Engineering geological properties of the rock mass along the Kastela Bay sewage system

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Abstract: Kastela Bay is situated on the Adriatic coast of Croatia, between the cities of Split and Trogir. The bay is 15 km long and 5 km wide and Ciovo Island lies at its mouth. The area is urbanized, densely populated, has heavy industry, and includes the cargo port of Split. At present, most of the waste water in the area is discharged untreated, and in an uncontrolled manner, directly into the sea. Therefore, design of a waste water treatment system has started. The system consists of a sewage system (30 km long), 18 pumping stations, a waste water treatment plant, and a waste water transfer tunnel through the Ciovo Island. The tunnel will be 2824 m long with a maximum overburden of 180 m.

Engineering geological and geophysical investigations, exploration drilling and laboratory tests have been carried out in support of the project. These investigations have identified considerable heterogeneity in the clastic flysch sediments that occur in the coastal part of the area, and more uniform limestone formations on Ciovo Island where the waste water transfer tunnel is located. Generally, there is a clear zonation in the 15 m of the clastic flysch sediments. Three geotechnical units have been differentiated: Quaternary cover, and highly and moderately weathered bedrock. The tunnel on Ciovo Island will pass through well-bedded and karstified Turonian, Senonian and Early Eocene limestones. In terms of engineering geological properties and RMR classification there are 7 units. The investigation has also identified very low groundwater levels on Ciovo Island. Therefore, it is considered that there is only a limited possibility of groundwater ingress during the tunnel excavation.

Résumé: La baie des Kastel est située sur le littoral croate de la mer Adriatique, entre les villes de Split et de Trogir. La baie a une longueur de 15 km et une largeur de 5 km et elle est fermée par l'île de Ciovo. C'est une région urbanisée, densément peuplée, qui se distingue par son industrie lourde et le port de marchandises de Split. Actuellement, la quasi-totalité des eaux usées de la région est rejetée de manière dispersée directement dans la mer de la baie. Pour y remédier, il a été procédé à la réalisation du projet d'un système d'évacuation des eaux usées. Le système est constitué d'un réseau d'égouts (d'une longueur de plus de 30 km), de 18 stations de pompage, d'une station centrale d'épuration des eaux usées et d'une galerie hydrotechnique qui traverse l'île de Ciovo. La galerie est longue de 2824 m, avec une couverture maximale de 180 m.

Des travaux de reconnaissance géologiques et géophysiques, des sondages de reconnaissance et des essais en laboratoire ont été réalisés dans le cadre de l'étude géotechnique. Les résultats des reconnaissances et des essais ont révélé une forte hétérogénéité des sédiments clastiques du flysch trouvés dans la zone côtière de la baie, ainsi qu'une formation plus uniforme des calcaires constituant l'île de Ciovo dans la zone traversée par la galerie hydrotechnique. D'une manière générale, une structure zonée de l'aire constituée de sédiments clastiques du flysch se distingue nettement sur une profondeur de 15 m ayant fait l'objet de reconnaissances. Trois milieux géotechniques ont été différenciés: une couverture quaternaire, une zone d'altération supérieure et le substratum rocheux. Du côté opposé de la baie, la galerie hydrotechnique traversera des calcaires turoniens, sénoniens et de l'éocène inférieur, bien stratifiés et karstifiés. Le long du tracé de la galerie, 7 unités ont été séparées selon les critères de la géologie de l'ingénieur, qui ont fait l'objet de la classification RMR des roches. Les travaux de reconnaissance ont également permis de déterminer que le niveau des eaux souterraines est inférieur à celui de la galerie. Donc, des irruptions des eaux souterraines en grandes quantités sont peu probables durant l'excavation de la galerie.

Keywords: waste water, engineering properties, weak rocks, limestone, foundations, tunnels

INTRODUCTION

Kastela Bay is situated on the Croatian coast of the Adriatic Sea, between the towns of Split and Trogir, and is 15 km long and 5 km wide. The bay is partly enclosed by the island of Ciovo which lies parallel to the mainland coast (Figures 1 and 2). The area is urbanized, densely populated and industrialized, and contains the cargo port of Split and Resnik International Airport.

Currently, all waste water in the area is discharged untreated, and in an uncontrolled manner, directly into the sea which is detrimental for the ecology of the bay. To stop this, plans have been drawn up for a sewage system, comprising a collector sewage network more than 30 km long, 18 pumping stations, a central plant for purifying water to an ecologically acceptable level, a seabed pipe-line across Kastela Bay to the Ciovo Island, a waste water transfer tunnel, 2824 m long, through Ciovo Island, and a maritime vent into the open sea.

Engineering geological and geophysical investigations, exploration drilling and laboratory tests have been carried out in support of the project. The design of the Kastela Bay sewage system takes full account of the engineering properties of the rocks that it will pass through; clastic flysch sediments for the section on the mainland, and carbonate, dominantly limestone, rocks on Ciovo Island.

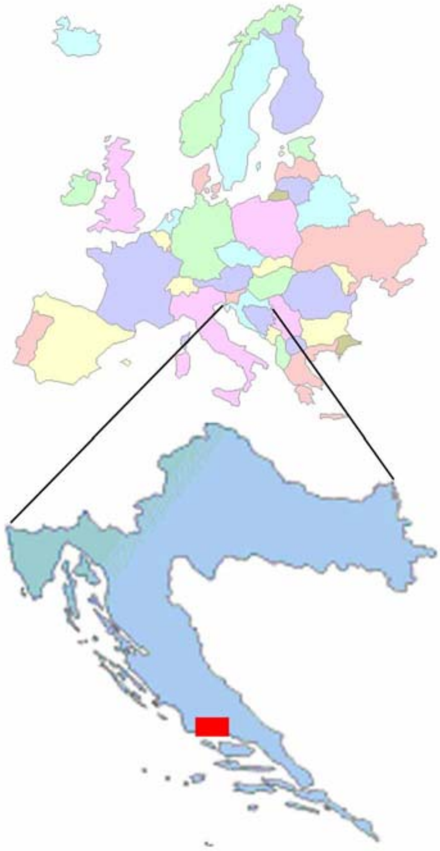

Figure 1. The location of Croatia and of the Kastela Bay area (red rectangle).

REGIONAL GEOLOGICAL AND TECTONIC CHARACTERISITICS

In terms of the tectonic model of Herak (1991), the area forms part of the Adrijatik structural unit (comprising carbonate sediments). This was overthrust in a north-easterly direction by the Dinarik carbonate structural unit and the Epiadrijatik structural unit (comprising clastic flysch sediments). The compression tectonics, evident especially in the brittle carbonate sediments, resulted in intense folding, reverse faulting and thrusting, numerous recumbent and overturned folds and various forms of faults. Overall the area has an "imbricate structure" (Figure 2) but there are also normal faults.

The Kozjak reverse fault dominates the northern part of the area. Older Upper Cretaceous sediments were thrust over younger Upper Cretaceous sediments, and the entire carbonate complex was thrust over clastic Eocene flysch sediments (Marincic, Magas & Borovic 1973).

The Kastela Bay area comprises part of a flysch basin, several hundred meters thick, which contains folded Eocene clastites, and Quaternary sediments. Ciovo Island comprises Upper Cretaceous and Eocene carbonates, and Quaternary sediments. Structurally, it comprises an isoclinal or overturned anticline with an eroded crest. The strata dip at 6-44º to the north-east and strike at 280˚.

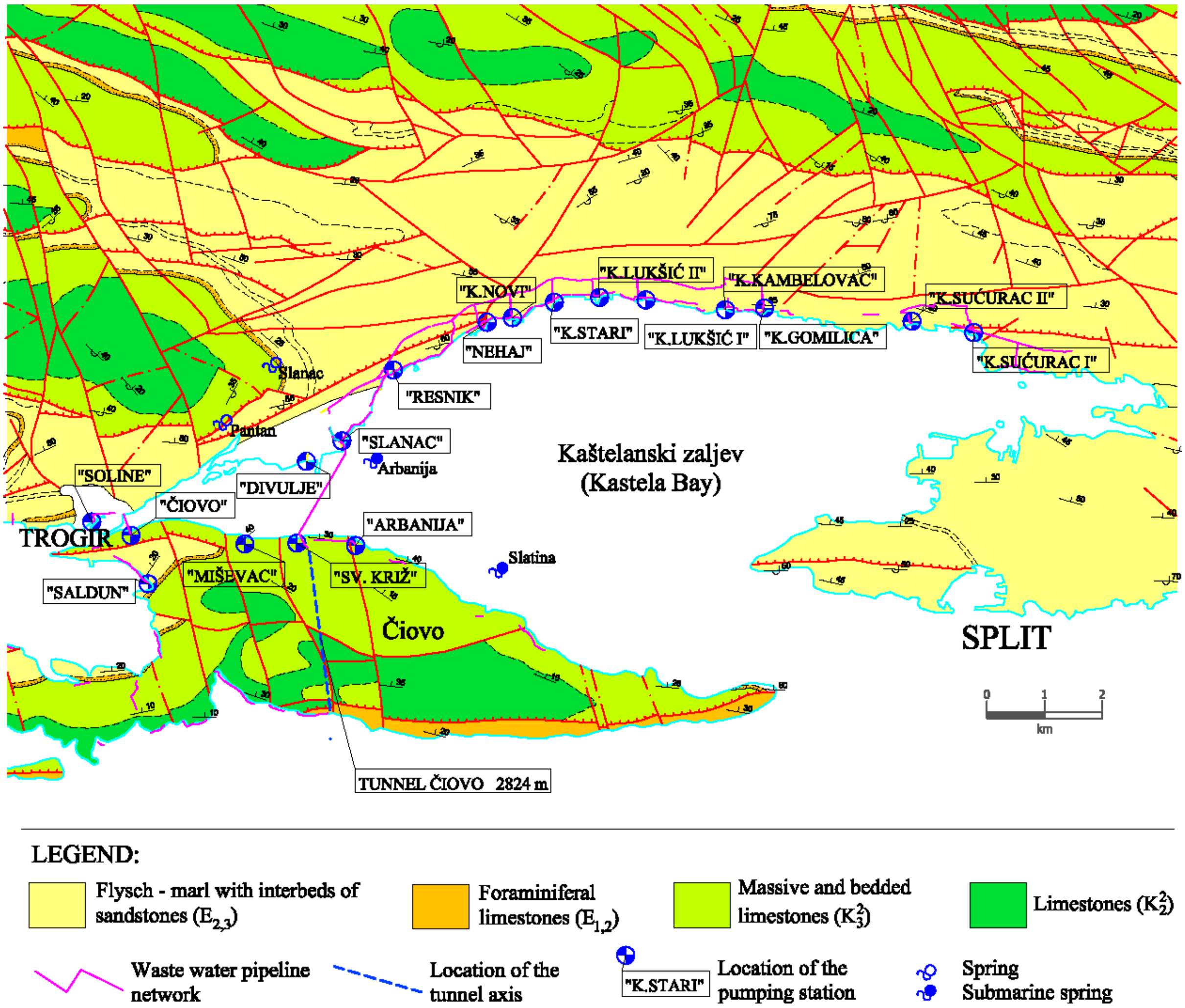

Figure 2. Geological map of the region (after Marincic et al. 1973), and the Kastela Bay proposed sewage system.

Geology of the Kastela Bay area

The oldest sedimentary rocks in the area are Upper Cretaceous (Turonian and Senonian). The Turonian sedimentary rocks are well bedded limestones that were deposited in a relatively deep environment, which became gradually shallower with time. The Senonian limestones are massive or poorly bedded reef limestones rich in fossils. Later diagenetic processes enabled recrystallization of a greater part of the rock mass and Late Senonian tectonics caused uplift throughout the region (Dinarides) resulting in a long period of karstification.

Following Tertiary marine transgression, transgressive breccia, bituminous plate limestones and miliolidae limestones were deposited (Marincic et al. 1973) and during the Eocene, the basin became larger and deeper, and foraminiferal limestones were deposited.

The Turonian to Eocene limestones were deposited on the same carbonate platform that had existed throughout the region from the Middle Triassic to the Middle Eocene, but clastic deposition followed Late Eocene tectonism and the basin at the foot of the Mesozoic “cordillera” attained its maximum depth. Clastic flysch deposition (breccia, conglomerate, sandstone, siltstone and marl) was characterised by complex vertical and lateral facies variations. The marls were deposited during periods of low turbidity current activity. At the same time the exposed carbonates suffered intense karstification and terra rossa developed locally.

Hydrogeological characteristics of the region

There is a highly productive brackish spring 2.7 m above sea level near the coast at Pantan (Figure 2). Fed from a hydrogeological basin, with a surface area of 270 km², the spring occurs at the thrust contact between permeable carbonate sediments above and impermeable clastic sediments below. Its yield varies from 600 l/s to 12 m^3/s. In the rainy season, groundwater also flows from submarine springs at Arbanija and Slatina in Kastela Bay (Figure 2), whose maximum depth is 41 m. These, together with the Pantan spring, have been interpreted as part of an interconnected system – the Pantan basin spring area (Fritz, Renic & Buljan 1991). The submarine springs demonstrate that water from the carbonate hinterland flows beneath the complex of impermeable clastic flysch sediments which function as a hydrogeological “hanging” barrier. There are no such springs on Ciovo Island.

The Pantan spring lies upstream of the planned sewage system, but is not intended to be used as a water supply because of it brackish nature, and because of its potential pollution by a nearby waste dump. Groundwater is abstracted for local needs from numerous small wells within the clastic sediments. These are located upstream of the planned collector network and the sewage system infrastructure.

INVESTIGATIONS FOR FOUNDATIONS OF THE PUMPING STATIONS

The area investigated extends along the coast of Kastela Bay (Figure 2) and is covered with artificial beach aggregates or waterfront embankments. At the 18 locations investigated, seismic refraction, drilling (26 cored boreholes) and some laboratory tests were carried out.

Engineering properties of the clastic flysch sediments

The regional sedimentology and stratigraphy of the clastic flysch sediments (Figure 2) are described by Marjanac (1993). While the thickness of the flysch complex is uncertain, it extends below the level of the proposed construction. Engineering properties of the flysch were explored in cuttings by Sestanovic, Stabmuk & Samardzija (1994). In the Kastela Bay area, the sediments are variable in grain size, but are dominantly fine-grained and contain sufficient calcite (Miscevic & Roje-Bonacci 2001) for the main part of the flysch complex to be described as "marl".

Flysch sediments properties

The engineering properties of the flysch are related to its mineral content. Miscevic & Roje-Bonacci (2001) divided the sediment complex into 3 groups, based on carbonate content and its relation to weathering properties. The marl-dominated part of the clastic complex is also irregularly interbedded with coarser sediments including siltstone, sandstone and breccia. As the abundance, thickness and nature of these interbeds influence the engineering properties of the complex, the Geological Strength Index (GSI) classification for heterogeneous rock masses was applied (Marinos & Hoek 2001). The rock mass quality of the flysch varies widely and the GSI values range from 20 to 60 (Figure 4). The GSI value dominates with heterogeneity of the complex and in more homogeneous areas with mineral composition (Figure 4). The calcite marls are harder and more compact than the clayey marls and therefore were rated higher. Discontinuities properties are more or less uniform.

In slightly weathered or fresh bedrock, P-wave velocities range mostly between 2000 and 3000 m/s, and rarely exceed 3000 m/s. Drill cores were moderately fractured to compact with RQD ranging from 50-75%. In highly fractured zones, RQD ranges from 25%, or less, up to 50%.

Weathered bedrock properties

Weathered parts of the bedrock were differentiated solely on the basis of borehole core and geophysical data. No laboratory tests were carried out. The weathered zone was identified on the basis of P-wave velocities, ranging from 1000 to 1500 m/s, and was confirmed by drill core with RQD values of 0-25% (Figure 3).

The weathered zone above the flysch sediments is consistent but gradually decreasing with depth. Its thickness varies between 1 and 4 m. In the area in which siltstone predominates, there is no apparent weathered zone (Figure 4).

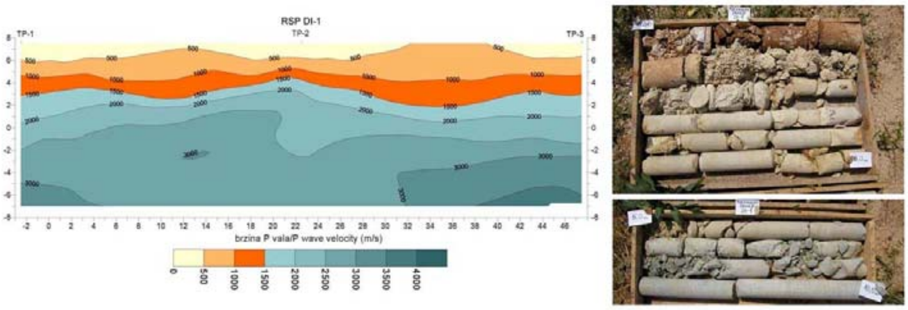

Figure 3. Seismic refraction profile and borehole core at the location of the Divulje pumping station.

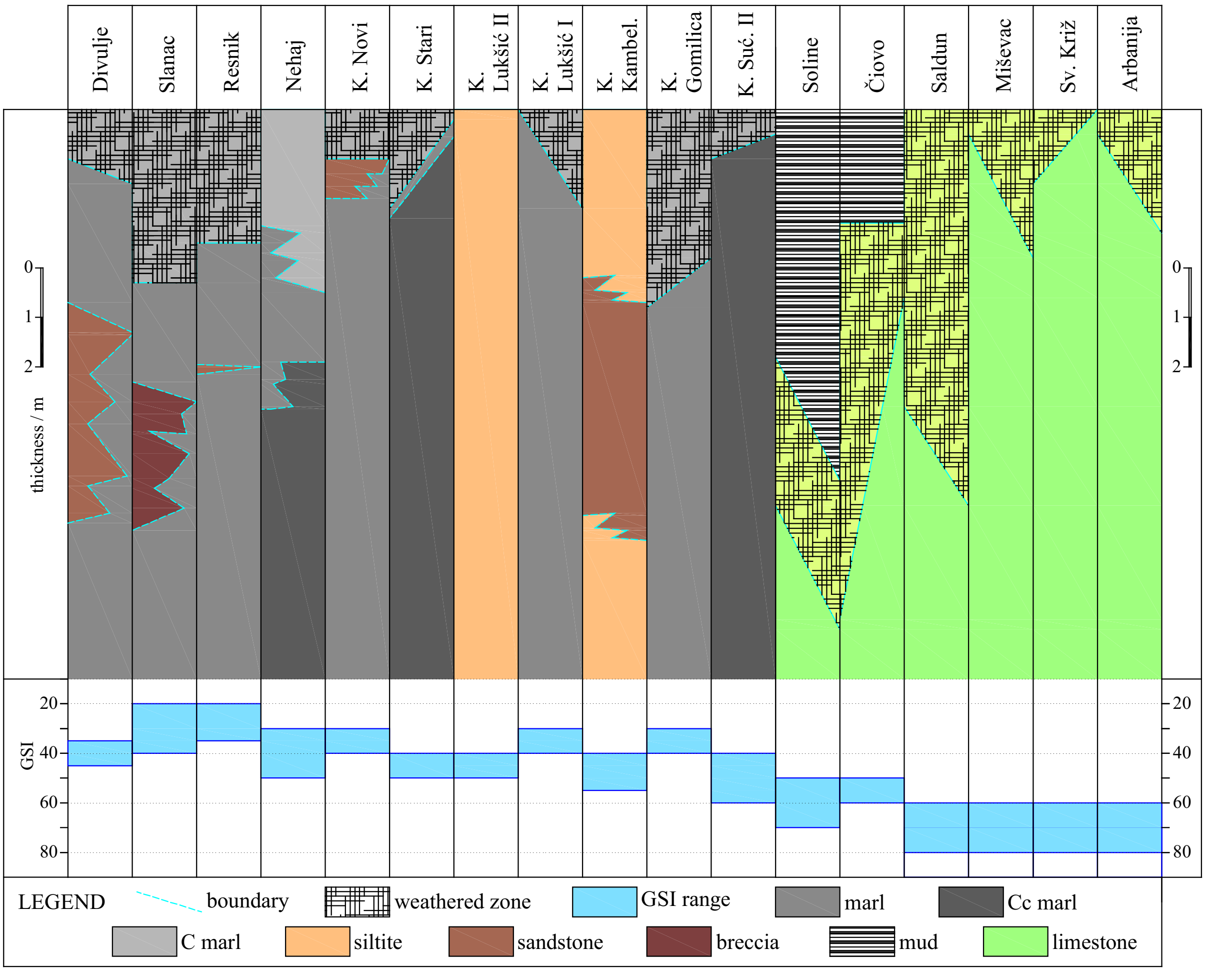

Figure 4. Schematic and simplified cross-sections (excluding anthropogenic layers) through the flysch and limestone, showing the weathered zone and clastic components of the flysch. Geological Strength Index (GSI) values are for fresh or slightly weathered bedrock.

Engineering properties of limestones

The southern part of Ciovo Island comprises karstic and recrystallized Senonian limestones (Figure 2), and is a mature or complex karst according to the classification of Waltham & Fookes (2003). The thickness of the limestone here is uncertain, but greatly exceeds the depth of proposed construction. Around the proposed Soline and Ciovo pumping stations (Figure 2) recent organic marine mud overlies the limestone bedrock.

Karstified bedrock properties

The limestones are locally strongly fractured and are intensely and deeply karstified, especially along steep and sub-vertical discontinuities, most of which are infilled with clay. Narrower discontinuities are dominantly filled with calcite.

GSI values for the limestones range from 60 to 80 (Figure 4). Locations with lower GSI values are more fractured. P-wave velocities are greater than 2500 m/s and may exceed 3000 m/s. RQD varies from 60 to 90%. The mechanical properties of the “intact” rock do not vary greatly, and are not dependent on weathering of the rock mass.

Strongly weathered zone with terra rossa

The strongly weathered zone is associated with wide, infilled or open, discontinuities. In some areas, “terra rossa” is present, which comprises a semi-coherent or coherent mixture of clay and fragments of limestone. The limestone fragments vary in size and abundance, but increase in abundance towards the bedrock.

The form of this zone, which varies greatly in thickness (Figure 4), was determined mainly by seismic refraction (Figure 5) and is characterised by P-wave velocities, which vary between 1000 and 2500 m/s.

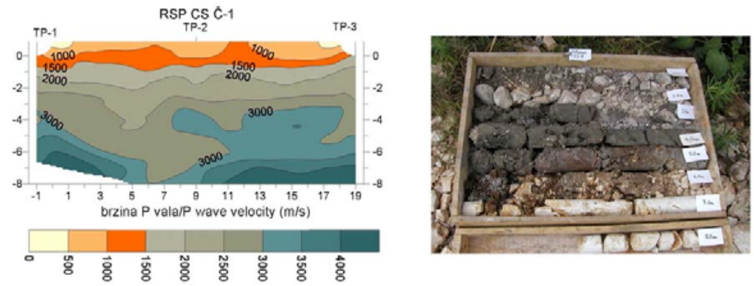

Figure 5. Seismic refraction profile and borehole core at the Ciovo pumping station location.

ENGINEERING GEOLOGICAL CHARACTERISITICS OF THE CIOVO WASTE WATER TRANSFER ('HYDRO-TECHNICAL') TUNNEL

The waste water transfer ('hydro-technical') tunnel, which will cross Ciovo Island, has a design length of 2824 m and is the most important single component of the Kastela Bay sewage system.

The area through which the tunnel will pass comprises an extremely permeable karstic landscape. However, karst sinkholes are rare, and shallow and small in diameter. The carbonates include Upper-Cretaceous Turonian and Senonian sediments and Early Eocene limestones, and the Quaternary cover, which is up to 30 m thick, comprises various types of sediment (Marincic et al. 1973). The structure and related rock mass engineering geological characteristics and permeability are described by Buljan & Pollak (2003). Most of the terrain is terraced, enclosed by dry-stone walls, and is overgrown by dense macchia and olive trees, and is sparsely wooded with pine-trees. The tunnel elevation will be between 17.6 m and 12.0 m, and overburden, other than in the portal areas, will be mostly between 80 and 180 m (Figures 6 and 7).

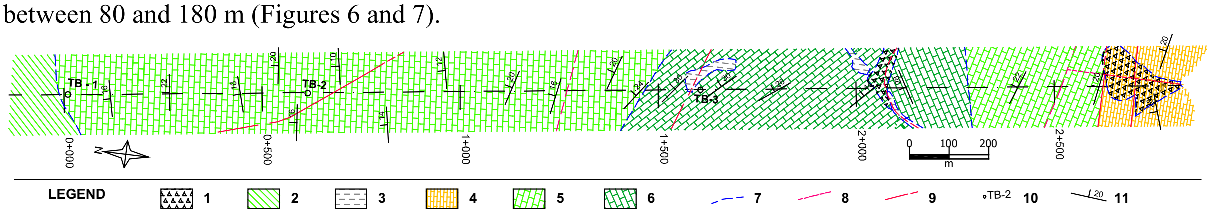

Figure 6. Geological map. Legend: 1) blocks and rock fragments; rockfall breccia – Quaternary s-Q_2; 2) mixed silty-clay and limestone fragments from the bedrock; deluvium – Quaternary Q_2; 3) silty-clay or clayey-silt with few bedrock fragments – Quaternary Q; 4) limestone, foraminiferal, well-bedded, light brown - Early and Middle Eocene $E_{1,2}$; 5) limestone, recrystallized, partly dolomitic, light brown - Late Cretaceous, Senonian K_2^3; 6) limestone; with sporadic chert nodules, well-bedded, light brown - Late Cretaceous, Turonian K_2^2; 7) boundary; 8) fault; 9) regional fault; 10) borehole; 11) bedding orientation.

The Ciovo tunnel will be constructed through the following materials (Figure 7):

- chainages 0+000 to 1+470 km, and 2+285 to 2+625 km (total ~ 1810 m) comprising well layered (layers 15 to 40 cm thick), fully re-crystallized and dolomitized limestones, karstified along discontinuities and cavernous;
- chainage 1+470 to 2+285 km (total ~ 815 m) comprising well layered (layers 15 cm to 20 cm thick), cavernous limestones (wackestone and packstone), karstified along discontinuities and pervaded by calcite veins (<1 mm thick), with chert nodules and thin dolomite interbeds;
- chainage 2+625 to 2+825 km (total ~ 200 m) comprising tectonically brecciated, locally well layered (layers 10 cm to 25 cm thick) weathered limestone, and hard foraminiferal limestones (grainstone), with abundant irregular clay-infilled fractures.

Regarding discontinuities along the tunnel alignment:

- discontinuities dip north-north-east, typically at 10-30°, at 10 to 40 cm intervals, and are closed or partially open, with or without a calcite infill. Their orientation relative to the axis of the tunnel (trend c.172°) is rather adverse for tunnel excavation from north to south, with potential rock block detachment from the tunnel roof;
- fold axial planar discontinuities orientated variably perpendicular to, or at an angle of up to 30º from, the tunnel axis, dip south, typically at 70-85°, which is rather favourable for tunnel excavation; and
- discontinuities striking perpendicular to the fold axial planar discontinuities, extending parallel, or at an angle, to the tunnel axis, persisting latterly for 1-3 m, with apertures of 1-5 mm, mostly without infill, and typically dipping 75-90°, which is rather adverse for tunnel excavation with potential detachment from the tunnel walls.

Seismic refraction (Figure 7) has established that the weathering zone of the rock mass extends to a depth of approximately 20 m (Pest & Salkovic 2003). The rock mass becomes less weathered with depth, except in fault zones. At the depth of the planned elevation of the tunnel tube the rock mass is slightly karstified and compact (v_p velocities exceed 4000 m/s). This was confirmed in three different places by exploration drilling.

A geoelectrical tomographic profile (Figure 7) revealed zones of low electrical resistance (1000 – 2000 m) which comprise brecciated (tectonised) carbonate typically infilled with clay. Zones of medium electric resistance (2000 m to 5000 m) comprise less fragmented carbonate sediments either without infill, or partially infilled, while zones of high electrical resistance (5000 m to 20000 m) comprise slightly fragmented to compact rock without infill. The geoelectric tomography also revealed tectonic blocks separated by faults.

Based on all the data gathered along the tunnel route, Table 1 lists 7 engineering geological units (EG) to which RMR classification of the rock mass (Bieniawski, 1989) was applied:

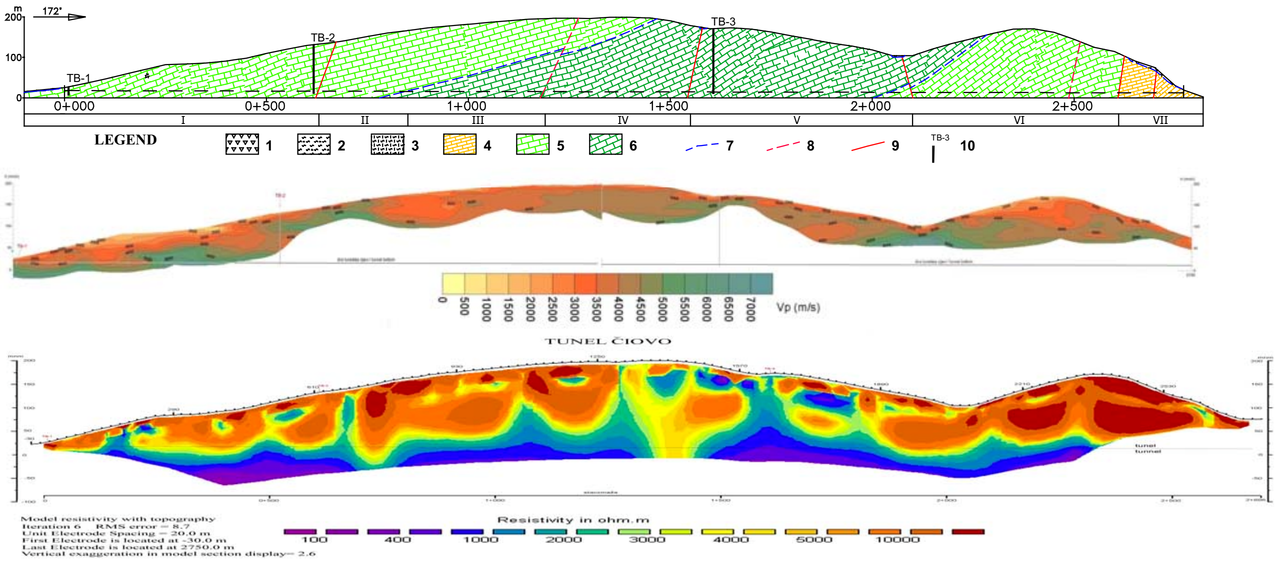

Figure 7. a.) Geological profile with engineering-geological units (legend is the same as in Figure 6). b.) Seismic refraction profile. c.) Geoelectrical tomographic profile.

Table 1. Inferred rock mass quality at the tunnel level. Categories based on RMR classification.

EG unit	Chainage	L (m)	Category II (m)	Category III (m)	Category IV and V (m)
I	0+000-0+630	630	180	415	35
II	0+630-0+850	220	202	-	18
III	0+850-1+190	340	326	-	14
IV	1+190-1+550	360	344	-	16
V	1+550-2+100	550	501	-	49
VI	2+100-2+610	510	391	-	119
VII	2+610-2+824	214	-	193	21
Total length		2824	1944	608	272
Percentage of length (%)			69	21	10

Water level occurs below the lowest tunnel elevation, at a few metres above sea level, and can not rise above the level of the tunnel. During heavy rains, there is a danger of water ingress from above, especially beneath the topographic depressions that are filled with Quaternary sediments, and through fracture/fault zones; however, it is considered that such water would drain rapidly (within several hours or days) to groundwater level through vertical cracks.

CONCLUSIONS

From the site investigation carried out for the Kastela Bay sewage system ("EKO Kastela Bay"):

- the planned sewage network will be constructed in a complex of flysch and carbonate sediments. The rock mass characteristics associated with these two basic rock types differ in many respects and require different approaches to foundation design. The weathering zones in the clastic flysch sediments and limestone result from different processes and have different characteristics; relatively uniform and thin in the case of the flysch and extremely variable and significantly deeper in the case of the limestones.
- The Ciovo tunnel is designed in well layered, fractured and locally brecciated carbonate sediments. There are some potentially adversely orientated discontinuities along the tunnel alignment. The most sensitive zones for

excavation include those lying beneath two topographic depressions that are filled with thin Quaternary sediments, and a sequence at the southern portal of hard, fragmented foraminiferal limestone with vertical crush zones. There is also a reasonable possibility that metre-scale cavities may be encountered during excavation. However, there are no large sinkholes along the tunnel alignment. There is minimal likelihood of a large ingress of groundwater during excavation.

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