85 m. The highway over Jama nad Škrinjarico has been opened to traffic since 1997. The cave has developed in limestones of Liburnian formation (K, Pc). The entrance is situated at 482 m. The horizontal passage has rich flowstone decorations and many old Italian inscriptions. The cave map has already been published in the book "Il Timavo" (Boegan, 1938).

Between Škocjanske Jame and Kačna Jama, there is an unknown passage of the river Reka, which runs about 200 m beneath the highway, which means that the thickness of carbonate rocks between the cave and the surface is about 150 m. During the excavation works carried out on the Divača–Kozina highway, small entrances to shafts were discovered in the base of dolines. These entrances were covered by large blocks and further reinforced by concrete. Next, a layer of rubble was spread on top and consolidated by a vibration roller. The depth of the deepest shaft that was treated in such a manner was 51 m (Slabe, 1997b).

The Kastelec tunnel

In order to estimate the degree of karstification for the planned Kastelec tunnel, preliminary karstologic and geologic studies were preformed. Within the studied area, only two caves (Brezno na Škrklovici and Udor na Škrklovici) had been known from cave register (Kataster jam IZRK ZRC SAZU). The position of Brezno na Škrklovici was precisely determined. The entrance shaft that is about 10 m deep has developed within Dinaric (NW–SE) and cross-Dinaric (SW–NE) oriented fissures. Alveolinid-nummulitid Eocene limestone dips towards SE for 20°, *i.e.* in the same direction as the cave passage. The cave is 200 m long and 115 m deep.

In the cave Udor na Škrklovici, two fissure sets prevail, one is of E–W, the another of Dinaric (NW–SE) orientation. The cave has two entrances. One is from collapse doline, while the other represents some 8 m deep shaft. The cave is 35 m long and 10 m deep. Thick-bedded Alveolinid-nummulitid Eocene limestone dips towards NW for 10°. Between Brezno na Škrklovici and Udor na Škrklovici, bedding-planes are folded into a gentle anticline, as shown on the cross-section in Figure 4.

During the excavation of the NE entrance to the Kastelec tunnel, some unroofed caves were discovered (Knez & Slabe, 2002, 2005b). The biggest cave had a diameter of 18 x 9 m and was filled with cave sediments (Fig. 5). Individual portions of the caves, which were unroofed and resembled dolines, were clearly evident on the surface before the construction work began. During the excavation of the Kastelec tunnel, the largest cave complex (LC-S647) was discovered in the tunnel near the cave Brezno na Škrklovici (Fig. 4). In the tunnel, three

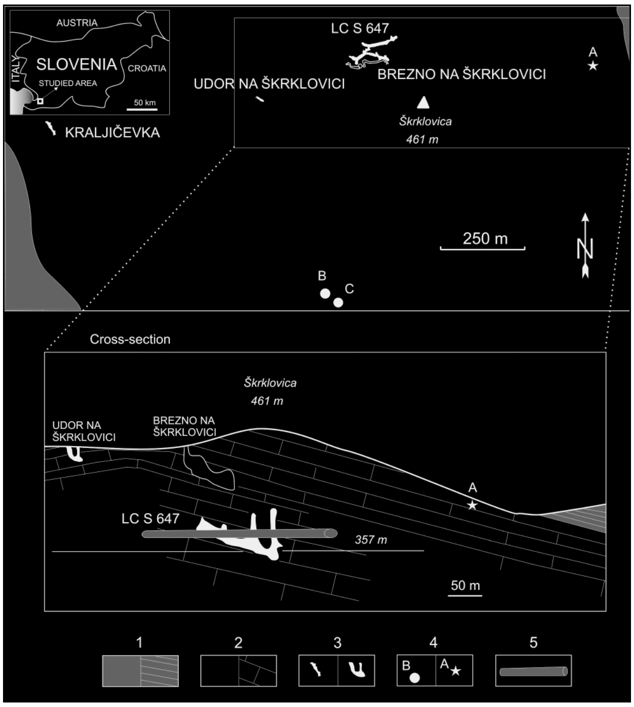

Fig. 4: Kastelec tunnel. Cross-section height is 3-times enlarged. Legend: 1 = Eocene flysch; 2 = Eocene alveolinid-nummulitid limestone; 3 = cave ground-plan and cave cross-section; 4-black point = rock shelter: B-Podmol, C-Acijev spodmol; 4-black star = position (A) of an old cave filled with sediments in Figure 5; 5 = Kastelec tunnel.
Sl. 4: Predor Kastelec. Višina prečnega profila je 3x povišana. Legenda: 1 = eocenski fliš; 2 = eocenski alveolinsko-numulitni apnenec; 3 = tloris jame in prečni profil jame; 4-črna pika = spodmol: B-Podmol, C-Acijev spodmol; 4-črna zvezda = položaj (A) stare jame, zapolnjene s sedimenti na Sliki 5; 5 = predor Kastelec.

major passages that were not interconnected were discovered, but in speleogenetical view they are part of the same cave complex. The dip angle of the limestone layers is 30–40° towards the west. The cave passages follow, in general, the dip of the layer with a declination of 15°. More powerful tectonic zones have Dinaric and cross-Dinaric orientations and an almost north-south orientation. Collapsed zones predominate. Chimneys in the cave, which reach up to 40 m in height, usually follow the tectonic zones.

All four caves (Brezno na Škrklovici, Udor na Škrklovici, the cave in the left pipe of the Kastelec tunnel LC-S647, and the old cave filled with sediments at the NE entrance to the Kastelec tunnel in Figure 5) formed in Eocene Alveolinid-nummulitic limestone. Although Brezno na Škrklovici and the cave in the left pipe of the Kastelec tunnel LC-S647 are no longer connected,

Fig. 5: Cave filled with sediments at NE entrance to the Kastelec tunnel. (Photo: S. Šebela)
Sl. 5: Jama, zapolnjena s sedimenti na SV strani vhoda v predor Kastelec. (Foto: S. Šebela)

speleogenetically they are part of the same cave system. Different passages of the cave system LC-S647 are today accessible through concrete pipes and door entrance accessible from the Kastelec tunnel (Knez & Slabe, 2009).

CONCLUSIONS

Highways in SW Slovenia run over the well developed karst. There are no bigger building problems because the rock is solid enough and not covered by thick sediments. Some problems during the construction are connected with karst depressions and caves, which are filled by the sediments having poor mechanical properties (Knez & Slabe, 2007). They may be detected by preliminary karstologic and geologic research prior to road construction, but most of them are discovered during the earthworks only.

Fig. 6: Doline remediation on Divača–Kozina highway, early spring 1995. (Photo: S. Šebela)
Sl. 6: Sanacija vrtače na avtocesti Divača–Kozina, zgodnja pomlad 1995. (Foto: S. Šebela)

Fig. 7: Unknown cave opened on Divača–Kozina highway, early spring 1995. (Photo: S. Šebela)
Sl. 7: Neznana jama, ki se je odprla na avtocesti Divača–Kozina, zgodnja pomlad 1995. (Foto: S. Šebela)

The karst features within the road construction must be suitably treated. From the dolines and the caves all sediments are removed and the bottom is filled by carbonate rubble, later grouted by the concrete (Fig. 6). The experience acquired during previous highway constructions, when the treatment was similar, indicate good results.

Almost 40 years of experience with studies of karst surface and underground features across SW Slovenia are showing good mechanical stability of highways (Kranjc, 1983; Kranjc *et al.*, 1991; Knez *et al.*, 2008). Some collapses occurred near or between highway lines. On the other hand, on highways, which are still under construction, collapses (Fig. 7) occur even during the last consolidation of gravel roadway by vibration rollers.

On our highways, we have just some examples of cave or doline collapses in the period when a highway has been opened to traffic for several years. Most causes are due to mistakes in construction or owing to incorrect wash out of sediments along highways. The Karst Research Institute ZRC SAZU makes detailed cave maps with special regard to thickness of cave roof and stability of newly opened caves. So far, the good stability on Slovene highways is probably also connected with the fact that the karst of SW Slovenia is not covered with thicker sediments or soil. However, regular monitoring of highway stability, especially at supposed weaker places (remediated shafts directly under highway), is recommended.

JAME KOT MOŽNE KRAŠKE GEO-NEVARNOSTI NA AVTOCESTAH V JZ SLOVENIJI

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POVZETEK

Med graditvijo avtocest čez kraške terene JZ Slovenije je bilo odkritih veliko novih neznanih jam. Ko je zgornji del (1–10 m) kraškega površja odstranjen, se pokažejo značilnosti zgornjega dela epikrasa in močno naraste število vhodov v neznane jame. V tem članku so obravnavane izbrane kraške jame pod avtocestami v JZ Sloveniji kot možne kraške geo-nevarnosti. Zabeleženih je le nekaj primerov nenadnih udorov vzdolž avtocest, ko so bile te že odprte za promet. Avtoceste v JZ Sloveniji so v tem smislu za zdaj stabilne.

Da bi razumeli jame kot možne kraške geo-nevarnosti, je treba izdelati natančne topografske karte predhodno znanih jam in novih jam, prav tako pa moramo natančno določiti jamske vhode glede na traso avtoceste. Nekaj krasoslovnih in geomorfoloških raziskav je bilo opravljenih pred graditvijo avtocest in med samo konstrukcijo. Dejstvo je, da je graditev avtocest v JZ Sloveniji odkrila najmanj trikrat več jam, kot jih je bilo znanih pred konstrukcijo (primer avtoceste Divača–Kozina). Nenadni udori med graditvijo avtocest so bili dokumentirani in nekatere praktične rešitve so bile predmet razprave in rešitve med krasoslovci in gradbeniki. Za gradbenike sta pomembni stabilnost in varnost avtocest, za krasoslovce pa je pomembno čim bolje ohraniti jame in druge kraške pojave.

Skoraj 40-letne izkušnje krasoslovnega spremljanja graditve avtocest čez kras v JZ Sloveniji kažejo dobro mehansko stabilnost avtocest. Večina udorov ali jam se je odprla ob ali med voznima pasovoma. Po drugi strani pa na avtocestah, ki še niso končane, udori nastajajo še po zadnjih utrjevanjih cestišča z vibracijskimi teptalnimi stroji.

Dobra stabilnost slovenskih avtocest je verjetno povezana tudi z dejstvom, da kras JZ Slovenije ni na debelo pokrit s sedimenti ali prstjo. Kljub vsemu pa je priporočljivo redno spremljanje stabilnosti avtocest, posebno na domnevno nestabilnih mestih, kot so sanirana brezna neposredno pod avtocesto.

Ključne besede: graditev avtoceste, jama, kras, geo-nevarnost, Slovenija

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