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FIRST REMARKS ON SOME VERY INTERESTING ARTIFICIAL CAVES IN CROATIA

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Abstract
Under the Old City of Zagreb (Capital of Croatia) lies a system of tunnels made in past. Even today nobody (not even cavers) knows the position of every channel in this cave system, since it is forbidden to come inside the unstable channels under the old city. At Isle of Pag in the town Novalja there is an artificial cave called Talianova Buza. This is an ancient Roman water supply pipe, more than 1050 meters long. The longest artificial caves in Croatia are located in the city of Pula. There are plenty of ancient tunnels and also some underground quartz sand mines. This system is longer than 15 km. Near the city of Drnis an ancient mine of aluminium can be found, with depth greater than 300 meters and length of several kilometers. Near the city of Omis there is an ancient marl mine, more than 2 kilometers long, with two vertical and one horizontal entrance.
Keywords: Speleology, Artificial Caves, Croatia, City of Zagreb, Omiš, Pula.

Riassunto
Il presente articolo riassume alcune informazioni sulle cavità artificiali del territorio croato. Sotto la città vecchia di Zagabria (capitale della Croazia) si trova un sistema di gallerie realizzato in epoche passate. Ancora oggi la localizzazione delle varie gallerie non è nota (neanche agli speleologi), perchè ne è vietato l'accesso a causa della loro instabilità. Sull'Isola di Pag, nella città Novalja si trova una cavità artificiale nota come Talianova Buza. Si tratta di un antico canale idrico di epoca romana, lungo più di 1050 metri. Le più lunghe cavità artificiali della Croazia sono presenti nella città di Pula. Si tratta di numerose antiche gallerie alle quali si aggiungono miniere sotterranee di sabbia quarzitica, per una lunghezza complessiva del sistema di 15 km. Presso la città di Drnis si trova un'antica miniera di alluminio, con profondità superiore ai 300 metri e lunghezza di alcuni chilometri. Presso la città di Omis, infine, vi è un'antica miniera di marna, lunga più di 2 chilometri, con due ingressi verticali ed uno orizzontale.
Parole chiave: *Speleologia, Cavità Artificiali, Croazia, Zagabria, Omiš, Pula.*

Introduction

Some very interesting cave explorations concerning artificial cavities were carried out by the team from the University of Zagreb, Faculty of Civil Engineering, in the year 2008. They performed detailed study after several days of speleological research in complex artificial underground structures (mine) in the node Omis, LOT 4, on the Split bypass highway, section 03, Dugi Rat - Omis, near Omis in Dalmatia, Croatia. More then several kilometers of previously unknown mine passages were explored.

Speleological research

One of the entrances is vertical (pit) and during the research it was necessary to use the caving equipment and techniques for accessing the cavity. For safe descent caving rope static design brand "Edelrid III", "Bluewater III" and "TSA Marbach", ø11,0 mm, and a hump of "Petzl - descendeur", and for climbing creepers "Croll", "Gibbs" and "Bloquer" were used. The research was carried out in the winter, during dry, sunny days, but also in rainy weather, with air temperatures at the surface from + 8° to + 15° C, while in the cave-house (mine) air temperature measured from + 8,8° C to + 9,5° C. Sometimes an intensified air flow from certain parts of cave-building to the ground surface was present, which was measured by a digital anemometer. Instruments and necessary caving and filming equipment was transported through underground channels in separate transport boxes called "Pellican". For controlling the chemical composition of the air and the potential presence of dangerous exhalation, a gas detector RK Instruments SC-type was used.

The position and dimensions of the entrance

Gates of the former marl mine (artificial caving facility), are located east of the city center of Omis on slopes of the coastal mountain ranges. The Gauss - Krieger coordinates of the vertical entrances in caves, located above the present main road Omis - Makarska are: x=4810 744.190 N, y=6395 621.148 E, at an altitude z=74.613 meters.
This measurement point is located on the southern fringes of the vertical mine entrance. Gauss - Krieger horizontal coordinates input in caves, located below the present-day main road Omis - Makarska are: x=4810 506.30 N, y=6395 638.15 E, at an altitude z=23.21 meters (measurement point located on the eastern part of the concrete reinforcement of the horizontal mine entrance).
In the past there were several entrances to the mine,

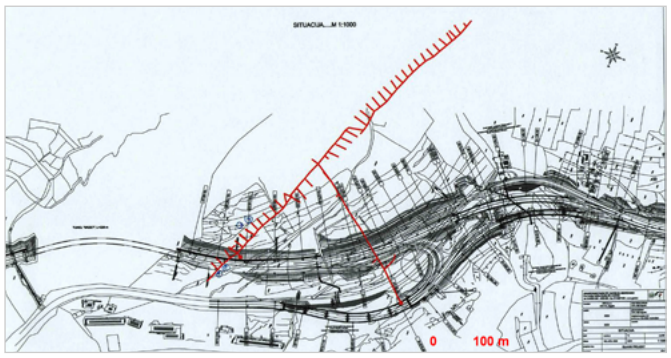

Fig. 1: general situation of marl mine near Omiš town.
Fig. 1: schema generale della miniera di marne presso la città di Omiš.

but in 2008 only two accesses were found. The first was found and investigated through a vertical entrance (depth approximately 44 meters). After some research the second entrance to the mine was found. It was under twenty meters of embankments and had to be dug out. The deposits were removed by our building machines and provided us a safe horizontal input in the cave. Inside the mine at several places an intensive air flow was established. It is safe to assume that shafts (or ventilation holes) used to be in those places. Today the only known vertical "entrance" in the cave has a function of ventilation hole. However, it could not be used for entering the cave because of its instability, and worked exclusively as a vent of the western part of the mine.

Fig. 3: horizontal entrance in mine after our excavation.
Fig. 3: accesso orizzontale alla miniera dopo lo scavo.

Before construction work started, the designer, the contractor and the investor did not know of the existence of this artificial underground structure. The underground marl mines were opened at the end of the 19th century, and provisionally closed in 1908.

Fig. 2: vertical entrance in mine.
Fig. 2: ingresso verticale nella miniera.

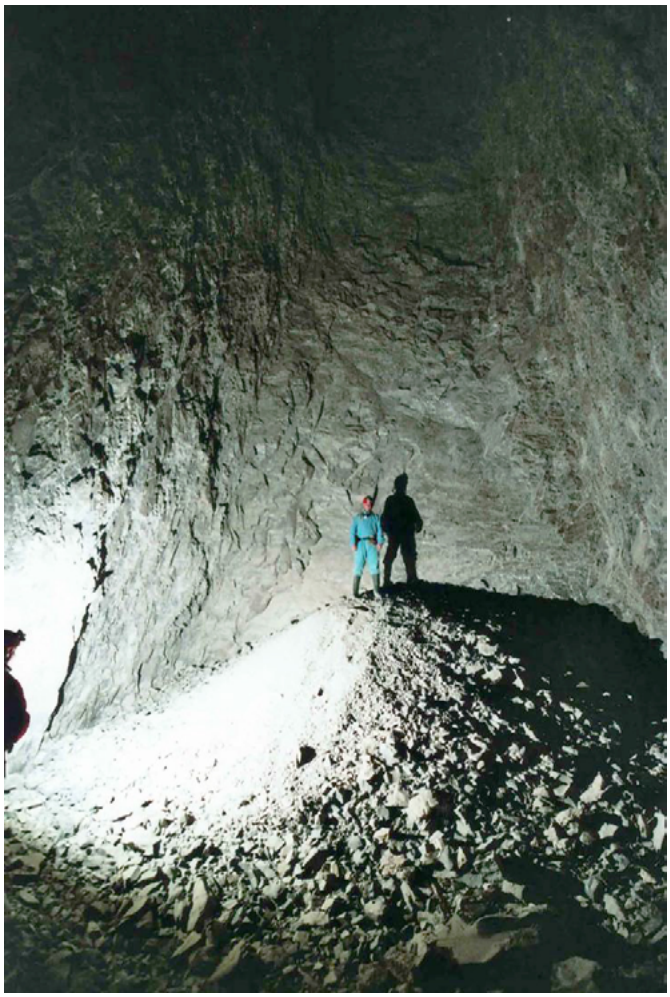

Fig. 4: inside the mine.
Fig. 4: all'interno della miniera.

Fig. 5: inside the mine.
Fig. 5: all'interno della miniera.

Fig. 6: the first descent into mine.
Fig. 6: la prima discesa in miniera.

Until 1930, they served sometimes in exploitation of marl for cement factory in Omis. Later, they were definitely closed for public use, and temporary used for military purposes. In May 1975, cavers (and one of the authors of this paper) reviewed the vertical entrance to the mine with a view to the eventual creation of air circulation for the planned incinerator garbage piled over single horizontal mine entrance. As far as it is known, the incinerator was never reactivated. No documentation or description of the entire mine was found. The consulted institutions engaged in mining had no data on the old marl mine near Omiš.
Vertical entrance to the mine was expanded and prepared for speleological research on January 8th, 2008. The originary dimensions of the vertical entrance of the mine amounted to 1.50 x 1.60 meters, and later they were expanded to 1.75 x 1.85 meters. The entrance to the speleological structure is of an erratic square shape. The rocks of the entrance area of the mine, due to weathering, geomechanical properties of the rock mass, and to intense karstification process, are intensively weathered, broken, cracked, and therefore not recommended for "anchoring" rope wedges and spits; therefore, binding for construction machines was needed. In the cracks on the entrance to the cavern, some secondary clays, in consistent state, of medium to high plasticity, have been noticed. Cracks width in this part of the cave varies from 5 to 20 cm. The marl (flysch) are very unstable, and in the western part of the input vertical channels several interlaminar cracks show aperture of 30-40 cm.

Lithostratigraphy, tectonics and engineering geology

The rock materials where the underground structure is hosted belongs to the so-called Flysch series, which is known for its heterogeneity in both the vertical and horizontal directions. These rocks are from middle to upper Eocene in age, mostly marls, with thickness varying between 10 and 70 cm. In particular, they consist of marl, marly limestone and lime marl, which are in turn part of a syncline structure bounded to the north by means of reverse faults with the Senonic Upper Cretaceous rudist limestones.
Flysch is a post orogenic facies characterised with rapid changes of diferent sediments. It's the youngest Tertiary sediments widely diffused over the SW slopes of Moser and Biokovo to the coast. Build of sandstones and limestones detrital alternating with marls. According to the petrological characteristics they are classified as calcirudite, calcarenite, quartz-calcarenite, calcisiltite and marl. Coarser varieties of detritic limestone fragments contain microfossils and limestone pieces, while calcarenite is made of fragments of microfossils and limestone particles. Sand varieties of limestone and quartz-limestone even contain grains of quartz, quartzite particles, low metamorphic slate, feldspar, chlorite, mica and regularly transparent heavy minerals. Layer thickness of detritic limestone varies from a few mm to 5 cm, and that of the sandy limestone and quartz-calcarenite from 2 cm to 1 meter. Marls are massive, and form the greater part of the complex. Cyclical changes of roughly detritic varieties from limestone to shale, indicating rhythmic flysch sedimentation, can be observed. Layer thickness rarely changes, and completely edges away in marl. Partially encountered traces of injection and life activities of organisms, and the remains of traces of flow and swelling, as well as lamination flow.
It is characteristic that this lithological heterogeneous complex also shows a variable fauna. Coarser sediments mainly contain micro-foraminifers association, characteristic for the marine littoral development, as: *Assilina perforatus*, and *Assilina incrassatus;* marls, on the other hand, contain microfossil association of relatively deep sea: *Turborotalia centralis, Globingerina aperture*, and *Cibicides dalmatinus*. Both associations indicate the time range for flysch deposition in the upper part of the Middle Eocene to the Upper Eocene. Mixing or relative fast exchange lithofacies characteristics in the same batimetrical scale indicate a flow of sediments and fossils from the shallower parts of the flysch sediment basin, probably as turbidite flows down a steep slope bottom. The approximate thickness of flysch is about 800 meters.
In the immediate vicinity of the cave facility, the

Fig. 7: connection with two passages in the tunnel.
Fig. 7: collegamento tra due gallerie.

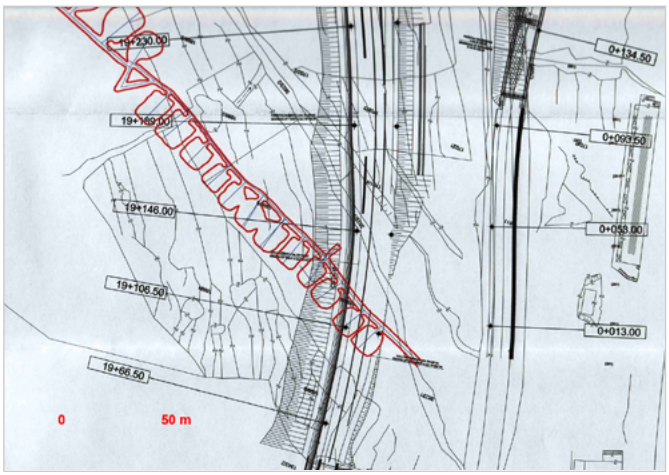

Fig. 8: plan of the exploitation halls in the old mine.
Fig. 8: carta delle stanze di coltivazione della vecchia miniera.

flysch deposits (marly limestone or calcareous marl) dip between 14° and 18°, and are directed towards the northeast (from 57° to 60°). The cracks that were noticed in the cave are up to ten centimeters, are flat and smooth. This is about the initial phase of speleogenesis in rocks that are poorly subject to the processes of karstification, but the process is still present in the contact areas (along the surface and with the Cretaceous limestones). In the vicinity of the entrance to the cave, interlaminar cracks are mostly filled with stiff clay material. In the deeper parts of the cavern on some places there are carbonate calcite binders, in crystalline or amorphous form. Speleothems are observed in the fracture zones that have contact with indigenous lime complex Cretaceous Senonian limestones. In the eastern part of the subterranean structure more intense cracking is visible (possibly a fault zone, about 1.0 to 2.0 meters wide). In the cave were observed milonite fault zones. Based upon direct observations in the cave, this is considered to be a relatively younger, but now inactive, fault. The main fault in the direction – 160° , with a very steep slope (from 88° to 90° to the southeast). The joint system is approximately perpendicular to the main fault and has a strike direction of 168° with a slope of about 75°. It intensely corrodes the surrounding rocks.
The engineering-geological properties of Eocene marls, marly limestones and calcareous marl are as follows: uniaxial compressive strength of the substrate (limestone in the level of the pit) is less than 50 MPa, RQD is different, but mostly below 40%, the distance between discontinuities is on average about 50 cm in the upper parts of the filling with clay. Some fissure systems are over 20 meters in lenght, and an average is about 10-15 meters. Aperture of cracks varies from 0,1 to 1 mm, but in some places in the surface layer it reaches up to 10 cm; the cracks in the upper parts of the cave are rough and wavy, while in the lower parts they are smooth.
According to the RMR and Q rock classification, the present artificial cavity (mine) can be classified as a poor rock mass (Category IV). However, due to the relatively small surface of the protective topsoil layer and intensive fault zones, the rocks are classified in category V.

Speleomorphology

According to the existing and recognized cave classifications (GARAŠIĆ, 1986, 1991), the artificial cavity here described, that is the tunnel located in the node "Omis" Split Bypass, Section 03, Dugi Rat - Omis, LOT 4, Tunnel Omis - Omis, belongs to the branched, multi-storey morphological type.
It is a mine of marl that was excavated decades ago. Mines have an irregular layout of the letter "T", where the horizontal entrance is in the extreme south (bottom) of the letters, and the vertical western part in the left side of the letter "T". In the right or eastern channel of the mine, intense air flow may indicate that there is a passage, so far undiscovered. From the horizontal entrance about 300 m in north-west direction, a cave is present. After about 50 meters from the entrance there is a turnoff to the east, that stops after thirty meters, but with airflow still present. In the "main channel" in several places groundwater creates larger or smaller ponds, one of which is over 50 meters long and 1 meter deep. At two places the channel is almost completely caved in. After about 300 meters of horizontal distance there is a larger "hub" channel. One part of the underground structure follows the direction toward the north-east ("Eastern branch"), the other goes to the south-west ("western branch"), while the third soon stops in north-western direction. The north-west branch about 450 meters. Every ten meters, starting from the south-east, and then moving to the north-western side of the "Eastern branch", there are the lanes with the logging halls from which the marl was extracted. This is an area of approximately 10 x 10 x 15 meters. The same situation is repeated in the "eastern Channel". Some halls are bigger, some are caved, and some are interconnected. Around the 20th branch in the "eastern Channel" a strong air flow was found. It is assumed that a vent for the eastern part of the mine existed in this area, but today it is not visible anymore. It's possible that the entrance could still be found on

Fig. 9: a groundwater lake in the mine.
Fig. 9: un lago sotterraneo nella miniera.

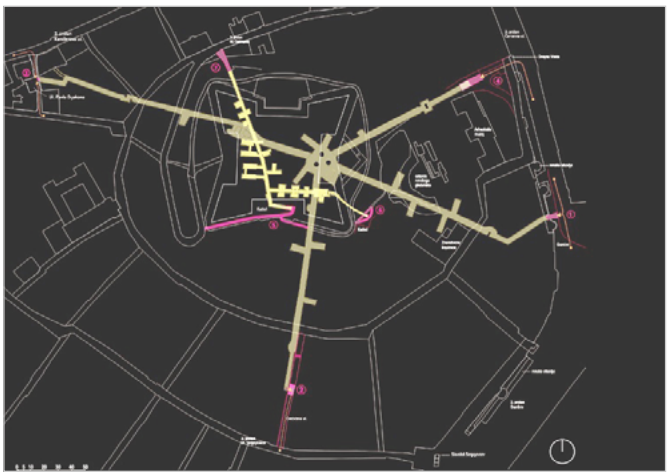

Fig. 10: one part of City of Pula underground.
Fig. 10: una parte della città sotterranea di Pula.

the surface. The channel is especially destroyed in the areas with presence of groundwater. This means that cracks and faults in the Cretaceous deposits interest also the area of the mine. The eastern part of the mine with its branches has been explored and measures about 800 meters.
The western part has 15 exploitation halls, first on the south-east, and later on the north side. Length is about 300 meters and the halls in total about 500 meters. In the westernmost part of the channel, in the fourth exploitation hall there is a ventilation shaft, through which the cavers entered this artificial cavity. It is a vertical unstable shaft about 44 meters deep.
It has been calculated that about 1,600 meters of mine spaces are in the area of the mentioned roads.
The mines are located in weathered marly rocks of Eocene age. At several places the mine voids, and in particular the exploitation halls, collapsed, and is very dangerous to remain in this part of the mine. Flowing water creates larger or smaller lakes because of impermeability of the marl sediments.
Two vertical shafts were found in the mine. The west one was used by the cavers for descending into the mine, and the second one was found from the inside by air circulation.
Mine galleries are of average height and width of about 2.5 meters. 40 exploitation halls have average dimensions of about 8-10 meters with heights of 16-21 meters, and are trapezoidal in shape. Some halls are connected, and partially collapsed. In a few places mine ceiling is supported with bolts. It is notable that all the galleries are very unstable.
From the gallery on the eastern and western parts of the mine air flows to the surface, and was measured with the digital anemometer (at east c = 0.72 m / s, at west c = 1.22 m / s). The depth or height difference from the highest to the lowest point in the cavity is approximately 52 meters. The total volume of the excavated part of the mine is estimated at about 70,000 to 80,000 m^3.

Hydrogeological observations

From the hydrogeological standpoint it can be said that this cavity has hosted a constantly active underground stream, and dripping water is constantly present. Depending on the climatic conditions at the surface, the water flow in the mine changes. The water in the mine comes directly from the surface through fissures and fault planes from the Cretaceous carbonate deposits (in most cases). The mine holds a secondary flow hydrogeological function.
Dripping water has intensive mechanical and chemical effects on the surrounding rocks (erosion and corrosion), but rarely create speleothems. The depth of karstification processes in the area of this structure, although the rocks are practically impermeable, is estimated at 300 to 500 meters, and the zone of vertical groundwater circulation at about 100 to 200 m. This is followed by horizontal groundwater circulation zone, transported through the Cretaceous limestones toward the Adriatic Sea.
Under Pula town in Istria more than 15 kilometers of quartz mine passages were explored, and the

Fig. 11: plan of some old tunnels under Old City of Zagreb.
Fig. 11: mappa di alcune gallerie sotto la città vecchia di Zagabria.

explorations have not finished yet.
Under the old city of Zagreb several kilometers of old catacombs were found.

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