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Engineering properties of marine sediments in Mali Ston Bay (Croatia) based on "Mainland-Pelješac" bridge investigations

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ABSTRACT

The complete geological characteristics of the wider area of the Pelješac peninsula are presented: lithostratigraphy, structural/tectonic geology and seismotectonics. The main emphasis is on the engineering geological characteristics of the clastic sediments in Mali Ston Bay, encountered during investigations for the building of the "Mainland-Pelješac" bridge project. The bridge has large proportions, as it is 2404 m in length and has 14 under-sea pylons. It required thorough and expensive in-situ and laboratory investigations which enabled the development of a detailed and reliable engineering model of the Quaternary clastic sediments at the exploration site. The results clearly indicate three different engineering units which are predominantly classified according to their obvious differences in consistency: Unit A – very soft and soft sediment; Unit B – soft to firm sediment and Unit C – firm sediment. Given the total sediment thickness, (locally over 100 m), the generally poor engineering properties, and the high seismic risk of the area, the substrate for the foundations is unfavourable. The units which are classified according to their engineering properties also tightly correspond to the depositional environments which represent a much wider area than just the exploration site. Therefore the authors presume the presence of units A, B and C in the wider area with similar geological settings to that in the proximity of the Zrmanja, Krka, and Cetina deltas.

Keywords: "Mainland-Pelješac" bridge, Sediment consistency, CPT, Marine sediments, Adriatic Sea

1. INTRODUCTION

The "Mainland-Pelješac" bridge is designed for the southern, Croatian part of the Adriatic Sea, to span the strait over the Mali Ston Bay providing a crossing with a maximum span of 2,404 m, width of 24.64 m, linking Kumara cove on the mainland and the surrounding area of Brijesta cove on the Pelješac peninsula (Figure 1). It is located in a geologically and tectonically complex area, marked by seismicity, and strong winds. One of the essential requirements of the bridge design was to allow passage of marine traffic below, which determined a bridge height of 55 m. This was an important aspect for the neighbouring port and city of Neum (Bosnia and Herzegovina).

Initial research work was conducted for the purpose of the main engineering design. The foundations were examined by geophysical methods, research drilling, and laboratory testing and in-situ measurements. During 2009, additional geotechnical and engineering-geological research work was carried out at the proposed location of each pylon in the Mali Ston Bay, and it is the results of these additional investigations that are the subject of the current work.

From the coastline to a water depth of 24 m, the seabed is steep and formed of carbonate rock for the remaining length of the bridge axis, the seabed is flat and muddy, on average at a depth of 28 m, and carbonate rock outcrops are absent. The bridge design stipulated 14 pylons in the offshore

Figure 1: Satellite view of the Pelješac bridge location.

area, two of which represent the central pylons, at a height of 176.15 m (RADIĆ et al., 2009). It was anticipated that the foundations of the pylons from S6 to S11 would be in a layer of hard clay, so that the bearing capacity is attained by friction against the pylon sheath. For the remaining 8 pylons the final depths of the piled foundations would be in the underlying carbonate sedimentary rocks beneath the clastic sediments.

The main aim of this paper is to present the engineering geological characteristics of very thick Quaternary sediments at the bridge location and wider region, which haven't been previously studied to this extent or from this point of view. Some major relationships between the engineering properties of the sediments and their genesis (deposition environment and rate) are also presented.

2. GEOLOGY OF THE STUDY AREA

The area under consideration is composed of Upper Cretaceous and Lower Eocene carbonate rocks, Upper Eocene flysch-like deposits, and Quaternary sediments covering the seafloor of the Mali Ston Bay (Figure 2) (RAIĆ & PAPEŠ, 1980, MARASCHINI et al., 2005, BULJAN & GULAM, 2007, BULJAN et al., 2010, POLLAK et al., 2010).

2.1. Bedrock geology

The bedrock geology of the broader area is composed of platform carbonate rocks ranging in age from the Middle Triassic to the Middle Palaeogene. Tectonic stress in the Middle Eocene resulted in variable uplift and differentiation of the carbonate platform. Gradually, palaeogeographic and, in general, geological conditions favouring development and deposition of terrestrial clastic material into the remaining marine basins produced the complex system of siliciclastic flysch deposits. During the Upper Eocene and Oligocene, the Dinarides were formed with a geological strike SW-NE. These are still the most characteristic structural-geomorphological feature of the region. Subsequent intensification of tectonic movements during the Neogene formed regionally extensive reverse-thrusting structures. During the Pliocene, the main stress changed from SW-NE to S-N which, accompanied with alteration of the direction of compression, caused the ongoing destruction of pre-existing geological structures.

The geological setting along the "Mainland-Pelješac" bridge reflects the structural-tectonic relationships within the broader area. The structural setting formed as a result of dislocation of the Adriatic plate towards the Dinarides (PRELOGOVIĆ et al., 1999). Spatially, this mass is subducting beneath the Dinarides (Figure 2), attaining depths of 15 to 20 km beneath the study area (ALJINOVIĆ et al., 1984). More resistant blocks are displaced closer to the surface. The carbonate complex of the Dinaric regional structural unit is thrust near the surface, over the Epi-Adriatic regional structural unit (formed of siliciclastic flysch deposits). The carbonate fault escarpment at the front of the Dinaric thrust in the neighbouring area, is >400 m high. Rock mass fracturing at the surface is simply the result of the spatial relationship and movement of the larger blocks at depth. The carbonate sedimentary rock complex in the area to the south of the flysch deposits belongs to the Adriatic regional structural unit. The proposed bridge is located in this area although it can be stated that this site lies in the broader contact zone of

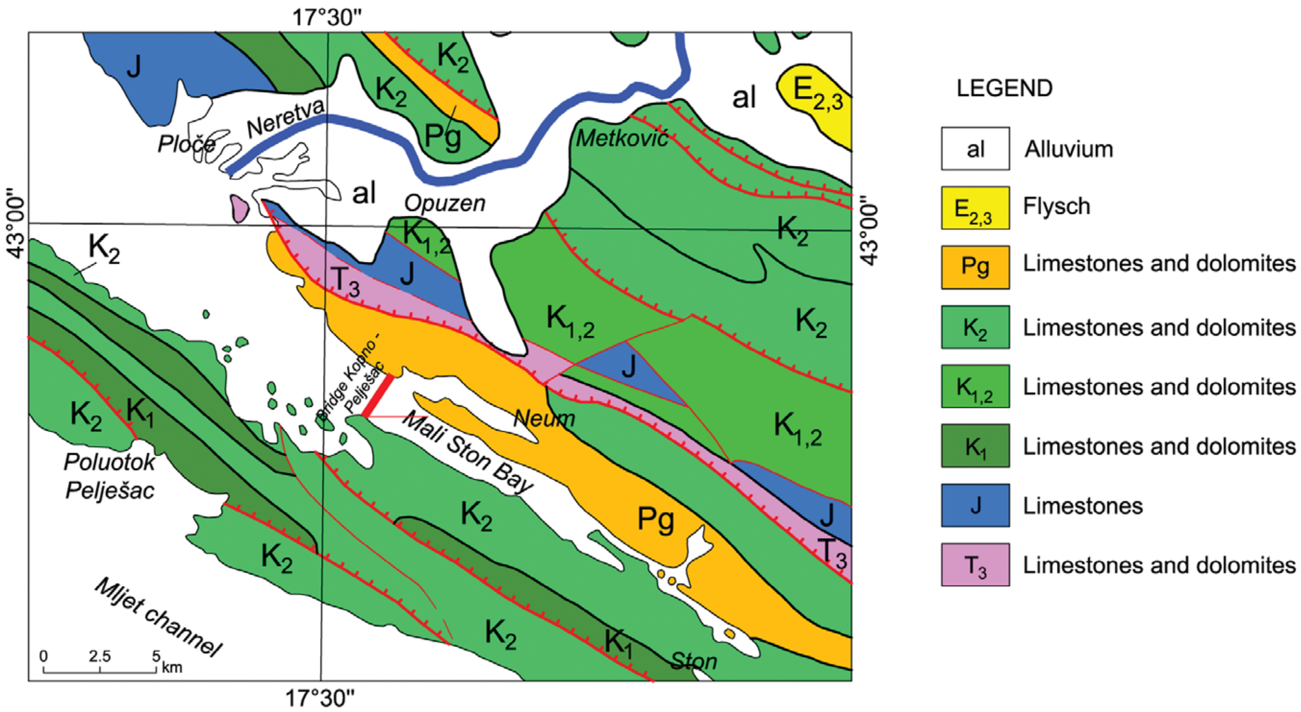

Figure 2: A simplified segment of the geological map of the Republic of Croatia (originally at 1:500 000 scale; Federal geological survey – Beograd, 1980)

the aforementioned regional structural units.The direction of the Recent stress is 20º–200º (PRELOGOVIĆ et al., 2004), effectively parallel to the axis of the proposed bridge. In the Recent structural setting, reverse faults are dominant. The main tectonic feature of the investigated terrain is the faulted folds, while the structures are monoclinal with a Dinaric strike (NW-SE) and beds dipping 20º–60º to the NE. Apart from the reverse faults and thrust planes, many normal faults of diverse orientations can be also observed in the area. The considered area, (and in fact the whole NE coastal part of the Adriatic Sea), is still a seismically very active region in Recent times (HERAK et al., 1996).

As a result of the constant compression of area over approximately the last 40 million years, and consequent tangential, reverse-thrusting tectonic movements, the rock mass thickness has been multiplied, while the tectonic area has been considerably reduced. The carbonate complex is tectonically uplifted; thrust over the complex of siliciclastic flysch deposits, which as a pliable medium, had served for the tectonic transport of the brittle carbonate rock mass. In Recent times, flysch is mostly eroded and reduced at the surface, and subducted beneath the carbonate rocks (Figure 2). The carbonate complex itself, is reduced by thrusting, often at the contact between carbonate and dolomite rocks. Together, this indicates the complex structural and tectonic relationships and intense tectonic and erosional activity in this area during the geological past and also in Recent times which is substantiated by the registered earthquakes.

2.2. Plio-Quaternary sediments

The main uplift with exhumation in the coastal zone of the Adriatic Sea occurred during the major tectogenic phase during the Oligocene and Miocene (KORBAR, 2009), whereas the final form of the folded and faulted structures is the result of tectonic reactivation since the Upper Pliocene (BLAŠKOVIĆ, 1997). The climate in the Mediterranean region was warmer and more humid during the Oligocene and Early Miocene. Therefore the processes of karstification and pedogenesis of terra rossa were active in this region (LEWIN & WOODWARD, 2009, MATHER, 2009). There was plenty of time for erosion of the emerged area and its' subsequent karstification. The lack of Miocene and Pliocene marine sediments indicates that the area of the Mali Ston Bay was probably terrestrial from the Neogene.

In the Quaternary, the surface erosion of carbonate rock complex was reinforced, brought about by exodynamics; the activity of sunshine, wind, water and ice. Fluviokarstic forms develop mostly in the first stages of karstification in areas of intense rainfall, when discharge into the karst system exceeds its conduit system capacity (FORD & WILLIAMS, 2007). During processes of karstification, surface streams could gradually disappear underground resulting in development of dry valleys.

During the Quaternary which lasted for the last 1.8 million years, various geomorphological structures were formed which still exist in the study area. This geological period is characterised by considerable climate change, marked by cool periods (glacials) interchanging with short warm periods (interglacials), and associated fluctuation in sea level. The Mediterranean Sea fluctuated between –40 and –60 m over the relatively long period of 80.000 years in the Late Pleistocene, (between 110.000 and 30.000 ka B.P.; LAMBECK & PURCELL, 2005). Plio-Quaternary sediments most often occur as a thin cover over the underlying carbonate rocks; more rarely thicker if the proper morphological conditions have been met. At the bridge site, in the area of Mali Ston Bay which was first formed as a karst polje, various types of Quaternary sediments were deposited in the form of eluvium, diluvium, aeolian, limnoglacial sediments. Colluvial sediments originated at the foot of the slopes of the steep carbonate escarpments in the peripheral areas (RAIĆ & PAPEŠ, 1980, BULJAN & GULAM, 2007, BULJAN et al., 2010, POLLAK et al., 2010).

The Recent formation and spatial setting of marine fine clastic deposits is closely related to: transport of the terrigenous material by the nearby Neretva River; permanent tectonic activity causing the uplift of the south part of Croatian Adriatic coast; and to oscillating sea level in the Mediterranean including the Adriatic Sea sedimentary basin during the Upper Pleistocene and Holocene. Remnants of the palaeostream of the nearby Neretva River can be traced even today from its present mouth further along the Adriatic Sea, via the seafloor along the Pelješac peninsula and Korčula Island, all the way to Vis Island (SURIĆ et al., 2005; SURIĆ, 2009; CRMARIĆ, 2009). These deposits transgressively overlie the older and more compact succession of clastic sedimentary rocks in the present submerged karst depression of Mali Ston Bay.

Sea level changes, from the peak of the Würm glacial period 20,000 years ago were caused by eustatic and glacial-hydro-isostatic changes due to global ice melting (LAMBECK & PURCELL, 2005). There was a sea level rise approximately 19,000 to 18,000 years ago, in accordance with a simultaneous global increase of temperature. Following melting of the ice cover, the sea level rose abruptly between 17,000 and 6,000 years ago. After this accelerated rise, a period of relative stagnation of sea level has occurred in the Adriatic Sea during the last 6.000 years due to the reciprocal relationship between tectonic subsidence and hydro-isostatic highstand in regional sea level (PIRAZZOLI, 2005, JURAČIĆ et al., 2009, SURIĆ & JURAČIĆ, 2010).

Sea-level lowstand during the last glacial age, along with humid climatic conditions, could have caused the restoration of fluvial processes in the steep downstream parts of karst valleys during pluvial periods (TZEDAKIS, 2009). Erosion processes by surface streams and the incision of valleys, were intense in the Kvarner area during this period (BENAC & JURAČIĆ, 1998), and probably also in the wider area, along the entire east coast of the Adriatic Sea. Erosion processes and terrigenous input into the sedimentary basin was reduced while simultaneous marine erosion/abrasion increased, Considerable gravely alluvial fans formed along the coast causing progradation of the coastline (JURAČIĆ et al., 2009).

The same sedimentary conditions also predominated in the nearby Mali Ston Bay, where due to the sea level rise in the Quaternary, the process of deposition of sediments transported by torrents along the then existing gullies, together with particles eroded from higher terrain and transported by slope processes or the wind had begun. The sediments from the mouth of the Neretva River, were carried by marine currents and also were deposited. This resulted in the gradual covering of the clayey sediments by clastic terrigenous particles in the central portion of the submerged karst valley and the carbonate landscape on the periphery.

3. THE INVESTIGATION METHODS

The detailed investigations presented in the paper were performed at each of the bridge submarine pillar foundation locations in the profile (Figure 3). These included in-situ testing: core drilling, down-hole seismic profiling, cone penetration testing with pore pressure measurements (CPTU), pocket penetrometer tests; engineering geological core examination/description; and laboratory analysis of the core samples: granulometry, Atterberg limits, X-ray diffraction analysis and mechanical properties testing.

Entire site investigations were performed from the adopted exploration ship platform in challenging submarine conditions. Additionally, both seashore zones were mapped by diver's expert in engineering geology.

The boreholes were located at the corners and in the centre of the proposed pylon locations. As the boreholes followed the geological predictions and geotechnical design requirements, the total drilled length exceeded 2900 m in 42 boreholes ranging from 12 to 112 m in depth.

During core examination and description, the usual procedures for field and manual determination of soil identification were carried out. The manual test procedures including determination of plasticity, consistency and dry strength, followed International Standards (ISO, 2002). Laboratory testing of soil mechanical properties were done in accordance with widely used standards: direct shear strength (ASTM, 2004), uniaxial and triaxial strength tests (BS, 1990).

Micropalaeontological and palynological analyses determined the fossil content of five soil samples, while absolute age was determined by the means of C^{14} determination (Pavelić, 2005). The mineralogical composition was determined by XRD analysis and carbonate content by the Scheibler method (ALTFELDER et al., 2007).

The same boreholes were also used for downhole seismic profiling in the 12 locations for a total length of 843 m. Analysis of the downhole records here, included data from the average of three metre interval velocities.

Seven profiles with cone penetration tests were performed at 5 locations (in the centre of the pylon locations S6 to S10) with a total depth of penetration of 457 m. The profiles were done with pore pressure measurements (CPTU) in accordance with draft standard (EN ISO, 2009) and the directives of EUROCOD 7 (CEN, 1999). Penetrations were performed by a "GEOMIL – penetrometer 200 kN" with a maximum penetration force of 200 kN. Penetration velocity was in the range of 20 ± 5 mm/s. After the measurements the sediment was classified according to Robertson's method (ROBERTSON, 1990). The cone penetration resistance measurements (q_c) which were continuously collected along each profile, were then analysed.

4. RESULTS

At the bridge location the sea floor is horizontal at a depth of around 28 metres (LEDER, 2004). Preliminary geophysical exploration with six borehole probes indicated a surprisingly thick sediment cover on carbonate bedrock (MARASCHINI et al., 2005). Detailed investigations confirmed that the sediment thickness at many locations exceeds 100 metres which wasn't expected given contemporaneous geological knowledge.

According to the on-site core examinations, descriptions and manual tests of sedimentary material, three engineering geological units could be distinguished. The units are regularly stratified and their boundaries are almost horizontal (Figure 3). These units were predominantly distinguished according to obvious differences in consistency and subordinately by their diverse mineral and grain size content and colour.

According to 14C radiometric dating of the extracted organic part of the marine sediment sample, the absolute age of samples from a depth of 5.5 m below the seafloor is 8,580 (±275) years, while sediments at 35.5 m are 17,100 (±530) years old (PAVELIĆ, 2005). These results indicate very rapid deposition during the period between 17,100–8580 years ago, of 2.08 mm per year, which slowed to a depositional rate of 0.64 mm per year during the last 8,580 years, which is in accordance with the aforementioned rate of sea-level rise in the Adriatic Sea.

Unit A – very soft and soft sediment. Very soft and viscous sediment represents the first 7 m (17 m in maximum) of the seabed profile. At depths of 7–8 and 16 m there are frequent organic lenses. Organic clays and silts occasionally contain fibrous peat material. Soft grey sediments in this unit have very low – low dry strength, and are high (CH to MH), or rarely low plastic clays/silts according to laboratory testing (Figure 4). Freshwater and marine bivalves and gastropod fragments are frequent, occasionally forming up to 20% of the content. The most recent sediments of the unit are strongly influenced by the Neretva river delta which is only 12.5 km to the NW. Older deposits (>8–9 ka) represented by those deeper than about 5m, suffer increasingly from the impact of the brackish water. Later on above 5m depth in this unit, freshwater and marine environments irregularly interchange. Carbonate minerals are dominant over smectite and vermiculite. The total thickness of unit A is generally 28m, increasing locally to a maximum of 38m.

Unit B – soft to firm sediment. Mainly grey to brownish grey highly plastic clay and silt (CH to MH). The manual test indicated medium to low dry strength. There are also segments with material of low plasticity (CL to ML) (Figure 5). This unit is also characterized by sandy intrabeds, and in the lower part, with rounded calcite concretions up to several

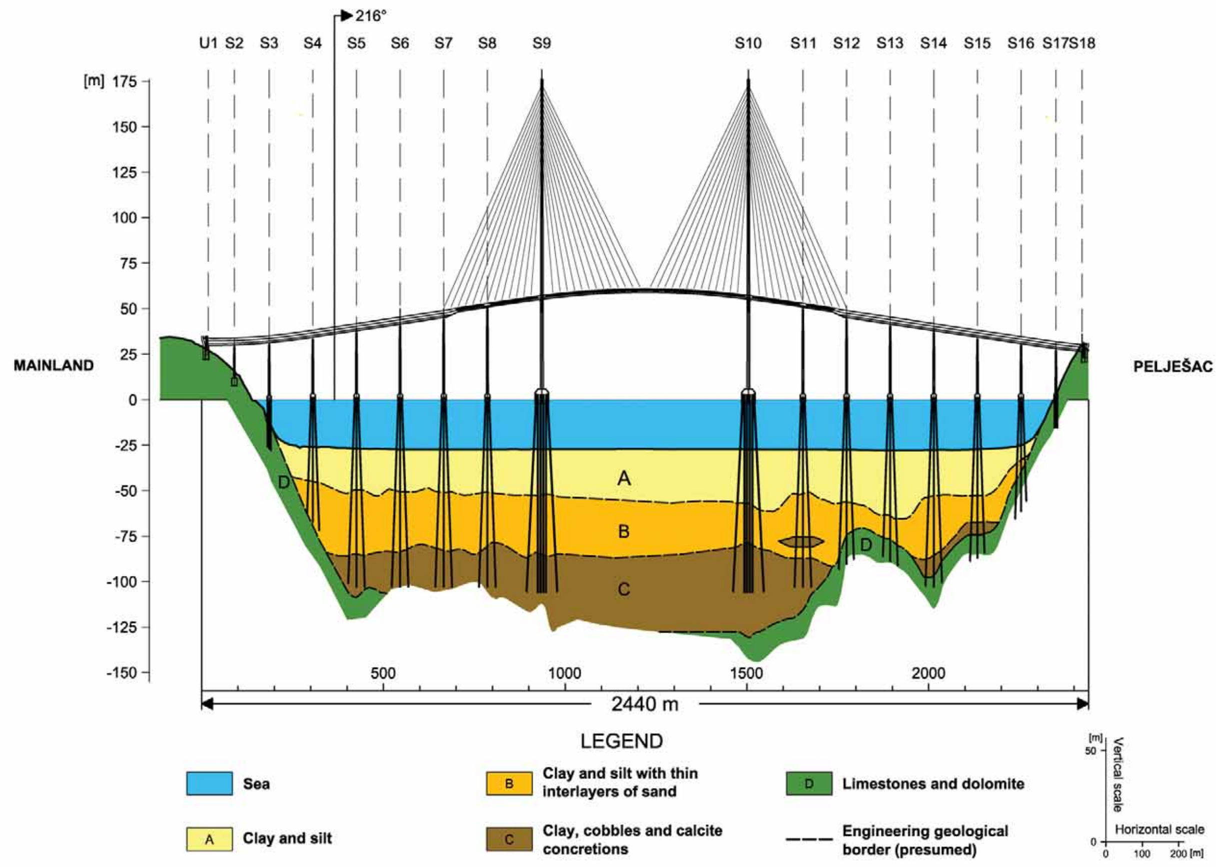

Figure 3: Schematic engineering geological cross-section with simplified bridge construction. Vertical scale exaggeration is x10.

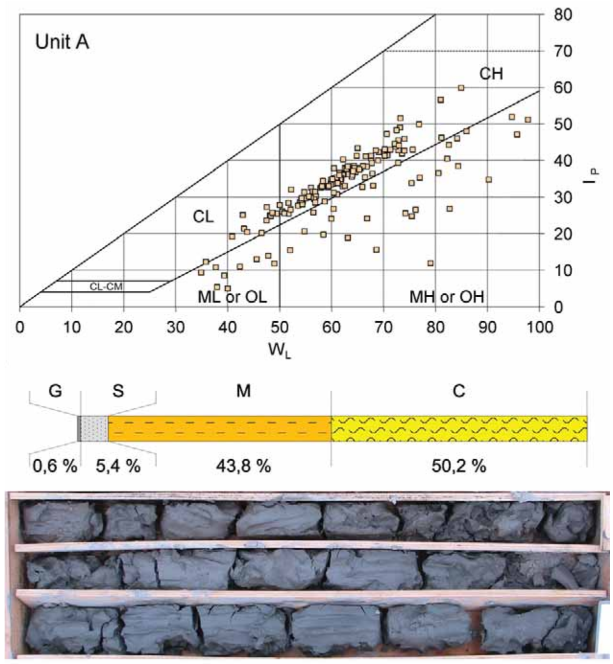

Figure 4: Unit A – plasticity chart (164 samples), granulometry histogram (162 samples) and characteristic borehole core in 1m boxes.

centimeteres in size. Marine bivalves and gastropods are usually randomly scattered and just occasionally enriched in some lenses. Sedimentation of this unit occurred in a predominantly shallow low energy marine environment. Carbonate minerals are predominant, but the calcite content is lower toward the base of the unit. Unit B varies in thickness from 25–38 m and has a gradational boundary with unit A.

Unit C – firm sediment. Highly plastic clay (CH), reddish brown in colour with calcite concretions. The manual test was uniform and indicated a high dry strength for the clay material. Rounded calcite concretions from one to several centimetres in diameter are frequent and in some locations constitute >10 % of the sediment mass (Figure 6). Several metres above the carbonate bedrock (1–5 m) the soil is a mixture of the same material and limestone detritus. The limestone clasts are irregular, subangular and up to several centimetres in size. Their proportion decreases upwards from the contact with the limestone bedrock. In unit C there are also some rare intrabeds (3 m thick) of sandy or even gravelly material. The upper boundary with unit B on top, and also the lower one with the limestone bedrock, are usually very sharp and easily detectable. In this unit quartz is dominant over smectite. The foraminiferal assemblage, mineral composition and absence of pollen are clear indicators of a deeper and open marine depositional environment (PAVELIĆ, 2005). The total thickness of unit C, as a consequence of the palaeomorphology, is variable, with a maximum of 40 metres (Figure 3).

The design of the pylons which remain in the sedimentary material was based solely on the much better engineering properties of unit C. Therefore, additional laboratory testing of its mechanical properties was performed (Table 1). The cohesion and internal friction parameters of direct shear and triaxial drained tests are comparable. The uniaxial strength of the soil material within unit C is 214 kPa on average, with a high standard deviation of 110 kPa.

Unit D – carbonate rock mass. The bridge abutments and adjacent pylons are located at the karstified carbonate

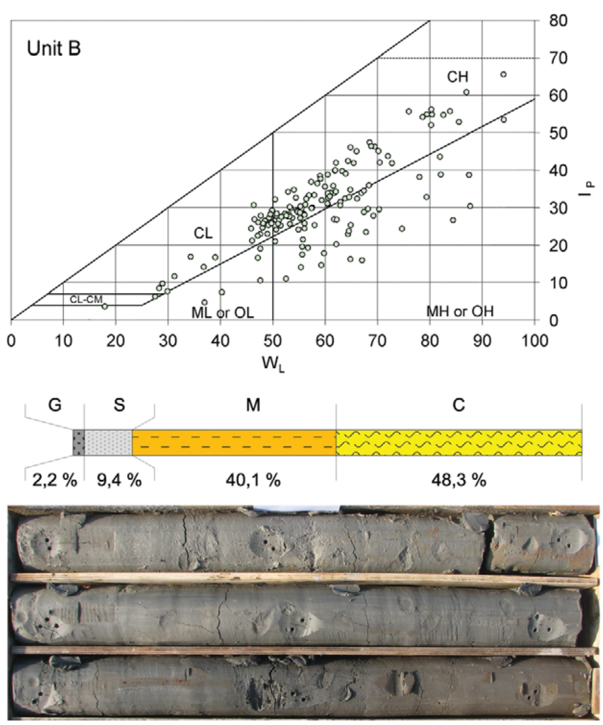

Figure 5: Unit B – plasticity chart (161 samples), granulometry histogram (170 samples) and characteristic borehole core in 1m boxes.

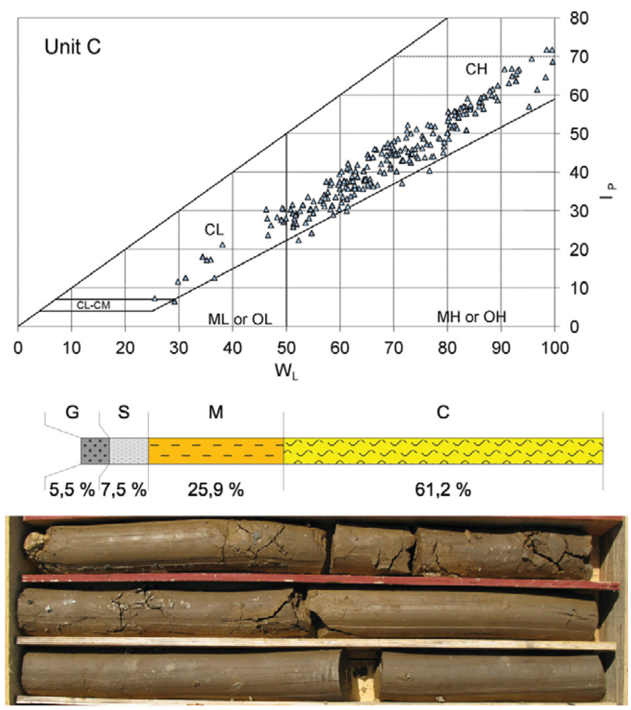

Figure 6: Unit C – plasticity chart (231 samples), granulometric histogram (252 samples) and characteristic borehole core in 1m boxes.

Table 1: The mechanical properties of samples from unit C.

Laboratory test	c / kPa		ϕ / °		No. of samples
	mean	st. dev.	mean	st. dev.	
"Direct shear (CD)"	43.8	17.7	18.8	2.1	13
Triaxial strength (CU)	37.2	21.3	20.8	2.2	5
Triaxial strength (UU)	1395	48.7	–	–	26

shore (Figure 3). This carbonate rock mass also represents the bedrock of the described sediments. Upper Cretaceous and Lower Eocene limestones are locally recrystallized, dolomitized, and are frequently very jointed. The karstification of these carbonates is evident, since there are many caverns and wide discontinuities with corrosion marks. Such diagenetic and post-diagenetic processes are the consequence of the intensive tectonics in the geological history. Mechanical properties of rock material within unit D were determined by uniaxial compressive strength and Young's modulus. The uniaxial compressive strength test, as one of the most important indicators of rock quality, was performed on 77 samples obtained by exploration drilling. The results show a large distribution where the minimum noted value was 28 MPa while the maximum was 227 MPa (Figure 7). Young's modulus has also shown a large spread in the results obtained, where the minimum value was 3 GPa and the maximum was 61 GPa (Figure 8).

In order to determine the mechanical characteristics of the rock mass in Unit D, the GSI categorization was performed using data gathered by the engineering geological mapping of the coastal area of Mali Ston Bay, together with data obtained from core drilling. This indicator, also, showed a large spread where the minimal GSI value recorded in the base of pillar S10 was 27, and the maximum in the base of pillars S15 and S16 was 80. Such a wide range of GSI can be primarily attributed to difficult drilling conditions which precluded the collection of high-quality core material.

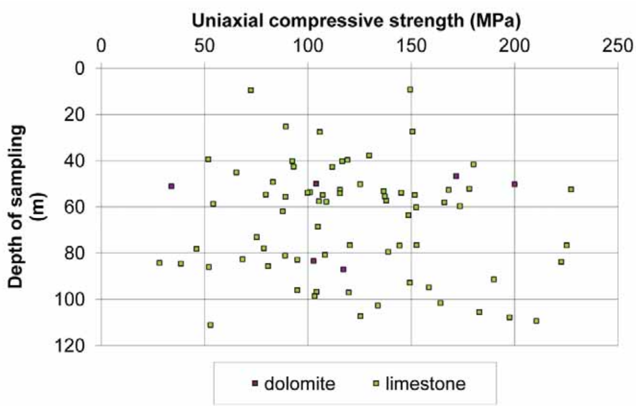

Figure 7: Unit D – distribution of uniaxial compressive strength (77 samples).

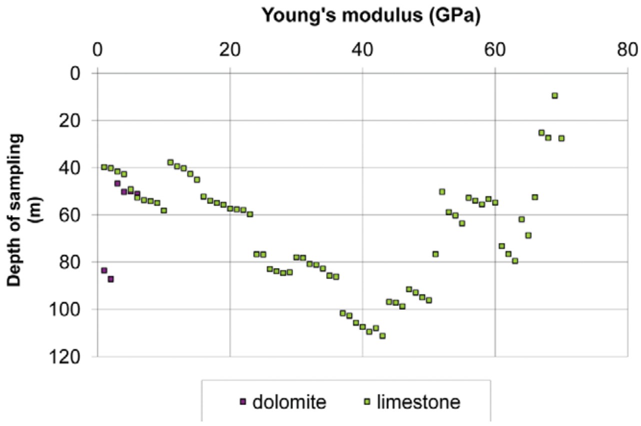

Figure 8: Unit D – distribution of Young's modulus (77 samples).

5. DISCUSSION

Here, core sample analysis and the most important laboratory results are compared to in-situ tests and measurements. According to several authors (ROMINGER & RUTLEDGE, 1952; MEANS & PARCHER, 1963) the liquidity index (I_L) gives reliable information about the degree of consolidation of clayey sediments. The same index was calculated for the tested materials and is presented in Figure 9. Since lower I_L values indicate a higher degree of consolidation, the trend of increasing consolidation with sample depth is obvious. It is also clear that unit A in general has I_L values closer to 1, which is the liquid limit, while materials in units B and especially C have I_L values much closer to zero.

These I_L values are also presented statistically for each unit (Figure 10). As expected, the upper segment of Unit A is lightly consolidated, but most of the tested material in unit A (average I_L=0.23) and B (average I_L=0.18) can be regarded as highly consolidated. The much higher consolidation rate of highly plastic clayey material (unit C) which has I_L values below zero (average I_L=–0.05) in comparison to the soils with carbonate content is also clearly observed.

In order to numerically express the consistency of the material, the consistency index (I_C) is presented (Figure 11). In accordance to the I_L values of the samples, the I_C indicates mainly firm consistency of the material in units A (average I_C=0.71) and B (average I_C=0.87). The average I_C values of unit C are, however around 1 (I_C=1.01) indicating that the sedimentary material is between stiff and very stiff in its consistency.

Both, Figs. 10 & 11 display much wider oscillations of I_L and I_C values in units A and B in comparison to unit C. In contrast, measured cone penetration (CPT) resistance values (q_c) are very uniform for unit A (Figure 12). In addition, the upper seven metres (rarely up to 20 m) of unit A are without any penetration resistance indicating very soft, even viscous media. The average values of q_c confirm the experience engineering geologists had during core examination in explored profile – the need to divide sediments into three units. Although units B and C have high oscillations in q_c values, the averages clearly indicate three totally different sediment mass properties, with CPT measurements of: A – q_c=0.93 MPa, B – q_c=2.12 MPa, C – q_c=3.81 MPa (Figure 12).

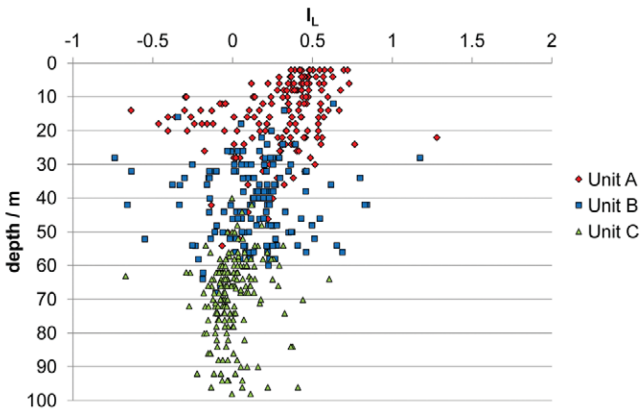

Figure 9: The liquidity index values (I_L) of 578 tested samples in relation to sampling depth.

Figure 13 displays the correlation between the consistency indexes of samples and cone penetration resistance at the same overburden depth. The chart displays certain dependence of the two parameters when sediment has I_C<0.75, or has a firm or soft consistency. However, according to the laboratory and in-situ measurements, the consistency index in stiff and very stiff material cannot indicate the order of magnitude of cone penetration resistance.

Downhole seismic profiles have easily and precisely determined boundaries between the bedrock and overlying sediments, but couldn't differentiate sedimentary units since the measured primary wave velocities for the whole complex are on average between 1550 and 1560 m/s.

Seismic parameters such as seismic intensity I_{max}=9.2° MCS, seismic amplitude of earthquake M_{max}=6.5 by Richter, soil acceleration (horizontal acceleration) at the level of the solid rock particle a_{max}=0.41 g have been calculated for the bridge site (PRELOGOVIĆ et al., 2004). Tectonic activity of the area and a very significant seismicity will have a very adverse impact on the bridge foundations. The regional geology, together with the specific local conditions which required undersea investigations enables conclusions to be drawn about the engineering geological properties, not just at the bridge site but also for a much wider area. The afore mentioned environments, and therefore engineering properties are expected to be very similar for other areas in the proximity of river deltas along the Dalmatian Adriatic coast (Zrmanja, Krka and Cetina) which are not yet explored in terms of engineering properties.

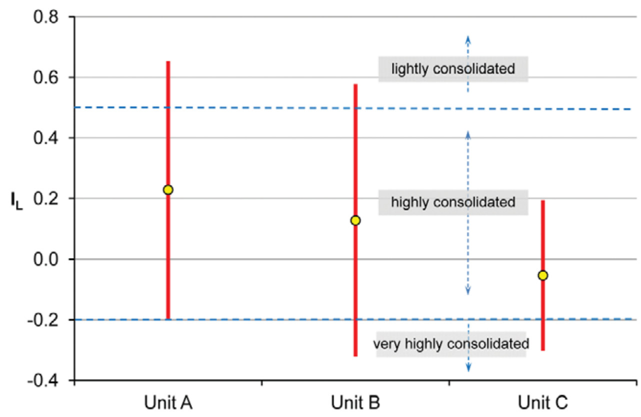

Figure 10: The average (circles) and standard deviation (red lines) values of the liquidity index (I_L) in sedimentary material of the units (578 samples). Dashed lines represent the boundaries between consolidation levels according to MEANS & PARCHER (1963).

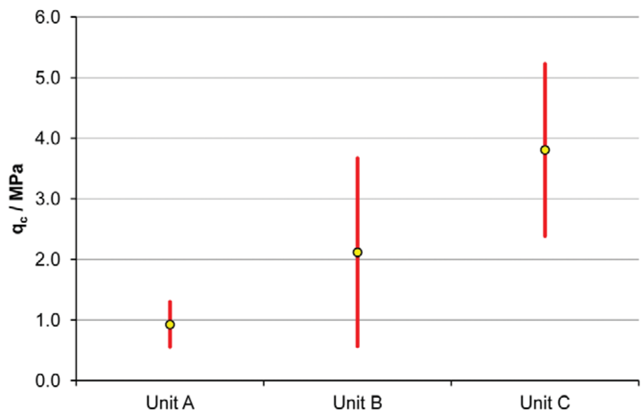

Figure 12: The average (circles) and standard deviation (red lines) of all cone resistance measurements in particular units. Based on 7 profiles with a total depth of 457 m.

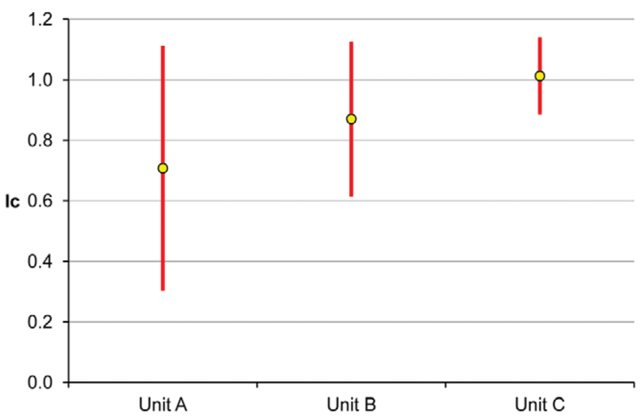

Figure 11: The average (circles) and standard deviation (red lines) of consistency index (I_C) in soil material of the units (551 samples).

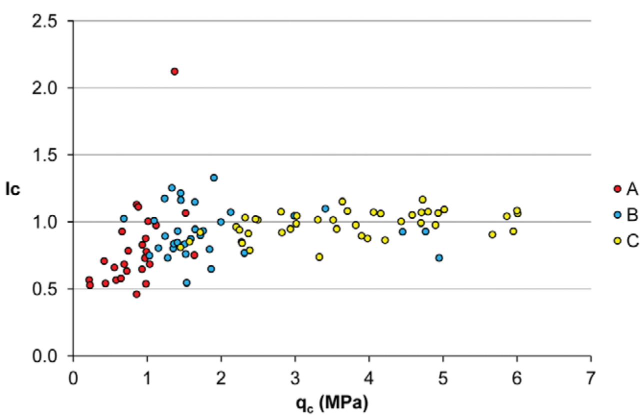

Figure 13: Comparison of the consistency index (I_C) and cone penetration resistance (q_c) in particular engineering geological units.

6. CONCLUSIONS

The location, geological situation and size of the bridge, required a demanding programme of exploration. From the presented data it is clear that the sediment thickness in the central locations of the bridge (pillars S5-S11) exceeds 75 m and reaches up to 100 m. Therefore, the depth to the consolidated rock mass at several locations is about 130m below sea level. Also, the presented data indicate that the upper 60 metres of the sediment profile generally has very poor engineering conditions. In addition, the geotechnical design should anticipate differential settling as several pylons are founded in strong carbonate rock while others are anchored in stiff plastic sedimentary material.

This, together with the bridge span, and seismicity of the area, leads to the conclusion that construction of the bridge will be very challenging, expensive and risky.

The engineering properties of the different sediment units are described by means of consistency which, in this case, together with plasticity, turned out to be a very indicative and valuable parameter. Additionally, consistency and plasticity can be detected by very simple manual tests, which enabled early subdivision of the soil material into three units (A, B and C).

The exploration works also documented sediments with several characteristic depositional environments, characterized by specific engineering properties in particular those related to overburden depth: unit A – alternately marine and brackish environment with low overburden – very soft to soft sediment; unit B – shallow marine with low and rare higher energy periods, with overburden of several tens of metres – soft to firm sediment; unit C – deeper and very low energy marine deposition environment, with overburden of more tens of metres up to hundred metres – firm sediment. Variations on the physical and mechanical properties within Units A and B are frequent and considerable, due to variation in composition and consolidation rate which also followed depositional environment and later sedimentation. Namely, due to variations in sea level and energy, the composition, mineral content, and grain size also vary accordingly.

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