Rudarsko-geološko-naftni zbornik	Vol. 5	str. 79–85	Zagreb, 1993.

UDC 551.42:625.7/8:624.13(497.13-13)

Stručni članak

GEOTECHNICAL PROBLEMS ENCOUNTERED IN ROAD CONSTRUCTION IN THE KARST AREAS IN DALMATIA (CROATIA)

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Key-words: Cavern, Road, Karst, Limestone, Collapse, Finite element method, Modeling

The paper deals with engineering geological characteristics of karst (karstified) terrain, with problems caused by the presence of caverns and small caves with thin vaults, and the possibilities and methods of studying such phenomena. The paper also presents a possible method of solving the interaction between underground caves located immediately below the surface and the construction of roads by applying the finite elements method, with the solution illustrated by an actual example. In addition, the second example presents a solution for the road location and its basic structure above the cave in the slope of the road cut.

Ključne riječi: Kaverna, Prometnica, Krš, Vapnenac, Prolom, Metoda konačnih elemenata, Modeliranje

Opisane su inženjersko-geološke značajke okršenih terena, problemi koji nastaju zbog pojave kaverni i manjih špilja s tankim svodom, te mogućnosti i metode istraživanja takvih pojava. Prikazan je mogući način rješavanja međusobnih utjecaja špilja neposredno ispod površine i konstrukcije ceste metodom konačnih elemenata, te rješenje na jednom konkretnom primjeru. Uz to, na drugom primjeru je prikazano rješenje prolaza trase i njene temeljne konstrukcije iznad špilje u boku zasjeka trase.

Introduction

The construction of roads in karst terrain frequently involves numerous problems, caused by various morphological features, both underground and surface, formed by the action of stream flows and precipitation in the limestone and dolomites. In the Dinaric karst of Croatia, which represents a locus typicus of karst, there exists a great number of structural phenomena caused by various displacements from normal faults and folds to scaly structures and nappes as described by Herak (1972 and 1976) and Herak, et. al. (1982). The rocks broken by tectonic movements enable underground water circulation, and this movement by its erosive and corrosive action expands and models the fissures, forming small openings (caverns) and caves, sometimes with rich cave forms (stalactites, stalagmites, columns and curtains).

The coastal karst of Croatia, which consists of limestones and dolomites, prevalently from the Jurassic, Cretaceous and Eocene eras, includes various karst morphological phenomena. An intensive engineering activity makes it possible to find new ones, not visible on the surface, i. e., underground spaces with thin vaults which have to be reinforced in order to ensure the stability of the structure which is being built in these karst terrain. This problem is multiplied in road construction, since the roads, being narrow and long, can rarely bypass the areas with such phenomena. The road structure has to be reinforced to avoid collapse. However, such caverns are sometimes discovered only in the phase of engineering works. They have to be studied in detail and to be reclaimed, since it is not possible to relocate the road along such a short section. Consequently, it can be stated that numerous engineering works in the karst of Croatia have initiated further investigations of that phenomenon, particularly regarding the speleogenesis, as dealt with by Božičević (1969, 1983 and 1992) and Garašić (1981, 1988, 1989 and 1991). Since the system of caverns in karst can be expanded into a system of caves with thin vaults, the problem in defining the interaction cave-structure should be solved in cooperation with speleologists. Accordingly, a relatively small cavern, which can be considered easy to be reinforced by concrete, can be transformed into a significant speleological phenomenon quite dangerous for the road construction. Namely, the karst caverns can represent a threat for the roadway in two ways. The first danger consists in the presence of caves with thin vaults, immediately below the terrain surface, and (more frequently) the appearance of sinkholes filled with loose material of unfavorable geotechnical features. The second threat refers to the occurrence of underground caves encountered during the tunnel construction, e. g. in the Učka tunnel (Hudec, et. al. 1980). The caverns located beneath the surface are more dangerous, since before building and excavating the tunnel, the investigation works are more extensive than for the surface routes, and thus, the caves are less likely to be discovered. The most dangerous caverns are those located immediately beneath the surface, along the road sections on the embankments, since in that case there are no engineering works on the terrain and thus it is not possible to discover these caverns. Considering the experience related to such problems, such phenomena in karst terrain should be studied more carefully than today, to ensure sufficient safety conditions. In addition, the karst forms often act as water collectors and deliver it directly underground, so that man's activites on the road construction can lead to pollution of underground reserves of drinking water. Consequently, the problems of road construction in karst should be dealt with by a multidisciplinary approach, by cooperation among engineers, geotechnicians, speleologists, geologists and environmentalists, as well as with experts from other fields. Thus, it will be possible to solve the problems efficiently, i. e. to build a road which will satisfy both safety and environmental conditions.

Specific engineering-geological features of caverns in karst areas

The karst areas in Croatia have been extensively studied from the engineering-geological standpoint, so that this natural phenomenon is not presently dealt with as somethnig new. However, the past experience has proved that karst should not be treated by using fixed schemes, since the established relations can frequently change over small distances (Herak, 1957). Numerous data on the engineering-geological and other characteristics of the karst in Croatia have been obtained in order to develop the Main Geological Map, at a scale of 1:100000, as well as during practical investigations carried out for various engineering activities. Unfortunately, not many examples of solving practical problems have been published and the data are usually stored in the files of firms or institutes which carried out the investigations. The karst of Croatia consists of limestones and dolomites, i. e. according to the engineering-geological classification strongly cohesive rocks of carbonate structure. Their properties primarily depend upon the mineralogical composition, structure and textures features, and various defects in the rock structure formed during the diagenesis phase and later by tectonic movements. These secondary, tectonically formed joints, are those which represent a basis for the development of karst processes occurring from the surface downwards. The characteristics of karstification in the fractured limestones and dolomites develop with time, depending upon the caverns filling and their physical-mechanical characteristics (angle of the internal friction φ and cohesion c). Since the water by its aggressive action, by erosion and corrosion, expands and models the existing fissures and fissure systems (caverns and cavern systems), the karstification process and the engineering-geological characteristic of the terrain will be also influenced by the climatological processes and characteristics of the eco-system as a whole. Furthermore, it is necessary to pay attention to the interaction between the pervious and impervious layers in the terrain, since these characteristics will also influence the possibility of the underground flow and further development of karsitification.

A great number of investigations carried out during various construction activities revealed some of the important engineering-geological characteristics of karstified terrain, which are completed only after considering the hydrogeological features of the terrain as well. The discovery and study of caverns under various structures in karst were dealt with by Božičević (1983. b) and Roje-Bonacci et. Miščević (1992). The engineering-geological characteristics of the karstified terrain in road building were studied in the area of Dalmatia (Southern Croatia) by Šestanović et al. (1984), Garašić et Ortolan (1987), Mitrović et Krsnik (1988), Šestanović et Barčot (1988), Rađa (1991) and Braun et al. (1992). These numerous data on the physical-mechanical characteristics show that they significantly change with depth, so that a distinction has been made between the areas with a depth up to 5 m and those below it, and those data are presented in Table 1.

Table 1 Physical Mechanical Characteristics of Limestone in the Area of Dalmatia (Southern Croatia)

CHARACTERISTICS	SURFACE PART UP TO 5m	DEEPER THAN 5m APPROXIMATLY 15 m
Speed of longitudinal seismic waves v_p (m/s)	1400-1900	2500-3200
Speed of transversal seismic waves v_s (m/s)	600-900	1200-1500
Cohesion c (kPa)	1000-3000	19000-23000
Angle of internal friction φ^o	25°	20°-40° max. 50°
Weight per unit volume γ (kN/m³)	26-28	
Compressive strength σ (MPa)	65-137	
$CaCO_3$ (%) content	97,60-99,8	
RQD (%)	25-50	75
Poisson coefficient ν	0,31	0,26
Dynamic modulus of elasticity E_{din} (MPa)	100	18000
Dynamic modulus of shear G_{din} (MPa)	400	7000

It should be noted that in most cases the carbonate rocks in the first meter of depth, have exceptionally unfavorable physical-mechanical characteristics, and that the caverns (either empty or full) can frequently be found exactly in the pressure zone of the structure acting upon the rock. If they are discovered in the slopes of the cut, the investigations are facilitated since they can be easily approached, and if they are discovered in the road structure (most frequently revealed by a joints which drains water), they can be studied in detail only after extensive preparations and by a multidisciplinary approach.

Evidently, many caverns and caves in the karst cannot be easily discovered, either by regional or more extensive investigations, since those small joints leading to them, are usually covered with terra rossa or karst fragments on the surface. A great help in studying underground caverns in road construction is provided by geophysical studies and exploration boreholes. However, it should be stressed that the geophysical studies cannot yield fully reliable data in all cases. Since they are often not carried out along the whole route, but only along the more complex sections, frequently some caverns remain undiscovered upon the completion of investigation works. The exploration borehole is a point source (datum) which can divert the cavern at a small distance, so that it is necessary in practice to monitor continuously the engineering works and to record all significant data indicating the existence of a cavern in the cut slope or below the road structure itself.

Caverns and the road

The presence of caverns in road construction is much more frequent in the areas of Dinaric karst than it seems at the first sight. This fact can be illustrated by an example on the road section between Solin–Klis (Split, Dalmatia, Croatia), where two caverns were found within a distance of less than 100 meters (Fig. 1). This phenomenon could be expected in the location under consideration as it was predicted by the preliminary investigation works.

ENGINEERING GEOLOGICAL MAP

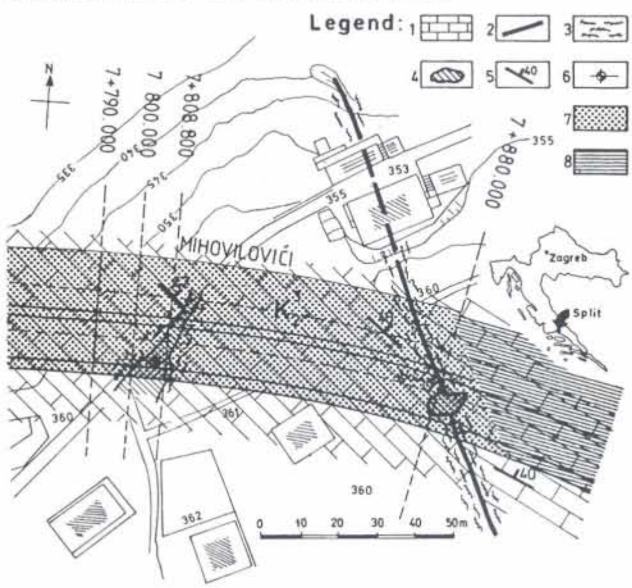

Fig. 1. Engineering geological map.
Legend:
1 Limestone of the Upper Cretaceous (senon-K_2^3)
2 Fault
3 Fault zone
4 Cavern
5 Dip of Bed
6 Location of investigation Borehole
7 Rocks in their natural state, conditionally stable, while after some engineering works they become unstable due to significant cracking and karstification. The bearing capacity becomes due to the occurrence of caverns and small caves.
8 Rocks of satisfactory bearing capacity and stability

However, the investigation works did not directly record any of those more significant phenomena. These two caverns of significant dimensions appeared only after a deep excavation carried out in order to find out the required road level, along the section where an artificial tunnel was to be built. If the route did not imply this additional excavation necessary for the foundations of the covering structure, one of the two caverns would not most probably have been discovered (Fig. 2). These caverns are very interesting since they are at a small distance apart, and have significantly different characteristics. The cavern from Fig. 2 was almost completely filled with various materials transported to the cavern by

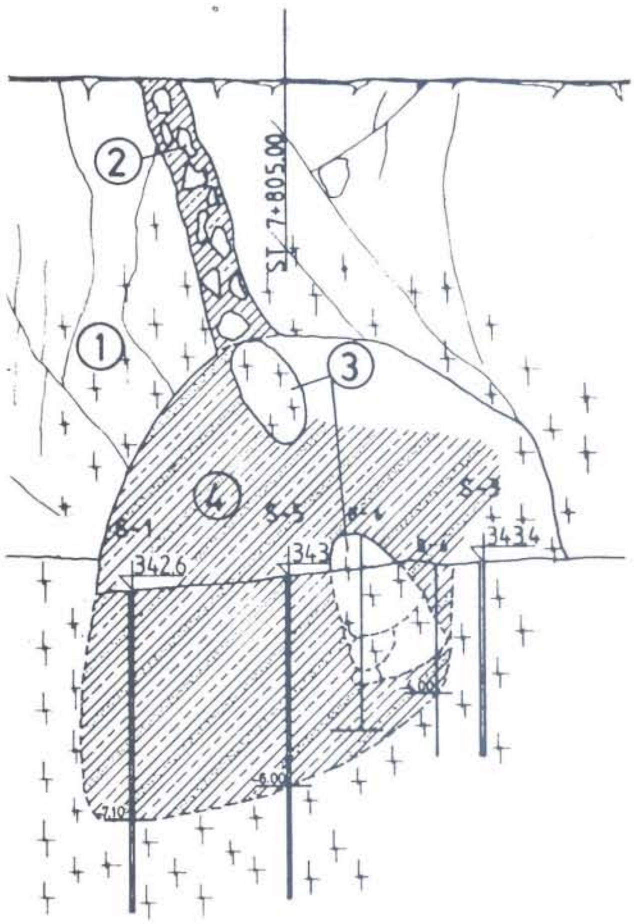

Fig. 2. View on Cavern in Eastern Slope and Cross-section of Boreholes
1 = very fractured and karstified limestone of the Upper Cretaceous K_2^3; 2 = crack filed with clay and limestone fragments; 3 = limestone blocks; 4 = clay.

the subsequent action of water, whereas the second cavern (Fig. 3) was completely empty with many cave decorations. It should be noted that the filled cavern was close to the surface, and it probably had a direct connection to the terrain surface. Each of these caverns presented a special problem with regard to the foundations of the covering structure and the route across the cavern.

Geotechnical solution of the foundations and route across the caverns

Cavern in the eastern slope

Figure 2 presents a cross-sectional area through the cavern in the eastern slope of the cut. It caused problems since the foundations had to be built using two types of material, which essentially differ regarding their compressibility. Since the artificial tunnel had to carry large loadings across its foundations to the soil, it was not possible to build the foundation on two materials with completely different properties. On the other hand, the depth of the cavern bottom and its width were such that it was not economicallly justifiable to carry out special types of deep foundations such as piles. The problem was solved in a very simple and most efficient way. An excavation was made by a machine almost down to

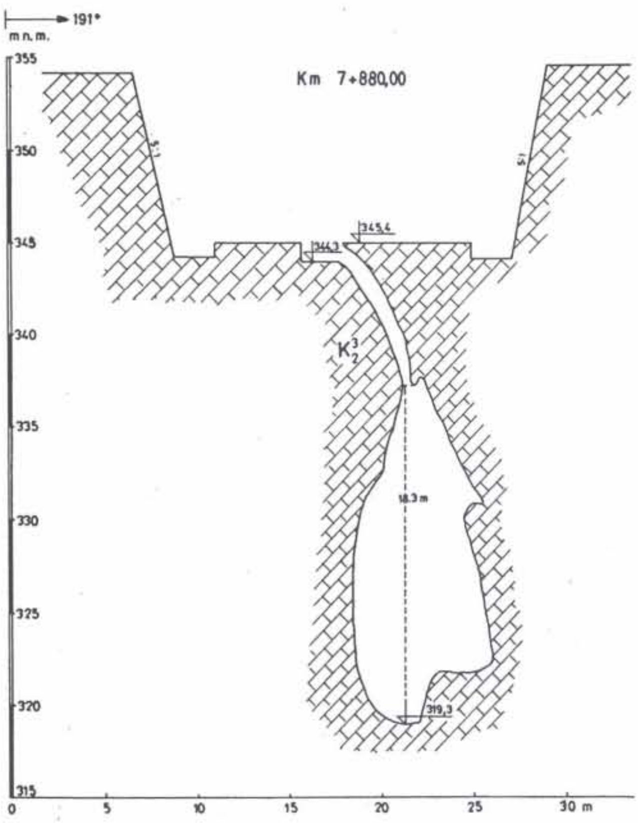

Fig. 3. Cross-section of Cavern under the road (according to: Rada, 1991)

the cavern bottom. A small part of the material which could not be removed by the machine, was removed manually, only after bringing down the unstable parts of the cavern roof, which were hanging over the excavation and the route, threatening to collapse. The bottom of the cavern in the foundation area fortunately had a form of the reversed funnel, which reduced the total quantity of the excavated material which amounted to 270 m^3. The emptied area was filled with concrete with the addition of one part of safe rock from the foundation excavation. The basis prepared in this way was used for building the foundations according to the project. The unexpected presence of the cavern delayed the works for ca. 20 days.

The Cavern under the Middle Foundation and the Pavement

The position of this cavern is presented in Fig. 3. This cavern would probably never have been discovered if it had not been necessary to make an excavation for the foundations of the middle wall of the artificial tunnel. Its presence posed several problems such as the possibility of transmitting the loads from the middle, highly loaded foundation, onto the rock mass without any consequences, and the influence of the pavement upon the cavern vault. In order to find an adequate solution to these problems, a model was developed applying the finite element method and the ZSOIL program. The model included the cross-section of the excavation, the cavern and the foundations with the respective loading. In order to distribute the load caused by the pavement influence upon the cavern roof, the project suggested that the cavern should be spanned by a reinforced concrete slab along the whole layout surface. The loading was transmitted from the slab onto the eastern and middle foundation. This loading was also taken into account.

Numerical model of the cavern analysis

The analysis of the stability of the studied problem of the cavern under the roadway, in an artificial tunnel, was performed applying the program ZSOIL (ZACE SERVICES Ltd. Lausanne Switzerland and ZEI ENGINEERING Inc. Washington, USA, 1989.) The program was developed using the finite element method, with isoparametric finite elements with four nodes at element angles and bilinear interpolation functions, and it analyzes the plane strain state. The yielding condition was defined by the Drucker-Prager criterion, as the approximation of the Mohr-Coulomb criterion along the internal boundaries (axial extension). A nonlinear analysis was performed with the non associate law of plastic flow, and the material was analyzed as elastic, ideally-plastic without reinforcement.

A cross section perpendicular to the route axis was considered in the direction of the cavern, at the point of the smallest distance from the cavern top to the pavement. The used finite element mesh with the material distribution is presented in Fig. 4. The characteristics of the material used in the analysis are presented in Table 2.

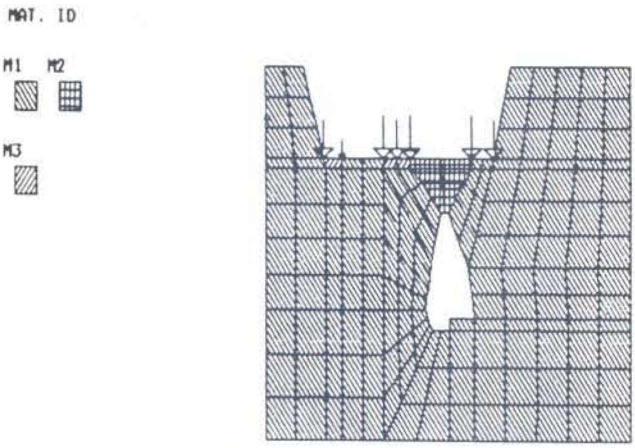

Fig. 4. Finite element Mesh with Material Distribution

Table 2 Characteristics of Material Used in Numerical Model
M1-limestone with several sets of joints filled with clay
M2-more deformable zone between the pavement and the cavern roof
M3-concrete foundation for the tunnel lining

MATERIAL	γ (kN/m³)	E (kPa)	ν	c (kPa)	φ (°)
M1	23,0	$2*10^7$	0,25	50	45
M2	23,0	$6*10^6$	0,25	50	45
M3	25,0	$2,7*10^7$	0,30	-	-

M1-limestone with several sets of joints filled with clay, was analyzed as a quasi-continuum; the lowest possible value was used for the parameters of the shearing strength in order to obtain the lowest possible value of the safety factor. M2-more deformable zone between the pavement and the cavern roof; the assumed zone of loose material (caused by the excavation). M3-concrete foundation for the tunnel lining (in the analysis considered as an elastic material, without yielding).

The loading which is transferred through the lining onto the foundation was presented by a linear loading:

- boundary foundation 370.800 kPa
- middle foundation 750.860 kPa

The influence of the slab shich spans the cavern is presented by a critical loading at the point of support onto the lining (slab sith free supports). The vertical force per unit of length of the considered cross section is 133 kN/m.

The analysis was performed by seeking the factor of the basic load increase, in which the system was still stable for the minimum values of shearing strength. The analysis showed that the system was stable for 50% greater loading than the one used for the dimensioning. Figures 5, 6 and 7 show the

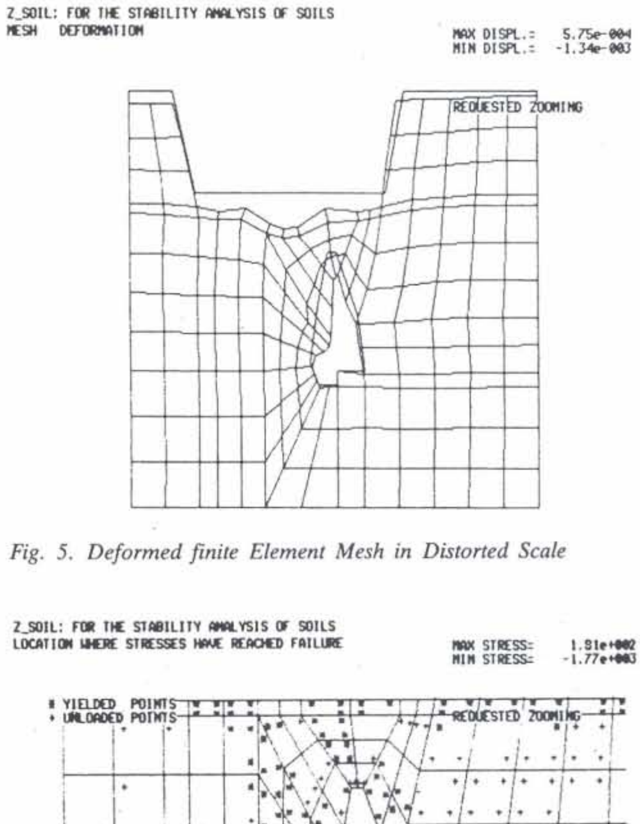

Fig. 5. Deformed finite Element Mesh in Distorted Scale

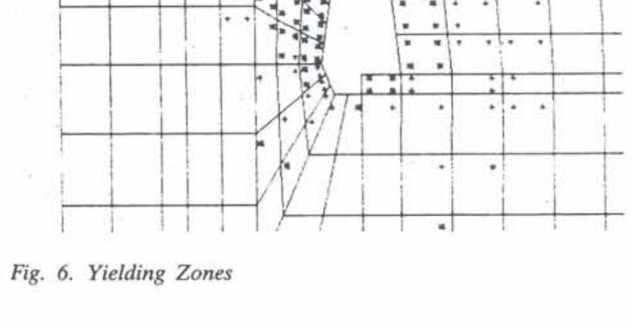

Fig. 6. Yielding Zones

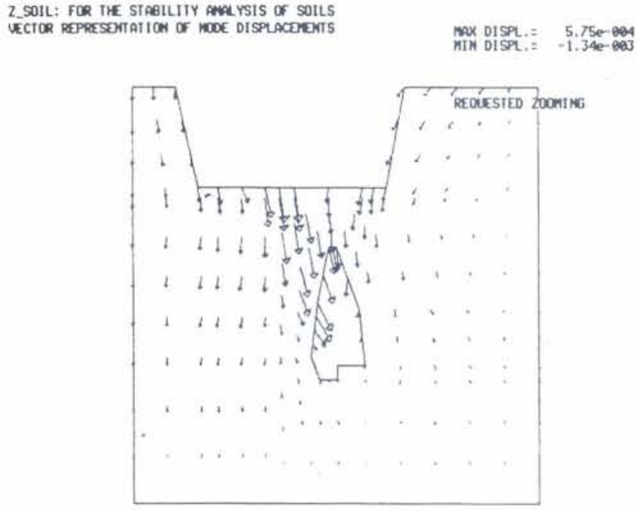

Fig. 7. Direction of Main Stresses in System

graphical presentation of the deformed finite element mesh in distorted scale, the yielding zones and the direction of the main stresses in the system. The analysis shows that if there exists a distinctive system of joints in the direction from the middle foundation towards the cavern, which could have a shearing strength smaller than the one used in the analysis, the system could become unstable.

Conclusion

The caverns in the karst can present serious problems in road construction. Consequently, it is necessary to expand the investigation works where these caverns can be expected (along the route), which to date has not been the practice. In the areas with sinkholes it is necessary to find out whether or not there is a swallow hole at the bottom, which can point to the presence of a cavity beneath the surface cover. Special attention should be paid to fissures and openings on the surface with large dimensions, since they can be cavern channels.

Thanks to past experience in that field and existing laboratory equipment used to process numerous samples and owing to a great number of geophysical investigations, there is a relatively great number of data on the physical and mechanical properties of the rock mass, which can be used as input data for the developed software program for personal computers.

Once the cavern has been detected and speleologically processed, there are no obstacles to model it and to study both its influence upon the structure near it or above it as well as the effects of the structúre upon the stability of the cavern, which presents the basis for a correct and comprehensive solution of the problem.

Received: 20. XI. 1992.
Accepted: 27. V. 1993.

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Geotehnički problemi gradnje cesta u područjima krša Dalmacije (Hrvatska)

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Prilikom izgradnje cesta u terenima krša nailazi se često na veoma velike probleme, uvjetovane različitim morfološkim pojavama, podzemnim i nadzemnim, nastalim radom tekućih voda i kišnice u vapnenačkim i dolomitnim stijenama. U hrvatskom dijelu Dinarskog krša, koji je »locus typicus« krša, razvijen je skup strukturnih jedinica komprimiranih svim načinima poremećaja, od normalnih bora i rasjeda, preko ljuskavih struktura do navlaka.

U priobalnom kršu Hrvatske, kojega grade vapnenci i dolomiti pretežito jurske, kredne i eocenske starosti, razvijene su sve krške morfološke pojave. Intenzivnom graditeljskom aktivnošću utvrđuju se i nove, s površine nevidljive, manje podzemne pojave tankog svoda koje je nužno sanirati u cilju sigurnosti konstrukcije koja se u okršenim terenima želi ostvariti. Taj se problem umnožava u slučaju izgradnje cesta, koje svojom malom širinom a velikom duljinom rijetko u krškim terenima »zaobiđu« područja podzemnih šupljina tankog svoda. Mogućnost prolamanja (kolapsa) kod cestovnih konstrukcija mora se izbjeći, a kako se ponekad podzemne šupljine otkriju tek u fazi izvođenja radova, nužno je takve šupljine temeljito istražiti i na odgovarajući način sanirati zbog nemogućnosti prelociranja ceste na kratkoj dionici. Zato se može reći da su brojni graditeljski zahvati u kršu Hrvatske inicirali daljnja istraživanja tog fenomena, naročito u smislu speleogeneze.

S obzirom na sustav pukotina u kršu koji može prerasti u sustav šupljina tankog svoda, očito je da pomoć u definiranju problema međuovisnosti šupljina i konstrukcija treba uvijek tražiti zajedno sa speleolozima. Jer, naoko mala šupljina, za koju se misli da ju je moguće sanirati, može uskom pukotinom prijeći u značajan speleološki objekt velike opasnosti za konstrukciju ceste.

Brojne spoznaje o inženjerskogeološim i drugim karakteristikama krša Hrvatske dobivene su istraživanjima za potrebe izrade Osnovne geološke karte (M 1:100000) ali i prilikom praktičnih istraživanja za pojedine graditeljske objekte. Nažalost, malo primjera rješavanja praktičnih problema je publicirano (podaci obično ostaju u fondu dokumenata poduzeća ili instituta koji je istraživanja obavio).

Okršenost razlomljenih vapnenačkih i dolomitnih stijena s vremenom napreduje, a ovisit će o širini, duljini, obliku, zastupljenosti i međusobnom položaju pukotina i njihovoj genezi, ali i o pukotinskoj ispuni i njenim fizikalno-mehaničkim karakteristikama (kutu unutarnjeg trenja φ i koheziji c).

Iz velikog broja podataka o fizikalno-mehaničkim karakteristikama, uočeno je da se one signifikantno mijenjaju po dubini, te su izdvojena područja do 5 m dubine i ona ispod, a podaci su prikazani u tablici 1.

Ovdje valja pripomenuti da je u većini slučajeva karbonatna stijena u prvom metru dubine izrazito nepovoljnih fizikalno-mehaničkih karakteristika, te da se kaverne (prazne ili ispunjene) često nalaze upravo u zoni djelovanja tlaka konstrukcije na stijenu. Ako se one otkriju u bokovima zasjeka, istraživanja su olakšana zbog mogućeg pristupa pojavi, a ako se otkriju u trupu ceste (najčešće indicirane pukotinom koja guta vodu ili »ispuhivanjem« bušotina prilikom miniranja), za detaljno istraživanje takve pojave nužne su studiozne pripreme aktivnosti uz multidisciplinarni pristup.

Činjenica je da je mnoge šupljine i kaverne u kršu teško otkriti, bilo regionalnim, bilo detaljnim istraživanjima, jer su manje pukotine koje do njih vode na površini u pravilu zatvorene kršjem i crvenicom. Velika pomoć pri istraživanju podzemnih šupljina u cestogradnji dobiva se geofizičkim ispitivanjima i istraživačkim bušenjem. Ipak, valja istaknuti da ni geofizička ispitivanja u svim slučajevima ne daju posve pouzdane podatke, a kako se ona često i ne provode po čitavoj površini trase već samo na »težim« dionicama, to se događa da dio kaverni u fazi istraživanja ostane neotkriven. Istraživačka bušotina je točkasti podatak koji može zaobići kavernu na maloj udaljenosti, tako da u praksi ostaje potreba stalnog praćenja izvođenja radova i registriranja značajnijih pojava koje indiciraju kavernu u boku zasjeka ili ispod same kolničke konstrukcije.

Pojava kaverni pri gradnji prometnica u području dinarskog krša je mnogo učestalija nego to izgleda na prvi pogled. Ilustracije radi na potezu trase ceste Solin-Klis, na udaljenosti od jedva 100 metara (sl. 1) pojavile su se dvije kaverne, (sl. 2 i 3). Na predmetnoj se lokaciji ova pojava očekivala i predviđena je prethodnim istraživačkim radovima. Inžinjerskogeološkim istraživačkim radovima izdvojene su:

- stijene u prirodnom stanju stabilne, a kod različitih graditeljskih zahvata postaju nestabilne zbog izrazite razlomljenosti i okršenosti. Nosivost je upitna zbog moguće pojave kaverni i manjih spilja. Ova grupa stijena se na trasi prometnice Solin-Klis nalazi u području navlačnog kontakta krednih naslaga i fliša, od stacionaže u km 7+533 do rasjeda u km 7+880.
- stijene povoljne stabilnosti i nosivosti. Ove se stijene nalaze sjeveroistočno od rasjeda u km 7+880 do kraja dionice u km 9+004.

Obavljeni istraživački radovi nisu direktno registrirali ni jednu kavernu. Tek iskopom dubokog usjeka za potrebe postizanja tražene nivelete ceste, a na dionici na kojoj je zatim trebalo izvesti umjetni tunel, pojavile su se dvije kaverne značajnih dimenzija. Da se radilo samo o trasi ceste bez potrebe dodatnog iskopa za temelje objekta, vjerojatno se jedna od dvije kaverne (sl. 3) nikada ne bi ni otkrila. Kaverne su veoma zanimljive s razloga što se nalaze na tako maloj udaljenosti, a bitno su različite. Kaverna sa slike 2 u km 7+805 bila je gotovo u potpunosti ispunjena različitim materijalom donešenim u nastalu šupljinu naknadnim djelovanjem vode, dok je kaverna sa slike 3 u km 7+880 bila potpuno prazna s mnogo spiljskih ukrasa. Valja napomenuti da je ispunjena kaverna mnogo bliže površini te je pukotinama imala direktnu vezu sa površinom terena. Svaka od kaverni je stvorila poseban problem u pogledu temeljenja konstrukcije natkrivanja i u pogledu prelaza trase preko šupljine u terenu.

Na slici 2 prikazan je poprečni presjek kroz kavernu u istočnom boku usjeka. Uzrokovala je problem temeljenja na dvije vrste materijala bitno različitih u pogledu stišljivosti. Za velika opterećenja koja je umjetni tunel trebao preko svojih temelja prenijeti na tlo, nije bilo moguće izvršiti sigurno temeljenje na dva ovako različita materijala. Dubina dna kaverne i njena širina je opet bila takva da nije bilo ekonomskog opravdanja za izvedbu posebnih vrsta dubokog temeljena na pr. pilota. Problem je riješen na vrlo primitivan, ali i najekonomičniji način. Izveden je iskop strojem gotovo do dna kaverne. Manji dio koji nije bilo moguće odstraniti strojem odstranjen je ručno, ali tek nakon obrušavanja labilnih dijelova krovine kaverne koji su visili nad iskopom i trasom i prijetili da se obruše sami od sebe. Dno kaverne je u području temelja imalo na sreću oblik obrnutog lijevka, što je nešto smanjilo ukupnu količinu iskopanog materijala koja je iznosila 270 m^3. Očišćeni je prostor zamijenjen betonom uz dodatak komada zdrave stijene iz iskopa za temelje. Na tako pripremljenu podlogu izvedeni su temelji prema projektu. Ta kaverna je zaustavila radove oko 20 dana.

Pojava kaverne u km 7+880 inicirala je traženje odgovora na pitanje mogućnosti prihvaćanja sila sa srednjeg, vrlo opterećenog temelja, u stijensku masu bez poslijedica, kao i utjecaj kolnika na svod kaverne. Da bi se dao adekvatan odgovor na problem, napravljen je model metodom konačnih elemenata. Model je obuhvatio poprečni presjek iskopa, kavernu i temelje s odgovarajućim opterećenjem. Da bi se rasteretila krovina kaverne od utjecaja kolnika, projektom je predviđeno da se kaverna premosti armiranobetonskom pločom na cijeloj tlocrtnoj površini. Opterećenje s ploče prenosi se na istočni i srednji temelj. I to je opterećenje uzeto u račun.

Analiza stabilnosti razmatranog problema kaverne ispod prometnice, u umjetnom tunelu, izvršena je programom ZSOIL (ZACE SERVICES Ltd Lausanne Switzerland and ZEI ENGINEERING Inc. Washington, USA, 1989.). Program koristi metodu konačnih elemenata, s izoparametarskim konačnim elementima sa četiri čvora u kutevima elemenata i bilinearnim interpolacijskim funkcijama, a analizira se ravninsko stanje deformacija. Uvjet popuštanja definiran je Drucker-Pragerovim kriterijem, kao aproksimacijom Mohr-Coulombovog kriterija po unutrašnjim rubovima (osna ekstenzija). Izvršena je nelinearna analiza s neasocijativnim zakonom plastičnog toka, a materijal analiziran kao elastično-idealno plastičan (nema ojačanja).

Promatran je presjek okomito na os trase (duž pružanja kaverne), na mjestu na kojem je udaljenost vrha kaverne od kolničke konstrukcije najmanja. Korištena mreža konačnih elemenata s rasporedom materijala, prikazana je na sl. 4. Karakteristike materijala korištene u analizi prikazane su u tablici 2, kod čega je:

M1 – vapnenac s više setova pukotina ispunjenih glinom, analiziran kao kvazikontinuum; za parametre posmične čvrstoće korištena je donja moguća vrijednost kako bi se dobila donja moguća vrijednost faktora sigurnosti.

M2 – jače deformabilna zona između kolnika i vrha kaverne; pretpostavljena zona rastresanja uslijed iskopa.

M3 – beton temelja tunelske obloge (u analizi elastičan materijal, bez popuštanja).

Opterećenje koje se preko obloge prenosi na temelje prezentirano je linearnim opterećenjem:

- rubni temelji 370–800 kPa
- središnji temelj 750–860 kPa

Utjecaj ploče kojom je premoštena kaverna prezentiran je vertikalnim opterećenjem na mjestima oslanjanja na temelje obloge (slobodno oslonjena ploča). Vertikalna sila po jedinici dužine promatranog presjeka je 133 kN/m.

Analiza je obavljena traženjem faktora povećanja osnovnog opterećenja, pri kojem je sistem, za minimalne vrijednosti parametara posmične čvrstoće, još stabilan. Analiza pokazuje da je sistem stabilan za 50% veće opterećenje od korištenog za dimenzioniranje.

Na slikama 5, 6 i 7 dati su grafički prikazi deformirane mreže konačnih elemenata u distordiranom mjerilu, zone popuštanja i smjerovi glavnih napona u sistemu. Analiza pokazuje da bi, ukoliko postoji izraziti sistem pukotina u smjeru od središnjeg temelja prema kaverni, (koji bi mogao imati manju posmičnu čvrstoću od one uzete u analizu), sistem mogao doći u nestabilno stanje.