Technical note

Some engineering properties of limestone: Tunnel Stražina case study (Croatia)

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Abstract

The paper presents geological and engineering geological characteristics of the Stražina Tunnel along the Bisko-Šestanovac section of the Zagreb-Split-Dubrovnik highway in Croatia. This paper compares the actual conditions of the rock mass during the excavation with a prediction model that preceded the excavation. From the engineering-geological viewpoint the rock mass in the tunnel was of a significantly higher quality than the prediction model. The specific geological feature of the Stražina Tunnel, with its right and left tunnel tube, is the passage of the right tunnel tube through a transgressive contact between Upper Cretaceous rudist limestones and Eocene foraminiferal limestones. Since this is the only tunnel in Croatia excavated through this particular transgressive contact, the geological and engineering properties of the transgression zone were up to now only assumed. Therefore, additional mineralogical, petrographical and engineering geological observations were carried out in order to determine and describe the transgression zone. The results are presented in this paper. In the left tunnel tube the contact between the mentioned lithostratigraphical Units is of the fault type. This paper also briefly deals with the significance and cause of the overprofile excavation during tunneling through strongly karstified carbonate rocks. Consequently, special attention was paid to the overprofile during excavation since it can significantly affect tunneling costs.

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1. Introduction

The Stražina Tunnel is located in the central part of southern Croatia (Dalmatia) along the Bisko-Šestanovac section of the Zagreb-Split-Dubrovnik highway (Figs. 1a and 1b). The excavation lasted from 09/2005 to 02/2006. The tunnel has two tubes at the axis distance of 25 m, horseshoe-shape with ten meters in diameter and approximately 75 m² in cross section. It was mined by drill-blast excavation methodology in its full length advancing from the east towards the west. The underground excavation of the northeastern (left) tunnel tube was carried out from chainage 26.775 to 27.335 km (560.0 m in length), and the southern (right) tunnel tube from chainage 26.777 to 27.3615 km (584.5 m in length). The total length of the tunnel underground excavation is 1114.5 m and overburden thickness for both tunnel tubes ranges from 6 to 42 m. The tunnel elevation above sea level ranges from 278.8 to 282.5 m.

The site investigations preceding the excavation included comprehensive engineering-geological mapping, exploration boreholes, geophysical investigations, laboratory tests, seismological and seismotectonical studies.

The results of all these investigations preceded the tunnel excavation enabled the development of the engineering geological prediction model. Furthermore, the engineering-geological model enabled designing of the tunnel support system as well as the selection of the excavation technology.

The excavation was accompanied by the engineering-geological mapping and rock mass classification procedure which was used to adopt the support system and the advance rates in the course of the excavation. The mapping carried out during tunneling also enabled comparison of the prediction engineering geological model and real rock mass properties and site conditions.

The specific importance of the Stražina Tunnel is that it is the first road tunnel in Croatia which was excavated through the transgressive contact between Upper Cretaceous rudist limestones (K2) and foraminiferal Eocene limestones (E1,2).

2. Rock mass prediction model

The prediction engineering-geological model of the Stražina rock mass quality was mainly developed in concordance of the experience of tunneling in Croatian karst and is based on three
models: petrological, structural and weathering model. The petrological model defined rocks along the trace of a tunnel and its physical and mechanical properties, primary discontinuities (bedding) characteristics, bedding thickness and block sizes in each of the lithostratigraphical units. The structural model defined: orientation of main sets of discontinuities, block sizes, main fault zones and characteristics of the secondary discontinuities in each of the structural units. The weathering model defined the discontinuity properties in each of the weathering zones and influence of the weathering processes to the physical and mechanical properties of the rocks.

2.1. Rock mass units

The first phase in generating the prediction model of the rock mass included the analysis and synthesis of all geological data at present (Marinčić et al., 1976). The second phase included comprehensive engineering geological site investigations in the scale 1:1000, exploration drilling, geophysical explorations and laboratory tests considering the mineral-petrographic composition and physical–mechanical characteristics of the rocks. The results were presented in the preliminary study on geotechnical investigations for the Stražina Tunnel.

The investigation results made it possible to distinguish two lithostratigraphical Units, two tectonic blocks and three weathering zones.

2.1.1. Lithostratigraphical units

Lithostratigraphical units will be described in the inverted stratigraphical order.

In order to determine more details about texture and limestone types, the data collected during the investigation phase were supplemented with macro and micro-petrological analysis during the excavation phase. Therefore, two samples were taken during the tunnel excavation in the right tunnel tube at chainage 27.141 km. The petrographical determination was carried out according to Dunham (1962) with supplement according to Embry and Klován (1972) and Folk (1959) with supplement according to Flügel (1982).

The lithostratigraphical Unit 1 contains well bedded foraminiferal Eocene limestone (E1,2). This limestone type consists mainly of clearly visible foraminifera tests and micritic matrix. Sizes of foraminifera vary, but more than 10% tests are greater than 2 mm; therefore the rock macroscopically corresponds to foraminiferal floatstone. According to micropetrographical characteristics, skeletal detritus is represented mainly by large (>2 mm) benthos foraminifera (alveolines and miliolidae, Fig. 2) and a micritic matrix. In a matrix small plankton foraminifera and small echinoid fragments can be observed. The micritic matrix displays signs of recrystallization and the occurrence of secondary fissures (Fig. 2). The sample was determined as foraminiferal biomicrudite.

Unit 2 consists of massive and faintly bedded rudist limestone (K2). Rudist limestones were macroscopically determined as dense, homogeneous, white, fossiliferous wackestone. Microscopically, the sample consists of biodetritus smaller than 2 mm and is composed of mollusks and echinoid fragments and benthic foraminifera tests in a micritic matrix (Fig. 3). A micritic matrix has been partly recrystallized. Large fragments of rudists (>2 mm) are rarely present (Fig. 4), never with the amount greater than 10%. According to performed microscopic analysis the sample has been determined as biomicrite.
According to the mapping results, contact between the litostratigraphical Units is of the fault type. The rock mass of each litostratigraphical Unit is characterized by respective engineering geological features so that litostratigraphical Unit 1 (Eocene foraminiferal limestone) is at the same time an engineering-geological Unit 1, while litostratigraphic Unit 2 (Cretaceous rudist limestone) represents an engineering-geological Unit 2.

The orientation and average discontinuity conditions are presented in Table 1. The presented characteristics refer to their characteristics on the surface and in the borehole cores.

The boreholes, B-59 TST and B-60 TST, were drilled in the karstified foraminiferal limestones whose values of the rock quality designation – RQD (Deere, 1963) mainly range from 60% to 85%.

In the B-60 TST borehole a solution cavity was drilled at intervals of 1.5 m. The solution cavity is located at an approximate depth of 27 m and is partly filled by terra rossa and limestone blocks.

The B-61 TST borehole was drilled in rudist limestone whose RQD values mainly range within an interval of 70–85%. In a tectonic (fault) zones RQD is 0%.

2.2. Weathering zones

The geophysical field investigations along the tunnel axis were carried out by seismic refraction and geoelectric profiling. The interpretation of data showed that the rock mass, considering the degree of karstification, can be divided into three zones: the
surface weathering zone, the upper karstification zone and the karstified base.

The surface weathering zone is characterized by limestone blocks separated by joints whose aperture reaches a few decimeters. The predominant soft infilling in those joints is composed of terra rossa and rock fragments; occasionally these joints are open, without the infilling. The velocity of longitudinal seismic waves is less than 1300 m/s and the electric resistance is less than 2000 $\Omega\cdot$m. This zone depth reaches 2 m and it does not affect the rock mass in the excavation zone.

The upper weathering zone is not regularly distributed. It is locally absent so the surface weathering zone directly overly the karstified base. This zone contains strongly karstified limestones which are still subjected to the karstification processes. Karstification is facilitated by the presence of open primary discontinuities and/or secondary discontinuities caused by tectonic activity which enable free flow of rainfall water. The velocity of longitudinal waves in this zone ranges from 1300 to 2500 m/s and the electric resistance from 10,000 to 15,000 $\Omega\cdot$m. The depth of this zone, according to geophysical investigations ranges from 2 to 20 m and affects the rock mass in the tunnel portal zones.

The majority of the rock mass at the excavation level is in the zone of karstified base. According to predictions based on the interpretation of seismic refraction and geoelectric profiles, solution cavities can be expected in that zone which can reach decameter dimensions and are genetically associated with tectonically weakened zones or with significant vertical and subvertical joints mapped on the terrain surface. The velocity of the longitudinal waves in the karstified base zone is higher than 2500 m/s and the electric resistance ranges from 2000 to 10,000 $\Omega\cdot$m.

<table>
<thead>
<tr>
<th>Engineering-geological unit</th>
<th>Orientation Spacing</th>
<th>Persistence</th>
<th>Aperture</th>
<th>Infilling</th>
<th>Roughness</th>
<th>Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bedded foraminifera limestone, $E_{1,2}$</td>
<td>5/42 (bedding)</td>
<td>0.2–0.6 m</td>
<td>1–3 m</td>
<td>None, &lt;0.1 mm, 0.1–1 mm</td>
<td>None, hard &lt;5 mm</td>
<td>Slightly rough</td>
</tr>
<tr>
<td></td>
<td>182/88</td>
<td></td>
<td></td>
<td>&lt;0.1 mm, 0.1–1 mm, 1–5 mm</td>
<td>Hard &lt;5 mm, soft &lt;5 mm</td>
<td>Rough, slightly rough</td>
</tr>
<tr>
<td></td>
<td>86/89</td>
<td>0.2–0.6 m</td>
<td>1–3 m</td>
<td>0.1–1 mm, 1–5 mm</td>
<td>Hard &lt;5 mm, soft &lt;5 mm</td>
<td>Rough, slightly rough</td>
</tr>
<tr>
<td></td>
<td>101/76</td>
<td>0.2–0.6 m</td>
<td>3–10 m</td>
<td>1–5 mm, &gt;5 mm</td>
<td>Soft &lt;5 mm, soft &gt;5 mm</td>
<td>Rough, slightly rough</td>
</tr>
</tbody>
</table>

| 2 Massive or faint bedded rudist limestone, $K_2$ | 17/32 (bedding) | 0.2–0.6 m | 1–3 m | None, <0.1 mm, 0.1–1 mm | None, hard <5 mm | Slightly rough, smooth | Unweathered, slightly weathered |
|                                                    | 181/75 |          |          | 0.1–1 mm | Soft <5 mm, soft >5 mm | Rough, slightly rough | Slightly weathered |
|                                                    | 101/76 | 0–0.6 m  | 3–10 m | 1–5 mm, >5 mm | Soft <5 mm, soft >5 mm | Rough, slightly rough | Slightly weathered, moderately weathered |
Tables and figures should be numbered and cited appropriately. Here is a sample text with tables and figures that are properly formatted.

### 2.3. The strength parameters of the rock material and rock mass

The strength parameters of the rock material were identified by laboratory testing on the samples from the exploration boreholes. The analysis included uniaxial compressive strength tests ($\sigma_u$) (according to ISRM (1979)) and testing of compressive strength in triaxial conditions (according to ISRM (1983)).

The analysis also included the determination of the: volumetric density ($\rho$), intact rock parameter "m"", modulus of deformation ($E_i$), angle of internal friction ($\varphi$) and the velocity of propagation of elastic waves by low frequency ultrasound technique.

The rock mass strength was determined by the Hoek–Brown failure criterion (1997) and the other parameters by means of "RockLab" software (Hoek et al., 2002). The intact rock parameters for foraminiferal and rudist limestone are given in Table 2, while the rock mass parameters are presented in Table 3.

According to the results of field mapping and core analyses, the lower and the upper GSI values for bedded foraminiferal Eocene limestone were determined between 50 and 73, and for massive and faintly bedded upper Cretaceous rudist limestone 50 and 71. Karstified zones in foraminiferal limestone have GSI value around 40 and in rudist limestone around 39.

GSI values were calculated according to equation:

$$GSI = \text{RMR}_{\text{Q90}} - 5$$

where $\text{RMR}_{\text{Q90}}$ is RMR value calculated according to RMR system published by Bieniawski, 1989 with groundwater rating set to 15 and adjustment for joint orientation set to zero.

### 2.4. Predicted rock mass classes

The determination of the rock mass class is one of the key elements during tunneling since it influences the advance rate and the supporting system. These are also the factors which directly influence the time length of the tunneling operations and their cost.

The geomechanical classification (Bieniawski, 1989) and Q system (Barton et al., 1974), used worldwide in defining the rock mass quality for tunneling designs, has been applied. Designing and tunneling through carbonate rock masses proved the applicability of Geomechanical classification and Q system in this kind of material too. However, the existing RMR and Q correlations seem to be slightly incompatible. Namely, based on classification results in the stage of exploration works (196 geological situations) and classification results in situ during tunnel construction (265 geological situations) the RMR and Q correlation in Croatian carbonate rocks has been given by the equation (Stojkovic et al., 2010):

$$\text{RMR} = 9.1 \times \ln Q + 43$$

According to the results of the engineering geological investigations, the excavation zone contains two engineering-geological Units. The classification parameters were assessed for each Unit separately which served as a basis for the prognosis of distribution of rock mass classes along both tubes.

According to the presented engineering geological properties, the tunnel orientation and the given direction of advance, the majority of rock mass of Unit 1 (foraminiferal limestones) has RMR value 49–68 and Q between 0.9375 and 13.333, while majority of Unit 2 (rudist limestones) has RMR value 44–71 and Q between 0.729 and 15.000, which classifies them between rock mass classes II and III (RMR). It can easily be inferred from Table 4 that the prediction model for rock mass classes underestimated by 21% for the class II of rock mass while overestimated by 15% for class III type rock mass.

### 2.5. Seismological and seismotectonic characteristics of the area

According to the report on seismological and seismo-tectonic investigations the entire Bisko-Šestanovac highway section is located in an active zone considering the seismo-tectonic conditions within the Mosor-Biokovo mountain seismic zone (central part of southern Croatia). The data show that tectonic activity is constantly present; for the Mosor-Biokovo mountain seismic zone the maximum magnitude was assessed to be $M_{\text{max}} = 6.5$. For the hypocenter depth of 15 km the following maximum acceleration values were obtained on the bridges and viaducts of this section: $a_{\text{max}} = 0.45–0.58$ g with an intensity of $I_{\text{max}} = 9.4–9.6$ MCS. The presented values refer to the features of P2 type earthquake, i.e. the maximum earthquake which can occur at the locations under study, from the deterministic standpoint.

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**Table 2**
The intact rock parameters for foraminiferal and rudist limestone.

<table>
<thead>
<tr>
<th>Engineering-geological Unit</th>
<th>$m_i$</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$E_i$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bedded foraminiferal limestone, $E_{1,2}$</td>
<td>9.479</td>
<td>206</td>
<td>2.71</td>
<td>66</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, $K_2$</td>
<td>10</td>
<td>148</td>
<td>2.71</td>
<td>61</td>
</tr>
<tr>
<td>1 Bedded foraminiferal limestone, $E_{1,2}$ (karstified zones)</td>
<td>9.479</td>
<td>145</td>
<td>2.71</td>
<td>66</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, $K_2$ (karstified zones)</td>
<td>10</td>
<td>135</td>
<td>2.71</td>
<td>66</td>
</tr>
</tbody>
</table>

**Table 3**
The rock mass parameters for foraminiferal and rudist limestone.

<table>
<thead>
<tr>
<th>Engineering-geological unit</th>
<th>$m_i$</th>
<th>$s$</th>
<th>$a$</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\sigma_t$ (MPa)</th>
<th>$E_i$ (GPa)</th>
<th>$c$ (MPa)</th>
<th>$\varphi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bedded foraminiferal limestone, $E_{1,2}$</td>
<td>Upper GSI value 73</td>
<td>3.614</td>
<td>0.0498</td>
<td>0.501</td>
<td>45.87</td>
<td>-2.84</td>
<td>37.58</td>
<td>16</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, $K_2$</td>
<td>Lower GSI value 50</td>
<td>1.589</td>
<td>0.0039</td>
<td>0.506</td>
<td>12.42</td>
<td>-0.50</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1 Bedded foraminiferal limestone, $E_{1,2}$ (karstified zones)</td>
<td>Upper GSI value 71</td>
<td>3.550</td>
<td>0.0399</td>
<td>0.501</td>
<td>29.43</td>
<td>-1.66</td>
<td>33.50</td>
<td>11</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, $K_2$ (karstified zones)</td>
<td>Lower GSI value 50</td>
<td>1.677</td>
<td>0.0039</td>
<td>0.506</td>
<td>8.91</td>
<td>0.34</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>1 Bedded foraminiferal limestone, $E_{1,2}$ (karstified zones)</td>
<td>GSI value 40</td>
<td>1.112</td>
<td>0.0013</td>
<td>0.511</td>
<td>4.80</td>
<td>0.17</td>
<td>5.62</td>
<td>6</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, $K_2$ (karstified zones)</td>
<td>GSI value 39</td>
<td>1.132</td>
<td>0.0011</td>
<td>0.512</td>
<td>4.20</td>
<td>-0.14</td>
<td>5.31</td>
<td>6</td>
</tr>
</tbody>
</table>

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The project values of the P1 earthquake for a recurrence interval of 500 years are: $a_{\text{max}} = 0.25–0.30$ g with the intensity $I_{\text{max}} = 9.0–9.1$ MCS.

However, the Stražina tunnel is not located close to the main reverse regional faults (Fig. 1b) on which most of the seismic activity is recorded. The fault between two engineering-geological Units in the area of Stražina tunnel is a minor one with NE–SW strike. The fault was generated during late Eocene and there is no evidence of its recent tectonic activity. Therefore there is no need for undertaking some additional preventative measures in the area of the fault regarding earthquake hazards.

### 3. Site conditions after the completed excavation

It is to be expected that the distribution of the predicted rock mass classes does not completely match with the actual distribution calculated during the excavation. However, it is important to ensure that the predicted and actual conditions of the excavation rock mass classes do not differ significantly.

The deviations of prediction model in intensively karstified area can result from expert's subjectivity, complex geology, insufficient data on the location, application of inappropriate investigation methods, insufficient experience and erroneous assessment of the actual conditions of the rock mass.

Engineering-geological mapping of the rock mass was carried out during the excavation of the Stražina Tunnel in order to obtain the parameters for the assessment of rock mass classes according to the RMR system (Bieniawski, 1989). Furthermore, the mapping also included defining of all other relevant geological and engineering geological characteristics of the tunnel (faults, weathering zones, changes in lithology and occurrence of solution cavity).

During excavation the rock mass was regularly mapped at intervals of 9–10 m. The contribution of rock mass classes is presented in Table 2, and the distribution of classes along the tunnel route can be seen in Figs. 5 and 6.

#### 3.1. Characteristics of the contact zones

The contact between two described engineering-geological Units differentiates in the left and in the right tunnel tube.

In the left tunnel tube the contact zone between engineering-geological units is of fault type (Fig. 5). The orientation of the fault zone is 280/70 (dip direction/dip angle). Contact is represented by a shear zone 3 m wide within which the rock mass is crushed and intensively karstified. Kartistification was made visible by the presence of terra rossa as a joints infilling and a solution cavity filled with hard silt and/or hard clay. The cavity size is $5 \times 6$ m and it was mapped in the left side wall of the tunnel tube.

In the right tunnel tube at the chainage from 27.156 to 27.066 km the foraminiferal and rudist limestones are in transgressive contact (Fig. 6). The orientation of the transgressive contact (zone) is 20/40 and is conformable with the orientation of the underlaying rudist limestones beds.

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The thickness of the transgressive zone between rudist and foraminiferal limestone is up to 3.5 m. It is composed of chaotic sediment with breccia structure, dominantly grey coloured and without visible bedding. Clasts have dimensions ranging from a few millimeters to more than 10 cm and differ also according to their roundness. The matrix between clasts is clay and/or marl and is generally faintly lithified or highly plastic clay in some portions. Within the chaotic sediment, which represents a transgressive contact, it is occasionally possible to observe vugs infilled with highly plastic yellow–brown clayey material (Fig. 7). Contact can be observed at the western approach cutting of the southern tunnel tube.

By the XRD diffraction analysis it was possible to determine the mineral composition of material found at the transgressive contact (grey-sample 1, yellow–brown sample 2). The diffraction diagrams were taken with a Philips diffractometer with a counter and with Cu Kα radiation (U = 40 kV, I = 35 mA). The diffraction diagrams of the original samples were taken as well as those which present their insoluble residual obtained by dissolving carbonate in 10% acetic acid. The insoluble residual was treated by glycerin, ethylglycol and heated for 2 h at 650°C and dissolved in 18% HCl. The diffraction diagrams of the samples were taken after each mentioned treatment.

Micaceous minerals (T) were dominant in both samples (Table 5). That term is used for referring to a mixture containing illite and interstratified illite–smectite with a low content of a smectite layers and possibly muscovite. The presence of illite–smectite with a greater content of smectite layers is also possible. In addition to the mentioned minerals, both samples contain other interstratified minerals, most probably irregularly interstratified illite–smectite (MM). Both samples contain a large portion of an amorphous component (AC) which made the identification of other minerals more difficult.

### Table 5
Mineral composition of the samples obtained from the material at the transgressive contact by XRD analyses (quantities in weight percentage). Legend: a – ≤5% quantity of the mineral, m – 5% < m ≤ 10% quantity of the mineral, c – 10% < c ≤ 25% quantity of the mineral, d – ≥50% quantity of the mineral, ? – presence of the mineral was not fully confirmed, – mineral was not found in the sample, T – micaceous minerals, MM – irregularly interstratified minerals (most probably illite–smectite), Kln – kaolinite group minerals, AC – amorphous component.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Calcite</th>
<th>Pyrite</th>
<th>Anatase</th>
<th>Amphibole</th>
<th>T</th>
<th>MM</th>
<th>Kln</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>a</td>
<td>a/m</td>
<td>?</td>
<td>d</td>
<td>a</td>
<td>c</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>–</td>
<td>a</td>
<td>–</td>
<td>d</td>
<td>a</td>
<td>c</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6
The average conditions and orientation of the discontinuities mapped during excavation along the tunnel route.

<table>
<thead>
<tr>
<th>Engineering-geological unit</th>
<th>Orientation</th>
<th>Spacing (m)</th>
<th>Persistence (m)</th>
<th>Aperture (mm)</th>
<th>Infilling (mm)</th>
<th>Roughness</th>
<th>Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bedded foraminiferal limestone, E₁,₂</td>
<td>15/42 (bedding)</td>
<td>0.2–0.6</td>
<td>10–20</td>
<td>1–5</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>174/68</td>
<td>0.2–0.6</td>
<td>1–3</td>
<td>&lt;0.1</td>
<td>None</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>346/53</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>0.1–1</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>262/81</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>1–5</td>
<td>Soft &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td>2 Massive and faintly bedded rudist limestone, K₂</td>
<td>5/40 (bedding)</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>0.1–1</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>150/53</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>1–5</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>335/65</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>1–5</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
<tr>
<td></td>
<td>280/80</td>
<td>0.2–0.6</td>
<td>3–10</td>
<td>0.1–1</td>
<td>Hard &lt;5</td>
<td>Slightly rough</td>
<td>Slightly weathered, Unweathered</td>
</tr>
</tbody>
</table>

3.2. Engineering-geological characteristics

As previously mentioned, the results of the site investigations were used to divide the rock mass along the tunnel route into two engineering-geological Units: the first consisting of foraminiferal limestones and the second of rudist limestone. During the excavation in both Units four identical sets of discontinuities were mapped. Their orientations slightly differ, depending on whether they were within Units 1 or 2. The average discontinuities characteristics and their orientation can be seen in Table 6.
3.2.1. Transgressive contact
The X-ray diffraction analysis of the matrix of transgressive contact confirmed the doubts about the presence of swelling clay minerals which refers to smectite layers in interstratified illite-smectite. The nature and properties of the material at a transgressive contact are completely different from the surrounding limestones and required urgent application of shotcrete during excavation in order to protect it from moisture. Consequently, this tunnel section can be considered as a separate engineering-geological unit not encountered before in Croatia. The described transgressive contact was present along 90 m on the excavation route because of unfavorable orientation with regard to the left tunnel tube.

The zone of the transgressive contact was handled as class III, unlike the surrounding rock mass which dominantly belongs to the class II in RMR classification (Fig. 6). Therefore, the excavation and primary support of the tunnel in the mentioned zone were approximately 25% more expensive in comparison to the surrounding limestones which significantly increased the total cost of the project. Support measurements for each RMR class applied in this tunnel are given in Table 7.

3.2.2. Rock mass classes
Still, comparing the predicted state and actual site conditions it can be observed that the rock mass quality had been underestimated (Table 4). Actually, class II had a significantly higher contribution than other classes and the class V during excavation is not find at all. The reason for the underestimation of the rock mass quality is probably overestimated depth of the highly weathered zone based on geophysical data. Namely, according to the surface data there are regularly three sets of discontinuities present, but at the elevation height of the both tunnel tubes just two sets of discontinuities were frequently present. It is evident that the third discontinuity set is not present in each part of the rock mass. Nevertheless, considering the total tunnel length, four discontinuity sets were mapped. RMR classes and its distribution along the tunnel route can be seen in Figs. 5 and 6.

3.2.3. Hydrogeological characteristics and solution cavities
The Stražina Tunnel is located far above the groundwater level. The water in tunnel, with a maximum of 15 l/min on 10 m² was drained from the surface during rainfalls. The water precipitates along highly karstified subvertical joints. The presence of water was caused also by fault zones and solution cavities which regularly accompanied them. The size of solution cavities greatly varies, from 1 m up to 6–7 m in diameter. The largest can be seen in Fig. 8. It extends from chainage 26.869 to 26.890 km in the left tunnel tube. It covered approximately 1/4 of the face, right side wall and the tunnel crown with maximum measured over profile length of 8.37 m. Most frequently the solution cavities had no infillings, but they were occasionally filled by terra rossa and/or limestone blocks.

Generally, the number and size of solution cavities in the tunnel reveal that the rock mass was subjected to intense karstification and suggests the necessity of detecting them below the excavated tunnel. Unfortunately, the geophysical investigations, which would make possible the detection of the solution cavities and potentially unstable zones at the tunnel bottom, were not carried out. However, according to the authors opinion they should be standard procedure following tunnel excavation in highly karstified carbonate terrains.

3.2.4. Overprofile excavation
The overprofile excavation can represent a significant cost in tunneling operations through highly karstified rock mass since, after the completed excavation; the tunnel profile should have the shape and dimensions defined in the geotechnical project.

The cause of overprofile excavation can be either technological or geological. The technological one results from errors appeared during drilling and mining operations. In that case the reclamation costs were paid by the contractor. The reclamation costs of the geological overprofile in tunnel Strazina were paid by the investor. The geological overprofile in karst terrains can be caused by the following engineering geological conditions: frequent solution cavities and cavity zones, faults and fault zones and the unfavorable orientation of discontinuities with regard to the tunnel axis.

In the tunnel Stražina the excavation profile was geodetically recorded after each blast of the rock mass. One of those recordings of the tunnel face with a solution cavity in the right side wall can be seen in Fig. 9. In the Stražina Tunnel, 261 m² of the geological overprofile excavation were recorded in the right tube, and

Table 7
Support measurements defined in tunnel project.

<table>
<thead>
<tr>
<th>RMR</th>
<th>Excavation</th>
<th>Crown</th>
<th>Side walls</th>
<th>Invert</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Full face, 4 m advance</td>
<td>Shotcrete 5 cm, systematic bolts Φ 25 mm 3 m long spaced 2.5 m</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>III</td>
<td>Full face, 3 m advance</td>
<td>Shotcrete 10 cm, systematic bolts Φ 25 mm 3 m long spaced 2 m, single layered wire mesh</td>
<td>Shotcrete 5 cm</td>
<td>None</td>
</tr>
<tr>
<td>IV</td>
<td>Top heading and bench, 1–2 m advance in top heading</td>
<td>Shotcrete 15 cm, systematic bolts Φ 25 mm 3 m long spaced 1.7 m, single layered wire mesh</td>
<td>Shotcrete 10 cm, systematic bolts Φ 25 mm 3 m long spaced 2 m, single layered wire mesh</td>
<td>None</td>
</tr>
<tr>
<td>V</td>
<td>Top heading and bench, 0.5–1 m advance in top heading</td>
<td>Shotcrete 20 cm, systematic bolts Φ 32 mm 4 m long spaced 1.4 m, two layered wire mesh, steel ribs spaced 1 m</td>
<td>Shotcrete 20 cm, systematic bolts Φ 32 mm 5 m long spaced 1.4 m, two layered wire mesh, steel ribs spaced 1 m</td>
<td>Shotcrete 20 cm, two layered wire mesh</td>
</tr>
</tbody>
</table>

Fig. 8. The largest solution cavity in the Stražina Tunnel extends from chainage 26.869 to 26.890 km in the left tube. It covers cca 1/4 of the excavated profile, the calotte and the right side while the maximum measured overprofile length at the cavern location is 8.37 m. The photograph was taken at chainage 26.874 km.
215 m³ in the left tube. Consequently, special attention should be paid to the reclamation of the over profile excavation and its classification (technological or geological).

4. Conclusion

The Stražina Tunnel is located along the Bisko-Šestanovac section of the Zagreb-Split-Dubrovnik highway. The tunnel was excavated through foraminiferal (E₁,2) and rudist (K₂) limestones. In the left tunnel tube the contact between the presented lithostratigraphic Units was of the fault type, while in the right tunnel tube it was transgressive. That is a specific characteristic of the Stražina Tunnel since it is the only road tunnel in Croatia excavated through the transgressive contact of Upper Cretaceous rudist and Eocene foraminiferal limestones. This contact directly influenced the quality of the tunnel rock mass and due to it the quality of rock mass was lowered from the second to the third rock mass class along 90 m of its length. This was caused by the fact that at the contact loose or faintly lithified clayey and/or marly material has been detected. The XRD analysis of the material at the Cretaceous–Eocene transgressive rock contact has revealed the presence of swelling minerals which, in geotechnics in general, represents a very unfavorable condition and requires urgent application of shotcrete to prevent moisture absorption and swelling of the material.

During the excavation process the rock mass along the tunnel route was classified according to RMR system. To sum up, the total contribution of the II rock mass class was 53%, the III rock mass class contribution was 36%, the IV 3% and the 8% of the tunnel length had defined support measurements (portal zones).

The example of the tunnel Stražina presents the case where the rock mass quality is underestimated in prediction model. It is supposed that the difference between the predicted and actual model is the result of wrong assessment of the depth of the weathering intensity. Another reason can be the fact that in almost 50% of cases when rock mass is mapped, engineering geologist found just two discontinuity sets, although, considering the total tunnel length, four discontinuity sets are mapped.

The presence of some solution cavities was predicted by the interpretation of geophysical investigations in the prediction phase and they occurred as ordinary phenomena along the mapped faults at the tunnel route. Presence of the solution cavities necessitated overprofile excavations. They required special reclamation of the tunnel crown and side walls with additional bolting and steel ribs sometimes. Apart from solution cavities, the overprofile excavation in the tunnel can be caused by faults and fault zones and by unfavorable orientation of discontinuities according to the tunnel axis. In tunneling operations special attention is paid to the overprofile excavation (both technological and geological) since its appearance automatically implies an increase in the final tunnel cost.

Finally, after excavation in carbonate rock masses, geophysical investigations should be carried out along the tunnel elevation height in order to detect solution cavities zones in the karstified rock mass which lies under the future highway, since the reclamation...
of only those solution cavities which are visible is not sufficient from a safety standpoint.

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