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Specific aspects of engineering-geological models in Croatian karst

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ABSTRACT

The experiences of developing engineering geological models in karst areas for designing and construction purposes prove the necessity of considering at least three basic submodels: sedimentological, structural-tectonic and the weathering one. The research presented here deals with very important and frequently neglected segments in each of the submodels. Therefore, particular attention should be directed to: better understanding of carbonate sediment deposition, determination of environment and diagenetic processes, study of the 3D anisotropy of discontinuity frequency, and differentiation of weathering zones. The given data and examples elaborate and justify such an approach, which enables a more realistic detailed engineering model, more reliable evaluations of the engineering geological/geotechnical parameters and real site conditions.

Keywords: engineering geological model, karst, limestone, anisotropy, heterogeneity, discontinuities, weathering, Croatia

1. INTRODUCTION

The engineering geological model of the construction project area is a very important segment of geotechnical design. Creation of an engineering geological model for geotechnical designs is usually based on experience, known data, various field observations and measurements, and assumes common engineering geological, laboratory testing, geophysical surveying and borehole researching. This paper elaborates on the main geological issues observed at many investigation sites, while developing engineering geological models for the main motorways in the Croatian karst, at the Rijeka-Zagreb and Zagreb-Split-Dubrovnik sections having together more than 400 km in length (Fig. 1).

The paper does not deal with detailed elaboration of every input data for future models, but with the generically important and sometimes neglected emphases that are found in building the engineering models for carbonate rocks. It is also the intention to document how the authors came to deal with the great heterogeneity of carbonate rock material and the heterogeneity/anisotropy of carbonate rock mass engineering properties.

Figure 1: Location map showing the recent distribution of Adriatic Carbonate Platform (AdCP) deposits (according : VLAHOVIĆ et al., 2005) and investigated areas along new motorways.

2. GEOLOGICAL SETTING

The Croatian karst area encompasses approximately 29,356 km^2, or nearly 50% of the land surface of the Republic of Croatia. Carbonate rocks compose the central, coastal and submarine Croatian territory (Fig. 1). These sediments mainly originate from the Adriatic carbonate platform (AdCP). The large carbonate platform in this area started to develop during the Upper Triassic. During the Early Jurassic period, it disintegrated into several smaller platforms, one of which was the AdCP (VLAHOVIĆ et al., 2005). Carbonate sedimentation in relatively calm and shallow marine conditions at the AdCP lasted during the Mesozoic until the Late Cretaceous. Afterwards, carbonate sedimentation was prolonged under somewhat different conditions until the Eocene.

The great thickness of carbonate sediments, (3500 -5000 m in Croatian territory), proves the constant subsidence of the carbonate platform during deposition (HERAK, 1991). Other factors, including the variability of the depositional environment and emersion periods, also testify to the significant dynamics of the whole carbonate platform. Tectonic activity between the Cretaceous and the Paleogene initiated regional emersion and termination of the platform sedimentation. Therefore during the Eocene, carbonate rocks were deposited at the margins of the disintegrated platform (VLAHOVIĆ et al., 2005). In addition, the flysch basin had been formed and the Dinarides uplifted. The uplifting of the Dinarides reached its maximum between the Oligocene and Miocene. The final result of formation of the Dinarides was an area with strongly faulted and crushed zones, reverse and overlapped contacts (HERAK, 1986). Since the beginning of the neotectonic episode, the Adriatic region continued to sink while the Dinarides uplifted (PRELOGOVIĆ et al., 2003). Later, more intensive uplifting caused erosion of the Dinarides and deposition of thicker sediments in depressions. The Quaternary deposits either cover Neogene sediments or are deposited directly on older bedrock.

Karst is an area of specific hydrogeology and morphology which is characterized by sinkholes, caves and karst poljes, predominantly generated by the chemical weathering of carbonate rocks. The area of Dinaric karst has been investigated since the middle of the 19th century and it is considered as a „*locus tipicus*”. Therefore, some local terms for specific karst features are accepted worldwide.

Mature and extreme karst with a great depth of karstification processes in Croatia is actually the consequence of lithology, tectonics, and action of water and climate conditions during geological history (HERAK et al., 1969; BAHUN, 1974; PRELOGOVIĆ, 1975; HERAK & BAHUN, 1979; HERAK, 1991; FRITZ, 1991; VLAHOVIĆ et al., 1999; VLAHOVIĆ et al.; 2005). According to up to date knowledge, karstification of carbonate rocks in the AdCP occurred during many emersion periods in the Mesozoic. However, more intensive karstification on a regional scale occurred during the Upper Cretaceous – Tertiary, Middle and Late Eocene and Oligocene periods (HERAK et al., 1969). The Pleistocene age is very important for Dinaric karst development because the tectonic and hydrogeological processes enabled the formation of karst poljes, (HERAK et al., 1969; PAVIČIĆ & RENIĆ, 1992) which are the largest karst phenomena.

3. THE BASIC POSTULATIONS FOR DEVELOPING AN ENGINEERING GEOLOGICAL MODEL

The Croatian karstic area is a region of great variability of rock properties and geological situations affecting engineered design. This variability is three-dimensional and it affects all dimensions of the project from one geologic model unit to another. Therefore, before developing a model in a carbonate rock mass, an engineering geologist should first differentiate the geological elements that control the engineering properties and character of the construction ground: lithostratigraphic units, rock material types, structural-tectonic blocks, discontinuity sets, karst morphological features, weathering intensity and weathering „zones”. Therefore, field mapping activity needs to identify the expected critical data types how such data will be observed and collected so that rock material and rock mass properties can be noted and processed separately for each of the aforementioned elements. When this plan is completed, the engineering geological report will relate strictly to the design needs of the proposed engineered construction.

Upon differentiation of the aforementioned geological elements, the authors propose the development of three models: a sedimentological model, structural model and weathering model. The final engineering geological model will be the synthesis of these models.

3.1. Sedimentological model

In carbonate rocks, most of the parameters set out above are investigated during sedimentological investigations meaning that the sedimentological model must be developed before the engineering model (POLLAK & BRAUN; 1998 POLLAK, 2002).

It is important to first define the expected lithostratigraphical units of the project site or route alignment. The geological column should contain the basic descriptions of the major relevant sedimentological properties including: mineral composition, lithology, bedding thickness, interbeds, regularity of boundaries, structure, texture and porosity. In most cases, similar lithostratigraphic units can be merged according to their relevant engineering geological properties and conditions in order to set up engineering geological units. The usual method is to make a reconnaissance inspection of the project area or route and to take representative laboratory samples of each apparent rock-unit material. These samples are than subjected to „index” testing in order to gain the first approximation of the gross engineering character of each apparently different rock mass.

It has been found that limestone texture can be ideally classified according to DUNHAM (1962), enabling a unified and simple description of rock material, according to depositional texture observed directly in the field. Depositional textures, furthermore, then lead to recognition of the parent depositional environment and of later diagenetic processes. The importance of these factors in an engineering-geological modelling is paramount, because most of these effects have degraded (weakened) the limestone rock material.

Considering the sedimentary nature of the limestone, each single unit is scrutinised for evidence of carbonate microfacies. Units are often composed of several irregular vertical or lateral alterations of different microfacies, which cannot be considered as separate units. Therefore we use microscopic determination to reveal valuable details about the rock material: mineral and microfossil composition, texture, porosity, cementation, diagenesis, weathering and secondary defects including micro-fissures and cracks. The basic limestone and dolomite micro-textural properties are defined according to FOLK, (1959). The limestone microfacies determination is further done according to standard microfacies types (SMF) (FLÜGEL, 1982). The authors have found that carbonate rock materials in Croatian karst are frequently structurally modified both by intensive diagenetic processes, as well as having frequent numeric defects due to intensive tectonics. When this form of „damage" is noted, the SMF should be modified and some new microfacies types added.

3.2. Structural model

The structural model now is used as a means of defining the presence of structural blocks, determined on the basis of separate discontinuity sets (of joints, as planar discontinuities) orientation and their spacing. The discontinuities are found in mutually rhombic sets of two attitudes, each set caused by a single palaeotectonic deformational phase during geological history. These are the main planar breaks of weakness that define each structural block (also called structural domains).

In the investigated area of carbonate rocks, four tectonic phases that conditioned the evolution of tectonic blocks were present (MATIČEC, 2009). The most significant tectonic activities took place in the Upper Jurassic period, when the phase of compression tectonics started. In the late Cretaceous period the structures with a NNE-SSW strike were formed (Laramian orogene). In late Eocene and Oligocene the final uplift of the Dinarides mountain range began, along with formation of structures with strike NW-SE (Pyrenean orogene). Consequently, the Middle and Upper Miocene neotectonic phase followed, when regional stress assumed a general orientation N-S (MATIČEC, 2009).

The relationships between the representative unit block (structural domains and major rock blocks) and the spatial position of the linear infrastructure constructions are considered here. The construction of new linear infrastructure in bedrock terrain often produces new, fresh rock faces in road cuts which are of prime consideration. This new planar face sometimes creates the fourth face of a new tetrahedral block of rock that can be acted upon by gravity, and thus becomes unstable at the highway cut, or in a more limited sense, at the face or crown of a tunnel, during the construction process.

The intensity of rock mass fracturing has fundamental importance regarding its great potential negative instability influence on rock mass characteristics before, during and after excavation. Therefore, evaluation of the discontinuity frequency has usually been performed during the field investigations for any important building structure or mining project. In many areas, it is possible to collect such data exclusively by drilling. However, the usage of a single value for the linear frequency (discontinuity number determined per the unit line length in the defined direction through the rock mass), is generally not enough to ensure the corresponding intensity of the fracture quantification for the needs of the engineering design. For the rock mass which contains a definite number of sets of parallel, planar and persistent discontinuities, HUDSON & PRIEST (1983) showed that the discontinuity frequency could be reduced to a single vector, as a rock mass property. For an example of the rock mass which contains N discontinuity sets, they also showed that their frequency along the scan line of any orientation is given with the expression:

$$\lambda s = \sum_{i=1}^{N} \lambda i \left|\cos\theta i\right| \qquad (1)$$

where θ_i represents the angle between the scan line and the normal of the *i*-set of the discontinuity set, λ_i is the frequency of the *i*-set of the discontinuity along the normal of that set where λ_i is defined as the reciprocal value of the mean value of the discontinuity spacing $\overline{x} = 1/\lambda$, and λ_s represents the total frequency along the determined scan direction.

From this method of processing the orientation and frequency of discontinuity sets determined by the investigation field works, it is possible to determine the maximum and minimum values of the linear frequencies, their directions in three dimensions, i.e. to define the plane of the greatest anisotropy or define the afore mentioned values for the directions which are characteristic and important for a particular linear object.

Usage of the RQD index as one of the engineering measures for classification of the fractured rock masses is widespread because of the easy measuring way on the outcrops and borehole cores. The analytical expression for the mutual relationship of RQD and random joint spacing, i.e. frequencies, is presented by PRIEST & HUDSON (1981) using the negative exponential distribution.

HARRISON (1999) sets up the analytical determination of the threshold value which he prefers to the arbitrary threshold value which is used in practice (0.1m), and which is not sensitive to the whole range of the discontinuity spacing, i.e. frequencies which are met in practice. The use of the optimal RQD index threshold value greatly expands the range of RQD values encountered in rock mass and as such increases the fidelity and hence the discriminatory nature of RQD.

On the basis of the exponential model, according to PRIEST & HUDSON (1981) and the values of minimum λ_{min} and maximum λ_{max} discontinuity frequency, HARRISON (1999) suggested the function for determining the optimal threshold value by means of the given formula:

$$t^* = \frac{2}{\lambda_{max} - \lambda_{min}} \cdot h\left(\frac{\lambda_{max}}{\lambda_{min}}\right) \qquad (2)$$

The simple classification of the rock masses for the purposes of engineering works such as tunnel construction, excavations, foundations etc., (which can be done by means of the RQD values), has been known and used practically for a long time. What's more, RQD presents an important parameter for the categorization of the rock masses developed according to BIENIAWSKI (1973, 1989) and BARTON et al. (1974). The connection of RQD with the fundamental characteristics of the rock structure, i.e. their discontinuity frequency resulted in its widespread practical application.

In literature, different statistical models for evaluation of the rock mass quality, PRIEST &HUDSON (1976), KULHAWY (1978), SEN (1984), have been suggested.

These models were used for connecting RQD with the mean discontinuity number or with the average length of the intact core parts. One such model, which is based on the usage of the negative exponential distribution for the modelling of discontinuity spacing, was presented by PRIEST & HUDSON (1976). This model has been shown to be rather limited in the geological application (SEN, 1984), with one of the main limiting factors being the basic property of the exponential distribution that its mean value is equal to the standard deviation. Namely, there are numerous situations in nature where such equality is not valid. Because the distribution of the intact parts lengths cannot be limited to the exponential distribution, the need to investigate other distributions is imposed.

PRIEST & HUDSON (1976) and SEN (1984) showed that the analytical curves for RQD index opposite to λ obtained on the base of the probability density function (p.d.f.) of the negative exponential distribution stand in the diagram almost always higher than the measured data, i.e. they overestimate the value of the RQD index. SEN (1984) noticed that the standard deviation of the intact parts length plays an additional important role in the rock mass quality classification, i.e. an increase in the standard deviation improves the rock mass quality. He therefore suggested the log-normal distribution as the more appropriate model for connecting the RQD index with the average number of discontinuities, where the expected RQD is expressed by the formula:

$$E(RQD) = 100\left\{1 - F\left[\frac{Ln(\lambda t)}{\sigma_{Lnx}} - \sigma_{Lnx} + \frac{1}{2}\right]\right\} \qquad (3);$$

in which σ_{Lnx} = standard deviation of the logarithmic intact lengths, λ = mean number of discontinuities, t = threshold value and $F(\bullet)$ = standardized normal probability distribution function. In this model $E(RQD)$ and λ are implicitly connected because the parameter λ originates from the Poisson distribution.

Figure 2, initially published by SEN (1984), shows the relationship between RQD and λ for two distributions (where t = 0.1 m):

– lognormal distribution with different values of σ_{Lnx} (two parameter distribution);

– exponential distribution (single parameter distribution).

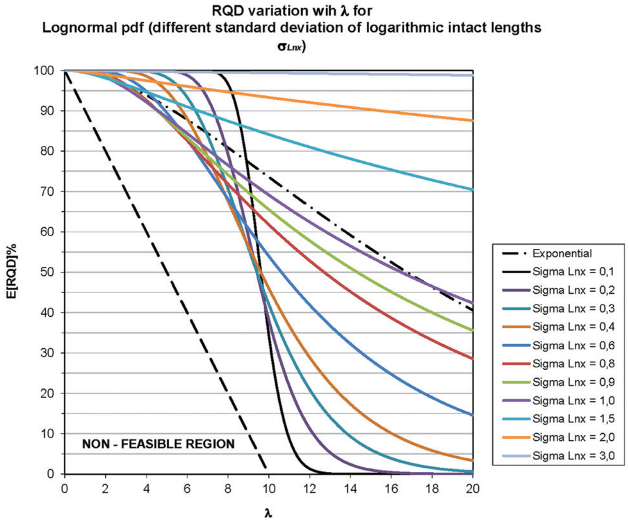

Figure 2: RQD variation with l for Lognormal p.d.f.

Lognormal distribution shows that RQD cannot be judged solely on the basis of mean intact length but, additionally, the standard deviation of the intact length must be considered. This property could not be identified with the negative exponential distribution.

The mutual relationship of Rock Quality Designation (RQD) and the discontinuity frequency in carbonate rocks based on analytical models reported in the literature has also been considered and analyzed.

3.3. Weathering model

The existing and generally used weathering engineering classification of karst ground (FOOKES & HAWKINS, 1988; WALTHAM & FOOKES, 2003) is mainly based on the number and size of karstic features and hydrogeological characteristics of the area. This classification is adequate and sufficient on a regional scale. An engineering geological model at a detailed scale, e.g. 1:1000 or 1:5000 requires additional thorough investigations of the weathering intensity of the rock mass regarding overburden depth. This aspect of weathering in karst is frequently neglected despite its obvious indicators and earlier studies (DEERE & PATTON, 1971; NOVOSEL et al., 1980).

Unlike other, indissoluble rock materials, carbonate rock material in this area demonstrates the minor influence of weathering to its mechanical and physical properties (POLLAK, 2007), due to rapid and effortless weathering progress along numerous discontinuities. Therefore, most of the investigations of the weathering processes in karst should be directed toward discontinuity properties from the surface zone into the interior.

4. RESULTS

Despite the continuous deposition of carbonate rocks in shallow and low energy environments, anomalous deposition conditions were encountered through the investigated area, which were acted upon by later diagenesis, intensive tectonic deformation, and weathering processes. It is our observation that even subtle differences in the depositional environment of individual carbonate sediments, led to the creation of major heterogeneities and anisotropy that affect the final engineering of the highways.

The authors here bring forth some important model findings, as gained from their route characterization work in carbonate rock masses (Fig. 1).

4.1. Sedimentological model

Detailed hand specimen evaluation, thin-section analysis, and the basic UCS testing usually explains the very high range of rock material mechanical properties and need for subdivision of the units. For example, it is very important to determine uniaxial compressive strength (UCS) of both crystalline and stromatolitic segments from the Upper Triassic dolomite – "Hauptdolomit" ($T_3^{2,3}$). The same dolomite in the Gorski kotar region, is present along more than 5 km of the Zagreb to Rijeka motorway. Stromatolitic dolomite represents about 10–20% of the dolomite mass, but its lower uniaxial strength and laminated texture disrupts the homogeneity and isotropy of the rest of the rock mass having a higher uniaxial strength (Tab. 1). The difference between the mechanical properties of the crystalline and stromatolitic dolomite is significant, especially in weathered rock material.

Table 1: Uniaxial compressive strength of different microfacies segments of "Hauptdolomite" in Gorski kotar region (POLLAK & BRAUN, 1998).

DOLOMITES	uniaxial strength / MPa	
texture (num. of samples)	mean	range
CRYSTALLINE (46)	85	39-131
STROMATOLITE (8)	43	26-60

In the area between the Maslenica settlement and the "Sveti Rok" tunnel (13 km of motorway), microscopic analysis confirmed the assumptions on close association of carbonate rock material strength and its microfacieses (Figs. 3, 4).

Despite the fact that just several samples were analyzed, some trends were noticeable. Firstly, a very strong and complete degree of calcite cementation made for a good and tight fit between the coarse grains of Neocomian limestone breccias (1d), which is the main reason for its greater strength in comparison to the other Lower Cretaceous (Neocomian) limestones (1a, b, c). The uniaxial compressive strength of recrystallized (2a) and dolomitized (2d) segments of Upper Cretaceous (Cenomanian) limestones has been significantly reduced in comparison to its parent materials (2b). Promina

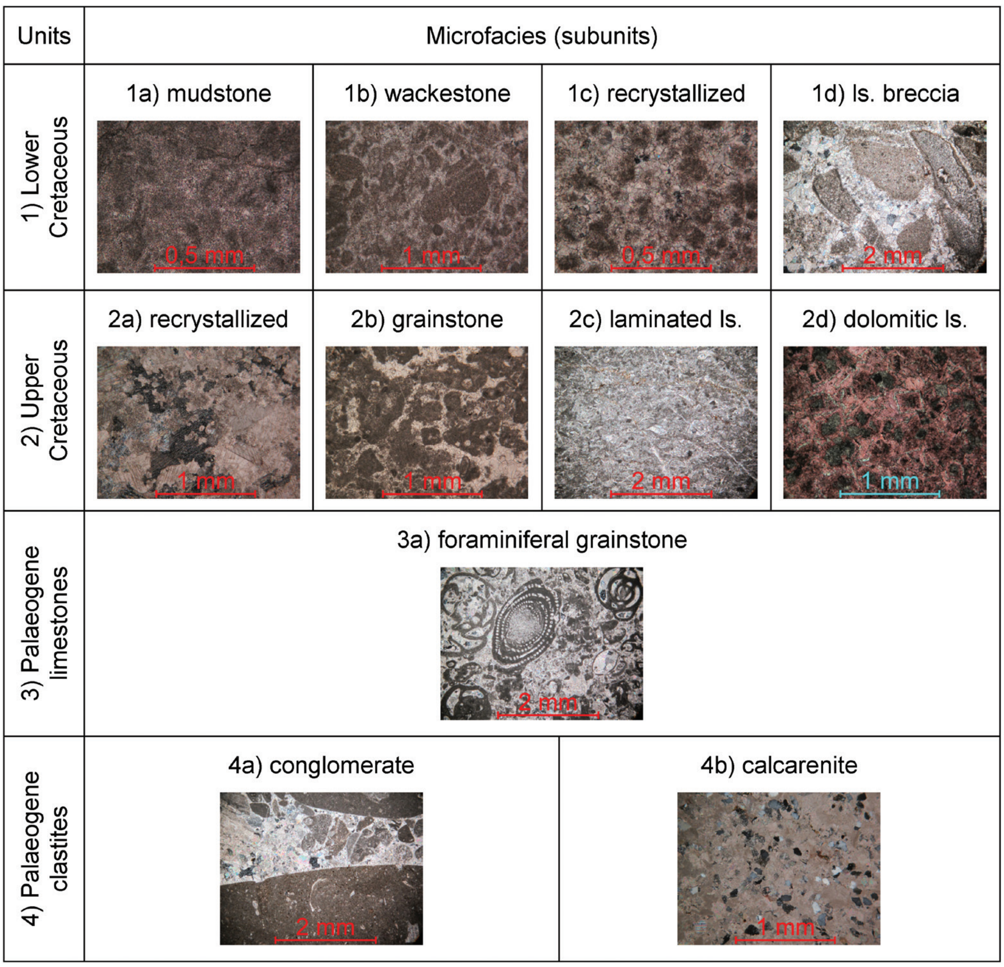

Figure 3: Subdivision of engineering geological units according to microfacies determination with appropriate microphoto. Zagreb-Split motorway, section Tunnel St. Rok-Maslenica.

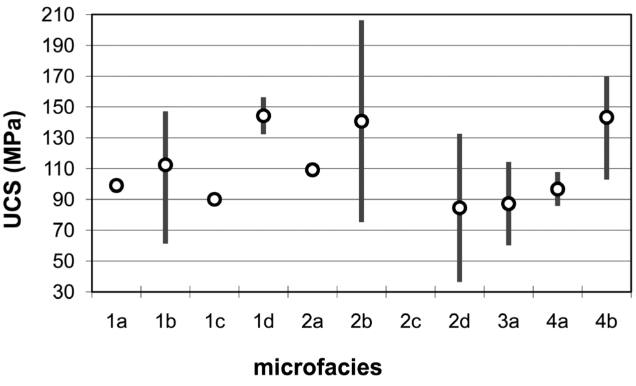

Figure 4: The ranges and averages of uniaxial compressive strength (UCS) for particular microfacies (19 samples in total). Zagreb-Split motorway, section Tunnel Sveti rok-Maslenica.

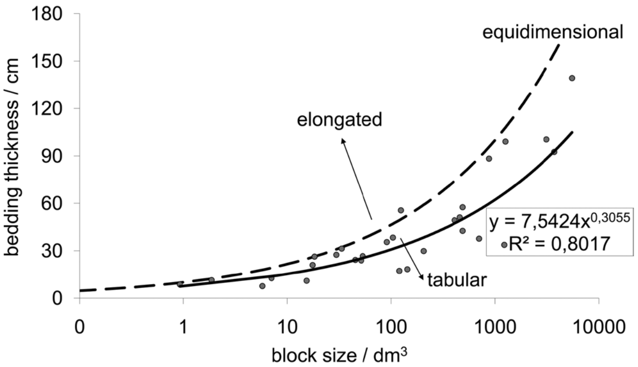

Figure 5: Correlation of the average bedding discontinuity spacing and block size in the Croatian carbonate rocks from the Middle Triassic to the Oligocene (continuous line). Dashed line represents ideal, calculated equidimensional blocks.

carbonate rocks (4) consist of poorly sorted conglomerates (4a) and uniformly graded calcarenites (4b). While considering these deposits, the significantly lower uniaxial compressive strength of conglomerates should be noted (Fig. 4). As opposed to the calcarenites, the matrix of the conglomerates is of variable quality and locally even porous which is, besides the grain size, considered to be the main reason for the lower strength of the conglomerate.

At this point we were rewarded with the fact that determination of subunits was possible on the basis of detailed field notes and some laboratory index property testing. In order to bridge the gap to the engineering geological recommendations, some of the sedimentological properties required consideration from the engineering perspective, e.g. the bedding thickness.

There are numerous examples to support the thesis of the influence of depositional and diagenetic conditions on the rock material and rock mass engineering properties. One of the most obvious examples is the influence of bedding thickness on block sizes of the carbonate rock mass.

Bedding is the consequence of changes in physical, chemical and biological conditions of sedimentary facies and diagenetic processes (COLLINSON & THOMPSON, 1989). Therefore a layer is considered to be a geological body separated from the surrounding rock mass by changes in its original grain-size distribution, mineralogical composition, lithological proprieties, orientation or pattern of particles or simply, by the termination of sedimentation. From the sedimentological perspective, the layer isn't always bounded with discontinuities while considering the sedimentary rocks in engineering sense it is usually very important to measure exclusively the spacing (frequency) of bedding discontinuities.

The importance of such an approach can be confirmed in many segments, but here it is elaborated through determination of the average field measured joint block size and shape in carbonate rocks. Based on the data from 32 mega lithostratigraphic units across the AdCP (3760 measurements of bedding thickness and 678 locations of block size calculations), the analysis confirms the assumption that the „engineering bedding thickness" in the investigated area greatly affects the spacing of the secondary sets of discontinuities and naturally also the block sizes (Fig. 5). The diagram also shows the average block shapes, which are dominantly slightly tabular in well bedded, or equidimensional in the poorly bedded carbonate rock mass.

4.2. Structural model

As previously stated, more than half of the Croatian territory is composed of carbonate deposits, i.e. a great number of linear infrastructural objects have been built in carbonate deposits in the last 15 years. Here, data collected in field investigations for the needs of geotechnical design are analysed, by means of the models mentioned in the previous section, with the aim of improving the definition of the engineering geological model. The collected data, which were obtained during the core drilling and engineering geological mapping for the design needs of important tunnels in carbonate deposits, were analyzed (the segment of representative input data are presented in Table 2).

Several lithographic units in the carbonate deposits were processed, where the blocks can generally be divided into equidimensional and tabular ones regarding the shape. In Table 3, the calculated minimum and maximum discontinuity frequencies, as well as their directions and planes of maximal anisotropy are presented. Table 3 also contains the calculated values of the discontinuity frequencies based on the surface data in the direction of the performed drilling hole and strike of the designed tunnel axis. It is obvious from the data that the equidimensional blocks have lower maximum anisotropy regarding the discontinuity frequencies in different directions than the tabular blocks, which can be expected with regard to the block geometry itself.

The values of the discontinuity frequencies and other parameters from Tables 2 and 3 are presented in the following items, for two characteristic block types (equidimensional and tabular) which most often appear in carbonate rocks.

Figure 6a presents the orientations of the separate discontinuity sets and the axis of the tunnel "Mala Kapela" for structural unit A – equidimensional block (Fig. 6c). In Figure 6b the 3D frequency values in all possible directions for the determined sets and their associated mean spacing are presented, the plane of maximum anisotropy is distinguished,

Table 2: Example of discontinuity orientation, strike of tunnel axis and frequency data for two characteristic block types analyzed for the design needs of tunnels in carbonate rocks.

Structure	Structural unit	Number of sets	Discontinuity orientation (dip direction / dip angle)	Normals of discontinuity sets (trend / plunge)	Strike of tunnel axis	Mean discontinuity spacing (m)	Mean frequency (m^{-1})
Tunnel "Mala Kapela"	A	3	148/37 050/77 306/67	328/53 230/13 126/23	3 – 183	0.78 1.05 0.94	1.28 0.95 1.06
	B	3	170/23 210/75 160/77	350/67 030/15 340/13	28 – 208	0.78 1.05 0.94	1.28 0.95 1.06
	E	3	179/22 025/70 092/80	359/68 205/20 272/10	41 – 221	0.58 0.98 1.01	1.74 1.02 0.99
	I	3	270/13 200/70 292/69	090/77 020/20 112/21	41 – 221	1.17 1.08 1.32	0.85 0.93 0.76
	K	3	190/15 259/73 318/78	010/75 079/17 138/12	17 – 197	1.17 1.08 1.32	0.85 0.93 0.76
Tunnel "Umac"	A	3	208/48 018/49 107/88	028/42 198/41 287/2	88 – 268	0.56 0.69 0.64	1.79 1.46 1.56
Tunnel "Brinje"	D	3	59/13 241/77 182/79	239/77 061/13 002/11	18 – 198	0.21 0.89 0.54	4.78 1.13 1.84
	D	4	59/13 241/77 182/79 129/84	239/77 061/13 002/11 309/6	18 – 198	0.21 0.89 0.54 0.54	4.78 1.13 1.84 1.84
	E	3	103/13 248/80 181/89	283/77 068/10 001/01	20 – 200	0.17 0.78 0.86	5.97 1.27 1.17
	E	4	103/13 248/80 181/89 300/83	283/77 068/10 001/01 120/07	20 – 200	0.17 0.78 0.86 0.86	5.97 1.27 1.17 1.17

Table 3: Global minimal and maximal frequency with their orientation and plane of maximal anisotropy, frequencies in direction of drilling, tunnelling direction and optimal threshold values for two characteristic block types of tunnels designed in carbonate rocks.

Structure	Structural unit / number of sets	Min. frequency (m^{-1})	Max. frequency (m^{-1})	Orientation of min. frequency (trend / plunge)	Orientation of max. frequency (trend / plunge)	Plane of extreme frequencies (max. anisotropy)	Calculated frequency in direction of drilling (m^{-1})	Mean frequencies from boreholes (m^{-1})	Calculated frequency in tunnelling direction (m^{-1})	Calculated optimal RQD threshold value (m)
Tunnel "Mala Kapela"	A / 3	1.00	2.17	220/10	290/20	281/20	1.65	4.6	1.79	1.32
	B / 3	0.72	2.80	250/5	0/35	334/38	1.66	5.5	2.00	1.31
	E / 3	0.92	2.55	115/10	265/55	202/73	2.13	8	2.02	1.25
	I / 3	0.65	1.91	285/15	65/50	8/66	1.42	4.1	1.17	1.71
	K / 3	0.64	1.89	175/15	95/40	103/40	1.25	3.25	1.02	1.74
Tunnel "Umac"	A / 3	1.52	3.03	195/45	55/5	142/59	2.21	3.45	2.52	0.91
Tunnel "Brinje"	D / 3	1.02	5.56	95/10	5/70	9/70	5.26	10.1	3.35	0.75
	D / 4	2.48	6.33	95/10	335/60	10/65	5.46	10.1	4.01	0.48
	E / 3	1.27	6.36	145/10	355/70	57/80	6.06	6.4	2.11	0.63
	E / 4	2.15	6.66	30/5	295/55	304/55	6.20	6.4	2.27	0.50

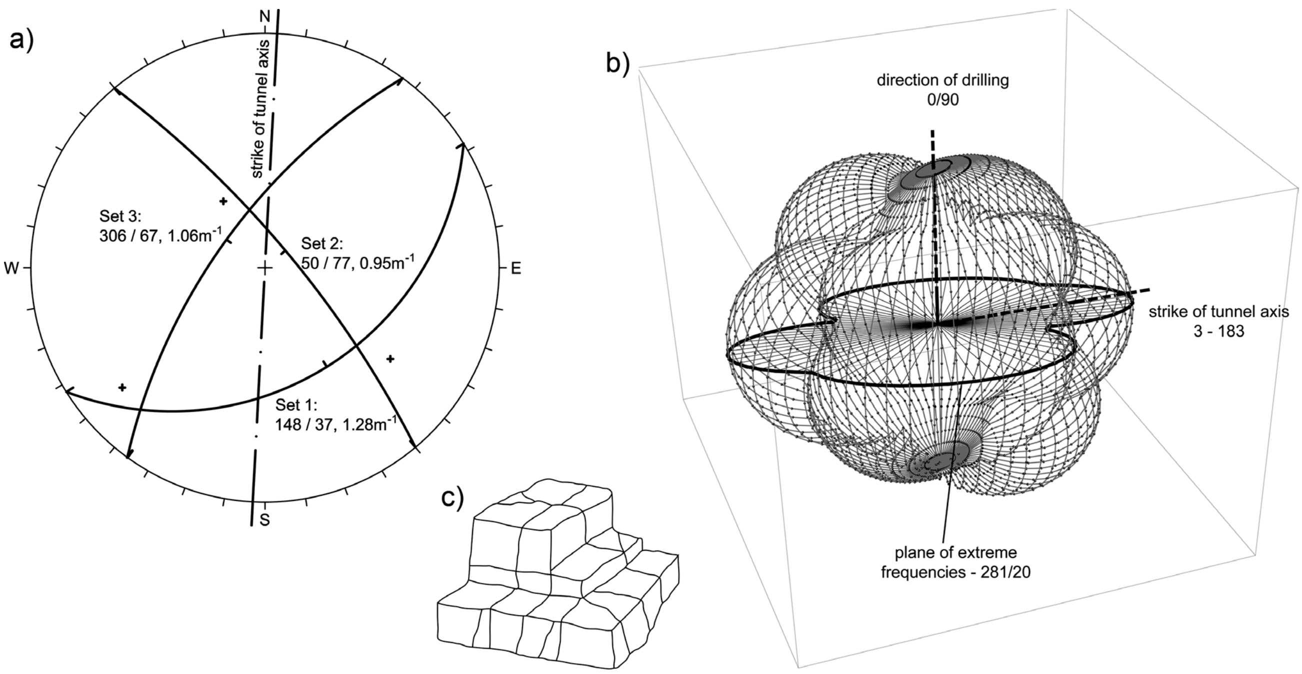

Figure 6: The "Mala Kapela" Tunnel – structural unit A (3 sets): a) Equal angle lower hemispherical projection of example data, b) three-dimensional locus of discontinuity frequency with plane of extreme (range) frequencies, c) equidimensional blocks.

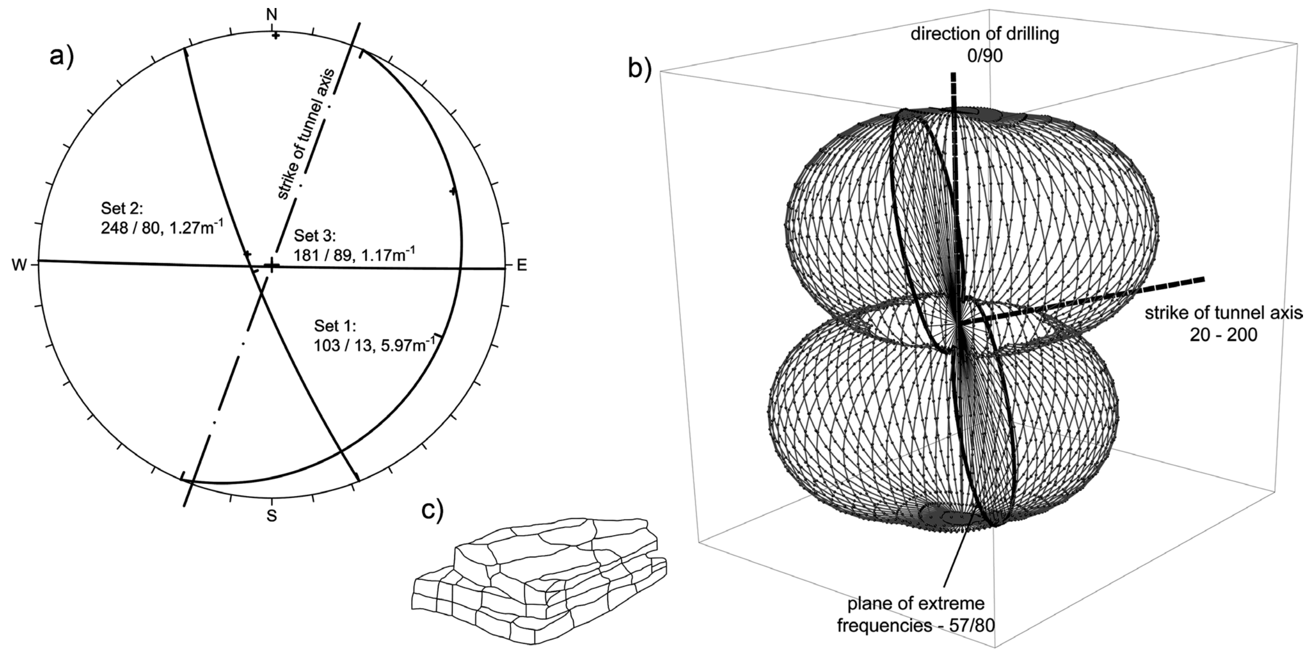

Figure 7: The "Brinje" Tunnel – structural unit E (3 sets): a) Equal angle lower hemispherical projection of example data, b) three-dimensional locus of discontinuity frequency with the plane of extreme frequencies, c) tabular blocks.

and the direction of borehole as well as the strike of the tunnel axis are marked.

Figure 7 provides a similar presentation for the tabular block (Fig. 7c), i.e. structural unit E in the "Brinje" tunnel (Fig. 7a and b). Figure 7b), which evidently shows a greater anisotropy of frequency for the tabular blocks.

According to the equation [2], for the calculation of an optimal threshold value of RQD, it is necessary to determine the value of the minimum and the maximum discontinuity frequency (λ_{min} and λ_{max}), with regard to the given orientations of the defined sets and their spacing (Table 3). Figures 8 and 9 present the polar plot of discontinuity frequency in the plane of extreme frequencies and differences in the discriminatory nature of the RQD index for the customary threshold value and calculated optimal threshold values for the structural units analysed in figures 6 and 7.

To establish the connection between the RDQ index and the average number of discontinuities (frequency), the afore mentioned exponential and log-normal model was applied. The data was collected from cores of 46 boreholes, drilled during the design phase of an important tunnel, through massive to thick layered limestones of Cretaceous age. The reason those rocks were chosen is because the data on all the intact length (not only of longer than 0.1 m) were available, which is necessary for the estimation of σ_{Lnx}. Highly fractured and cavernous zones were excluded during the calculation of RQD and average number of discontinuities.

Results of the analysis confirm the justification of the log-normal model usage, as opposed to the exponential one, for the purpose of connecting these two parameters (RQD vs. average number of discontinuities – λ) (Fig. 10). Log-normal function of the probability density is defined with the formula [3] where the standard deviation of the logarithmic intact lengths $\sigma_{Lnx} = 0.78$.

4.3. Weathering model

Despite the enormous importance of karstification processes on engineering problems in the Croatian karst, that segment of engineering-geological model is not the focus of this paper. The main superficial (sinkholes) and subterranean (caves, caverns) karstic features have been studied by many authors (ŠARIN & HRELIĆ, 1984; KAPELJ, 1985; BOŽIČEVIĆ et al., 1995; JAMIČIĆ & NOVOSEL, 1999; WALTHAM & FOOKES, 2003; KAPELJ et al., 2004; GARAŠIĆ, 2005;

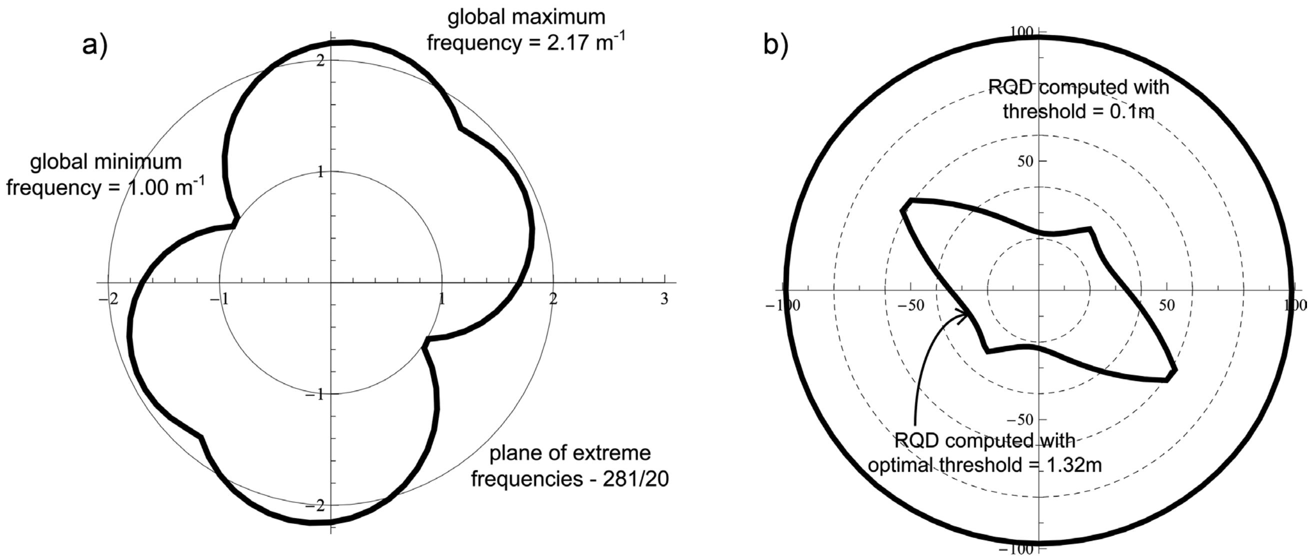

Figure 8: The "Mala Kapela" Tunnel – structural unit A (3 sets): a) Polar plot of discontinuity frequency; b) polar plot of RQD using customary threshold value 0.1 m and optimal threshold value.

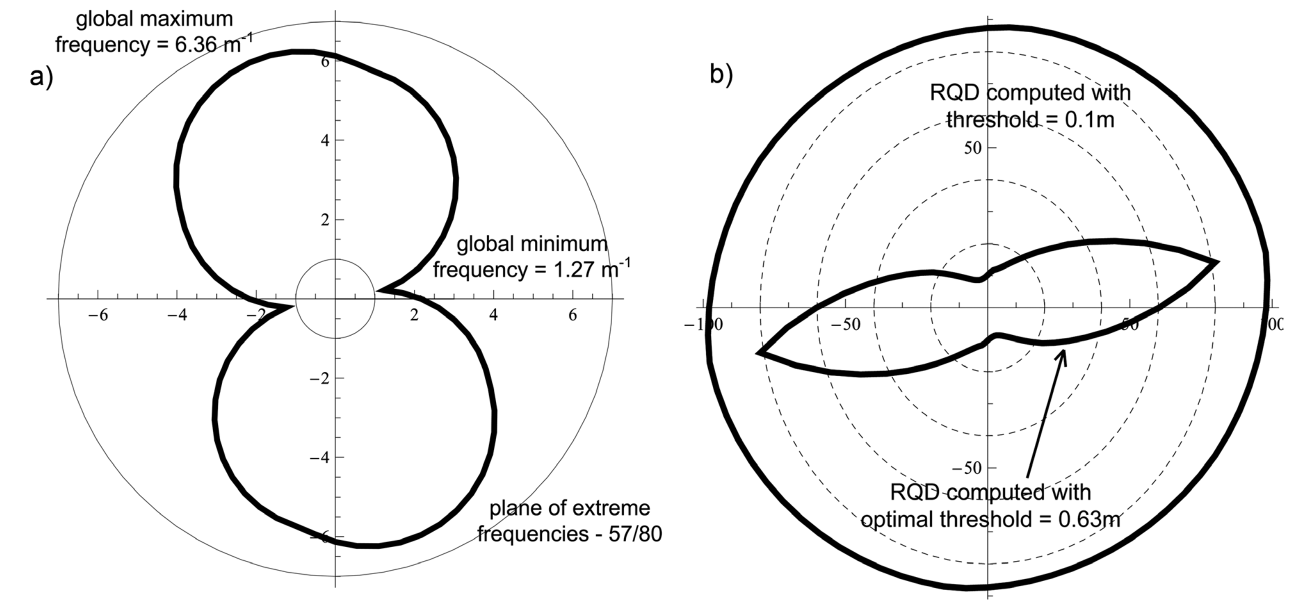

Figure 9: The "Brinje" Tunnel – structural unit E (3 sets): a) Polar plot of discontinuity frequency, b) polar plot of RQD using customary threshold value 0.1 m and optimal threshold value.

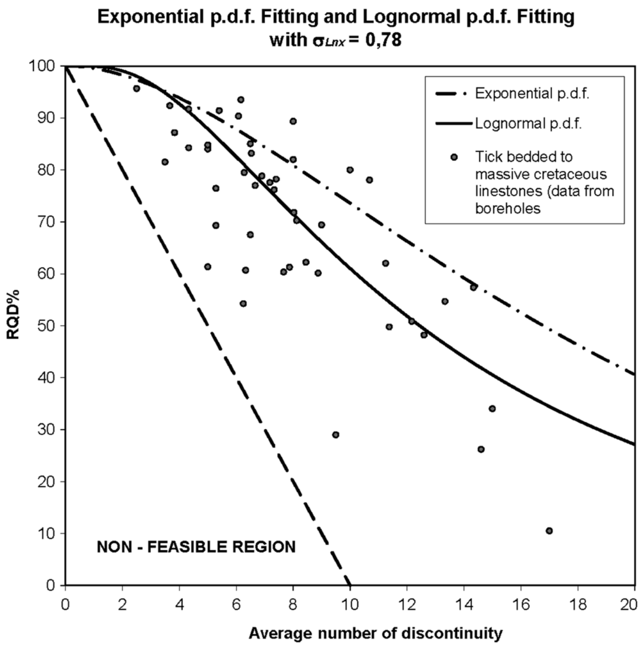

Figure 10: Variation of the RQD index versus I for Exponential and Lognormal probability density function (p.d.f.) in Croatian carbonate rocks (Upper Jurassic up to Upper Cretaceous limestones and dolomites).

BOSTJANČIĆ et al., 2011) and their results should be acknowledged in engineering design encompassing karstified media. Here, the influence of weathering processes on general discontinuitiy properties and rock mass quality is considered.

The carbonate rocks in Croatia are predominantly very "pure", with more than 92% carbonate mineral content. Carbonate composition and other properties of the area, including low primary porosity of rock material (< 5%), the thickness of the carbonate sediment complex, tectonics and climatic conditions enabled intensive weathering of the carbonate rocks and the formation of karst.

The probable "zoning" of the carbonate rock mass should be examined during the investigation phase for the engineering geological model. Initially that is usually done by thorough engineering geological mapping. In the later phases the "zoning" should be verified with geophysical investigations and core drilling.

Most of the analyzed geophysical profiles which are done in the investigation phase for the Croatian motorways across the AdCP display surprisingly ‘regular’ zones. The compilation histogram of 54 shallow refraction seismic profiles with total length of 4160 m, displays clear zones in the limestone rock mass (Fig. 11). Regarding the relatively shallow maximum reach of several decametres in most analyzed geophysical profiles, three zones can be noted: SWZ – surface weathering zone; UWZ – upper weathering zone; LWZ – lower weathering zone. It is also obvious that fresh rock mass, with expected Vp > 6000 m/s is rarely reached as a minor segment in LWZ.

Despite the clearly visible zoning in Figure 11, determination of the weathering zones at the specific location shouldn’t be based on geophysical investigations alone. The weathering processes and the discontinuity properties characteristic for each weathering zone can usually be recognized in the borehole core.

Besides the obvious variation of weathering marks at the discontinuities in borehole core, it is also noted that RQD values can show a trend of block size change as an indication of weathering intensity related to the rock mass depth. From the extensive amount of borehole data (based on 2930 intervals in 463 boreholes with the total drilled interval of 4877 m), the trend of block size increase with depth is clearly visible (Fig. 12). Still, it is important to say that such clear zoning is rarely visible in boreholes on smaller and extremely karstified areas.

The ‘zoning’ of engineering properties in the karst area is mainly a consequence of changes in the width and infilling of discontinuities. Namely, from the fresh rock to the strongly weathered rock mass, the width of discontinuities increases significantly but the infilling also generally changes from none, over carbonate through clayey to none. This leads to the derivation of characteristic weathering zones in the Croatian karst, which can usually be incorporated in the engineering-geological model (Fig. 13). The definition of the weathering zones in this model are mainly based on these two factors – the width and infilling of discontinuities.

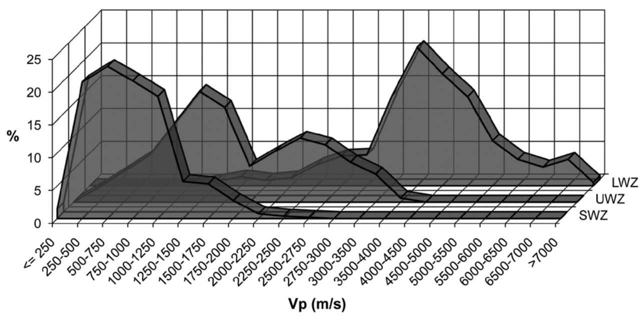

Figure 11: The distribution of the primary seismic waves velocities (Vp) in different weathering zones in limestones across the AdCP.

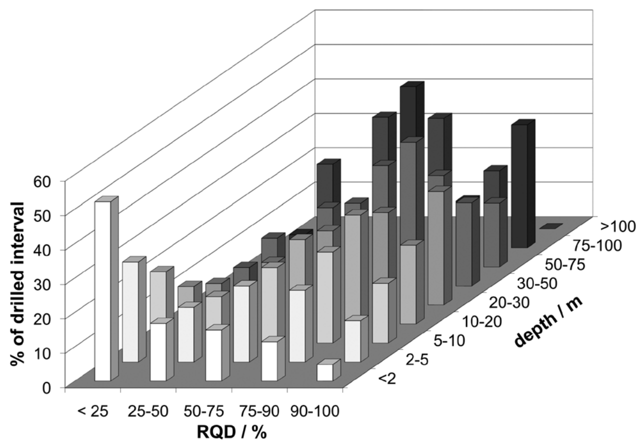

Figure 12: The histogram of RQD index values in relation to the depth of the drilled interval from boreholes across AdCP.

Zone	Symbol	Description	Photo
IV	**SWZ** **Surface weathering zone**	Eluvium Detached blocks and cobbles frequently with clay Occasional carbonate outcrops	
III	**UWZ** **Upper weathering zone**	*Weathering marks* Obvious and frequent *Discontinuity width* More centimeters to few decimeters *Discontinuity gouge* Clay or empty	
II	**LWZ** **Lower weathering zone**	*Weathering marks* Local or ambiguous *Discontinuity width* Few millimeters to few centimeters *Discontinuity gouge* Calcite and clay	
I	**FRM** **Fresh rock mass**	*Weathering marks* Not visible *Discontinuity width* < 1 mm *Discontinuity gouge* Empty or calcite	

Figure 13: Characteristic weathering zones in Croatian karst with corresponding basic descriptions. (Photo examples are from the "Mala Kapela" tunnel area).

5. DISCUSSION

The main objective during the engineering geological processing of the field and laboratory data is the synthesis of geological data and quantitative parameters for use by the design engineers. The synthesis of all the available data should produce an engineering geological model, which contains all the important engineering data and presents it in simple and practical way.

The authors advocate that beside the studies of the characteristic karstic morphological features, there are other very important segments of the engineering geological model of karstified rocks: the sedimentological, structural and weathering model; which enables a better and more reliable definition of weathered rock mass properties and quality. In that sense, the engineering geologist's eye must seek and appreciate mineral composition, formation, diagenesis, rock material texture, structural discontinuities and the evidence of alteration and/or weathering which tends to degrade the basic engineering properties and parameters of each rock-mass unit.

Engineering sedimentological modelling in carbonate rocks begins with detailed field observations and microscopic investigations of samples selected as being representative of each apparent three-dimensional rock mass unit.

Here the field-data collection needs are: unit lithology, geometry of the sediment body, texture, structure, bedding plane properties and bedding thickness. At the beginning of the field mapping and data collection stage, there is the natural challenge of making a preliminary evaluation of the likely impact of different factors on the engineering character of rock masses to be encountered.

Most of the carbonate rock mass in Croatia is bedded and the rock mass therefore has a basic anisotropy, and this requires constant attention to the need to identify three-dimensional block parameters, particularly as it affects the direction not only of motorways, but of all other linear infrastructural projects. With regard to the anisotropy of the discontinuity frequency in different directions, the question is whether the vertical boreholes drilled during the geotechnical design of the tunnels give a real evaluation of the rock mass, i.e. if they underestimate or overestimate the fracturing of the rock mass in the direction of tunnel excavation?

According to the presented data, the anisotropy of discontinuity frequency in equidimensional blocks is insignificant while in tabular blocks it is strongly expressed, especially in the case of the usual three sets of discontinuities, each resulting from a separate but severe historical phase of regional tectonism. Taking into consideration the realistic example (Fig. 6), the vertical core drilled at the "Brinje" tunnel underestimates the rock mass quality in the direction of the tunnel excavation concerning the fracturing state. In addition to the calculation, this was proven by comparing core logging data with data obtained during excavation of the tunnel.

Also, the mean values of the discontinuity frequencies obtained by core logging, in the majority of examples presented in Table 3; do not match the calculated frequencies in the drilling direction. The reasons for this can be manifold: 1) the "in situ" rock mass is disturbed during the drilling process, i.e. the obtained core contains more fractures than are visible on the walls of the borehole due to fracturing or opening along cracks where weakened part in the intact rock exists; 2) the objective impossibility of collecting enough qualitative data concerning the discontinuity orientations and their spacing on the surface. Therefore, it is not possible to reliably define the mean values of the set discontinuity orientations, i.e. the size and shape of the unit block, only on the basis of the surface data. The impossibility of collecting sufficient qualitative data is often connected with weathering in the surface zones, coverage by Quaternary deposits and with a smaller blocks size on the surface, caused by the process of chemical weathering of the carbonate rocks. Errors in defining the aforementioned parameters directly influence the results of the calculated frequencies obtained in the determined direction.

So the most appropriate model should consist of reliably defined mean values of sets orientations and their frequencies.

Therefore, it is necessary to bear in mind that the model for the analysis of the discontinuity frequency is based on three basic assumptions:

- rock mass structure is composed of planar sets of parallel discontinuities;
- all discontinuities are strictly planar, which is not the true case;
- each discontinuity is persistent along the observed area.

Using the analysis of the optimum threshold value of the RQD index, according to HARRISON (1999) it is clear that its usage maximises the range of values of the RQD index, which is marked in the rock mass and as such it increases the reliability and consequently the discriminative nature of the RQD index.

It is also clear from the diagram (Fig. 10) that the exponential model overestimates the RQD values for the analysed data, while the log-normal model is more justifiable regarding the security in geotechnical design in carbonate rock masses. However, it is necessary to have all the intact lengths for the estimation of σ_{Lnx}.

Given the specific weathering mechanisms, the weathering zones in extremely karstified areas are frequently irregular. Therefore, the expression "weathering zone" shouldn't be literally used in karstic regions. It is often the case that the separated environments mutually interlace and irregularly exchange vertically and laterally. Irregular "zoning" appears on the large faults or in tectonically fractured areas, where borders with other zones could be vertical or even inverse. Depending on the geological properties of the investigated area, the weathering zones in karst have very different characteristics, spreading and mutual relationships.

Therefore, it is difficult to judge the differentiation of the "zones" of variable degrees of weathering in the carbonate rock mass, because of its great irregularity in every sense. There are also usually great differences in discontinuity properties from the outcrop zone to the greater overburden depth of several hundred metres which should be quantified in the engineering geological model.

In general, weathering is most intensive at the surface zone where mainly the chemical but also physical action amplifies the appearance of the joint sets, which then appear to be open, and there are usually frequent wide discontinuities. In the areas with deeper overburden, the same discontinuity sets can be closed or even disappear. Therefore, in the carbonate rock mass one should expect an increase of block size (and a related decrease in spacing frequency) with the rise of overburden depth. This is visible in numerous cuttings along the newly built motorways in Croatia.

6. CONCLUSIONS

Beside the general and well known procedures for building the engineering geological model in any rock mass, a carbonate rock mass demands some additional perspectives. If we adopt the regional model which quantifies the karstification intensity of the area, the detailed investigations should also enable development of three main submodels: 1. sedimentological, 2. structural and 3. weathering. Here, some very important aspects of each submodel are studied and presented respectively.

1. The total understanding of the history of sedimentation provides explanation and answers about engineering behaviour and properties of both rock material and rock mass. Therefore, the sedimentological investigations of carbonate rocks are greatly improving the creation of the engineering geological model because they enable more precise and logical differentiation of engineering units through the described procedure. The microfacies are characteristic for strictly defined depositional environments and later geological conditions and they are proven to have a major influence on the many engineering properties of carbonate rock material and mass. Therefore, the definition of microfacies usually leads to better comprehension of the variability in mechanical properties in carbonate rock material of each of the engineering geological units.

2. The determination of the extreme values of the discontinuity frequencies has successfully been applied in planning the sampling strategy by drilling, different classifica-

tions and general understanding of the mechanical and hydrological characteristics of the fractured carbonate rock masses. Based on the considerable quantity of data from the boreholes in the massive to thick layered limestones of Cretaceous age, the justification supposition of the log-normal model usage was confirmed as opposed to the exponential one with the purpose of RQD connecting with the average number of the discontinuities.

3. Despite clearly visible weathering zoning in the carbonate rock mass on a great amount of data it is very important to stress that weathering "zones" in Croatian karst are very irregular in space and in almost every other parameter, as it is typical for all Dinaric karst areas. Still, creation of the detailed and valid engineering geological model of a karstified area should include consideration of possible weathering zones and its engineering properties. Four weathering zones regarding the properties of discontinuities and weathering marks are characteristic: fresh rock mass (I, FRM), lower weathering zone (II, LWZ), upper weathering zone (III, UWZ) and surface weathering zone (IV, SWZ).

Determination of the geological genesis of each three-dimensional rock mass is the key to understanding the overall condition of the rock for present construction. Once completed, this leads to the most accurate determination of the rock material and rock mass engineering properties and prediction of post-engineering behaviour.

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