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Deepening of the seabed for the construction of the LNG terminal on the island of Krk

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Professional paper

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Near Omišalj on the island of Krk, where the construction of a pier for liquefied gas is planned, hydrographic measurements revealed three shoals at depths of 13.5 and 13.6 metres. For the safety of navigation, the seabed had to be deeper than 15.4 m. The geological fabric of the seabed was determined using a hydroacoustic survey and remote operating vehicle. Shallows are formed in a solid carbonate rock mass. Special technology of excavation without blasting was applied. 11,000 m^3 of rock mass was excavated which was deposited nearby. The seabed habitat with an area of about 12,500 m^2 was changed.

Key words:
seabed, excavation, fill, carbonate rock, Rijeka Bay, Adriatic Sea

Stručni rad

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Produbljivanje morskog dna za potrebe izgradnje LNG terminala na otoku Krku

Kod Omišlja na otoku Krku, gdje je predviđena izgradnja pristaništa za ukapljeni plin, hidrografskim mjerenjima ustanovljene su tri pličine na dubinama 13,5 i 13,6 m. Zbog sigurnosti plovidbe, morsko dno je moralo biti dublje od 15,4 m. Pomoću hidroakustičkih metoda istraživanja i autonomne ronilice ustanovljena je geološka građa morskog dna. Pličine su oblikovane u čvrstoj karbonatnoj stijenskoj masi. Primijenjena je posebna tehnologija iskopa bez miniranja. Iskopano je 11.000 m^3 stijenske mase koja je deponirana u blizini. Izmijenjeno je stanište površine oko 12.500 m^2.

Ključne riječi:
morsko dno, iskop, nasipavanje, karbonatna stijena, Riječki zaljev, Jadransko more

1. Introduction

Coastal structures are usually very expensive, and the type of construction strongly depends on the natural features of the location, among which is the geological structure and consequently on the geotechnical features of the seabed [1, 2]. In recent decades, the methods of undersea research have improved significantly in the world, especially due to development of *offshore* constructions [3, 4]. Exploratory drilling methods of shallow seismic profiling (delta-t-V tomography) have been improved. The use of hydroacoustic measurement methods has advanced in particular. Using a multi-frequency echo sounder (*Multibeam*) it is possible to quickly and precisely measure the relief of the seabed. Using the panoramic echo sounder (*Side Scan Sonar*) it is possible to precisely distinguish the rocky bottom from the surface covered by sediments. By profiling using a structural-geological echo sounder (*Sub Bottom Profiler*) it is possible to establish the relief of the bedrock covered by sediments, as well as the thickness of these sediments. The first measurements of the seabed using modern hydroacoustic methods were carried out in the area of the Croatian part of the Adriatic Sea in 1994 using the then new GPS positioning technique [5].

The coastal Adriatic belt of the Republic of Croatia is specific in that it is mostly submerged karst [6], and the coastal lines of the island of Krk took their current form approximately six millennia ago [7]. In addition to phenomena specific to karst on land, such as sinkholes, swallow holes and fossil valleys, on the west coast of the island of Krk it is possible to encounter two extremely different geotechnical environments at meter intervals: solid rock mass and quick mud [8, 9]. In the wider area of the Rijeka Bay, as well as in the marginal water areas: Bakar and Omišalj bays, several very complex coastal structures were built [10-12]. It has been proved that the geological fabric and consequently the geotechnical conditions are very different and often very complex [13-15]. Due to the usually very steep slope of the seabed, coastal structures have complex reinforced concrete constructions or are built on a previously formed embankment [16]. More significant coastal structures that were built in the last two decades have not been described in the scientific and professional literature so far. The deepening of the seabed by excavating the rock mass using the blasting method in the Kvarner area was carried out in the seventies of the 20th century during the construction of the Krk Bridge and the coast in front of the former DINA petrochemical plant near Omišalj settlement on the island of Krk. In the 21st century, this method was used to deepen the entrance to Puntarska draga Bay on the island of Krk.

It is known that there are three shallows in front of the existing terminal near the Sepen cove which were marked with navigation buoys. Their position is also clearly visible on the 1:25,000 scale map [17] (Figure 1).

Those shallows represented a danger for the navigation of the ships/tankers envisaged in the project. The draft of the designed ship for liquefied gas is 12 m, so the minimum depth of the seabed should have been 14.40 m for safe maneuvering [18]. Research has established that large amounts of 11,000 m^3 of solid carbonate rock masses will need to be excavated and about 15,000 m^3 of excavated material be deposited in a loose state. It is certainly one of the largest underwater excavations in a solid rock mass in the area of the territorial sea of the Republic of Croatia. Since blasting was not allowed, innovative mechanical excavation techniques were applied, which are described in this paper.

2. Measurements and research

Research for future liquefied natural gas (LNG) terminal, located on the west coast of Krk, were carried out during the winter and spring of 2016 on the basis of a previously prepared research program for the main project level. Due to the awareness that there are shallows in the water area that could be dangerous to navigation of the planned ships that will transport liquefied gas, the research covered a relatively large area (Figure 1).

Since there was no detailed bathymetric map, the accuracy required for the development of the main project, geodetic surveys were also included in the research program. In addition, hydro-archaeological research was also carried out, as the remains of the late antique Fulfinium settlement as well as medieval sacral buildings are located nearby [19]. Hydrographic measurements have established three shoals, formed in a relatively solid carbonate rock mass. The shallowest parts of these shoals were at depths of 13.5 m to 13.6 m [20].

In the water area in front of the future LNG terminal, research was carried out in two phases. In the first phase, hydroacoustic measurements and engineering geological mapping were performed. The purpose of these investigation was to obtain a sufficiently accurate relief of the seabed and establish the geological fabric. In the second phase, exploratory drilling on the seabed and laboratory analyzing of samples was performed to determine the optimal excavation method.

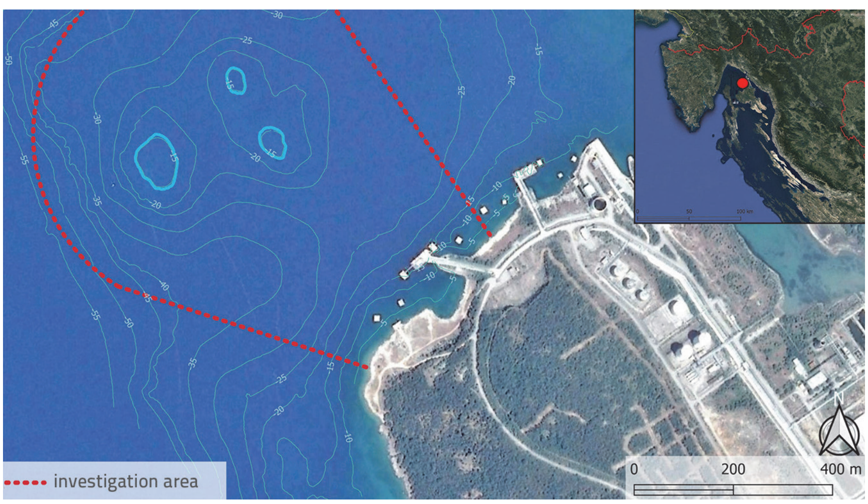

Figure 1. Shallows in front of the existing pier and a representation of the seabed included in the research

2.1. Hydrographic measurements

The following measurements were made in the researched water area [20]:
- bottom depth measurement using *Multibeam,*
- measurement with *Side Scan Sonar*
- measurement with a *Sub Bottom Profiler*.

A mulitbeam was used to precisely measure the underwater relief. Using side scan sonar, it was possible to distinguish zones of rocky bottom from zones where there are sandy sediments on the surface. Profiling using a sub bottom profiler established the relief of the bedrock covered by sediments, as well as the thickness of these sediments.
Immediately before the hydrographic measurement, the usual measurement of the vertical profiles of sound propagation speed up to a depth of 30 m was performed for later correction of the measurement results. In addition, the usual survey of the bottom was carried out using a magnetometer, in order to detect possible larger metal objects.
Navigation took place according to pre-planned profiles. The starting and ending point, as well as the central search lines perpendicular to the coastline, are determined by geographical coordinates on the GRS 80 spheroid and the Gauss-Krueger projection (Transverse Mercator), and the depths are reduced to the new Croatian geodetic zero HVRS 71.
For the purpose of high-quality and constant positioning and navigation guidance during the hydrographic-geological-magnetometric survey, two precise positioning systems were used that worked in parallel: DGPS-1 (SeaSTAR 8200 HP system DGPS – Fugro) with satellite telemetry system and DGPS-2 (Hemisphere GPS Crescent VS110 DGPS + Heading Receiver GPS, Beacon SBAS) with telemetry system also via satellite. DGPS-1 was the primary, DGPS-2 was the secondary navigation system. The measurement accuracy was 10 cm.
Using the program packages of the Croatian Hydrographic Institute (HIDRIS, HYDR Opro, AutoCAD 2002, ZWCAD 2010, etc.), measured data were processed, errors were filtered, and a depth map was drawn with seabed isobaths and a grid of coordinates in a given scale of 1:2,000, while the coastal part, where the construction of a new coastal structure is planned, is made on a scale of 1:500. The bathymetric maps are aligned with the geodetic measurement of the coastline and the land part of the area of the future LNG terminal in the HTRS 96/TM system [21].
Based on the results of depth measurements, it was established that the relief of the bottom is very pronounced. The position and shape of three shoals were precisely determined, the shallowest parts of which are at a depth of 13.6 m in shallows no. 1 and 2, as well as 13.5 m in shallow 3, according to HVRS 71 (Figure 2).
Searching the water area with a Side Scan Sonar was carried out on eight parallel profiles with an approximate distance of 100 m (perpendicular to the coast) and on two parallel profiles with a distance of 50 m (parallel to the coast). It was found that outcrops of the rock mass are visible in the shallows, and the deeper parts of the water area are covered with sandy sediments.
Using a sub bottom profiler, four parallel profiles were recorded. The oscillator of that device was towed astern of the ship and submerged about 0.5 m below the surface, and hydrophones were also towed behind the oscillator at a depth of 0.2 m. The operating frequency for better penetration was from 1.5 kHz to 4 kHz, and the emission power was 200 J. The maximum possible penetration depth of ultrasonic waves through sediments was 18 m.

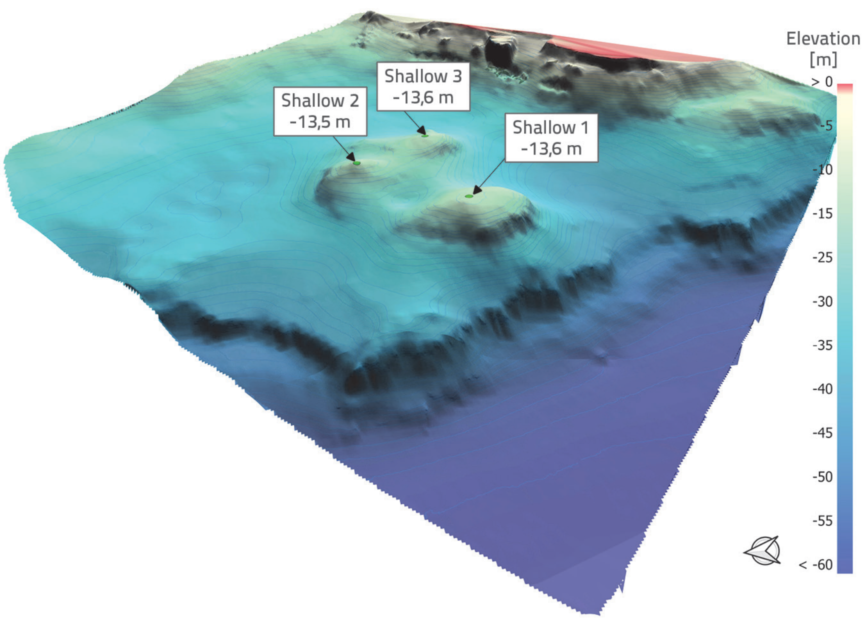

Figure 2. Three-dimensional representation of the underwater relief, according to [20]

2.2. Engineering geological mapping

After creating a working version of the geodetic map of the seabed, as well as reviewing the results of the survey using a side scan sonar and a sub bottom profiler r, the survey route was determined using a remotely operated vehicle (ROV) (Figure 3).
That remotely operated vehicle was positioned during the recording using the Tracking ORE LXT system. A signal transmitter was installed on that device, which communicates with the receiver every two seconds and provides the data necessary to calculate its position. Those parts of the investigated water area that proved to be interesting after the preliminary analysis of depth

measurements, as well as recording using a panoramic and geological-structural echo sounder were inspected in detail by an remotely operated vehicle [20]. These were the already described shoals as well as the coastal part where the construction of a new coastal structure is planned.

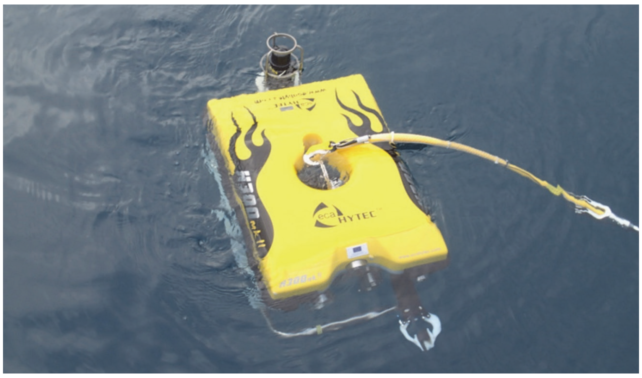

Figure 3. Remotely operated underwater vehicle (ROV) (photo: Č. Benac)

During the seabed survey, continuous video recording was carried out, and in some places also photography. By using an appropriate computer program on a monitor on the vessel named Hidra, the position of the remote operating vehicle in geographic coordinates was visible, as well as the relative position of the ship and that device. It was also possible to monitor video recording in real time. The entire system was connected to the ship's primary and secondary navigation.

After that, a targeted survey of parts of the seabed was carried out using scuba diving equipment. It was found that the shallows are predominantly rocky, i.e., outcrops of carbonate bedrock are visible on the surface. The inspected parts of the seabed were photographed. In the depressions between the shallows, the bedrock is covered by sandy sediments several meters thick (Figures 4 and 5).

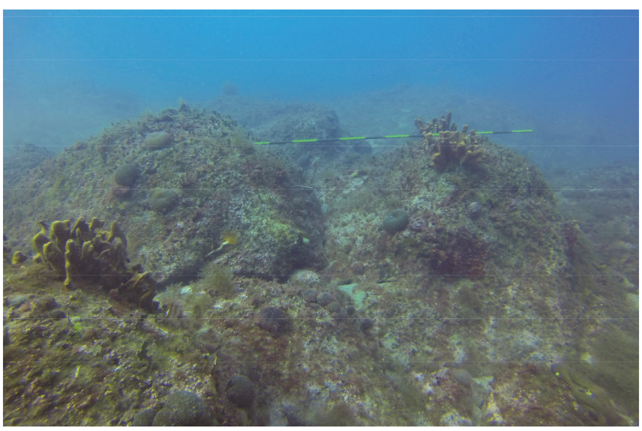

Figure 4. Outcrops of carbonate bedrock in shallow 1 (photo: Č. Benac)

Based on the results of the underwater survey using an autonomous underwater vehicle and geological mapping, a geological map was created in the scale of the new bathymetric map 1:2,000. Outcrops of carbonate bedrock are visible in two isolated zones. One zone includes shallow no. 1, and the other shallows no. 2 and 3 (Figure 6.)

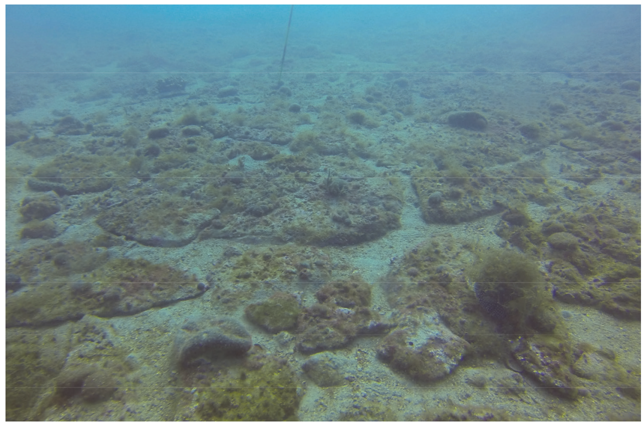

Figure 5. Outcrops of carbonate bedrock in shallow 3 (photo: Č. Benac)

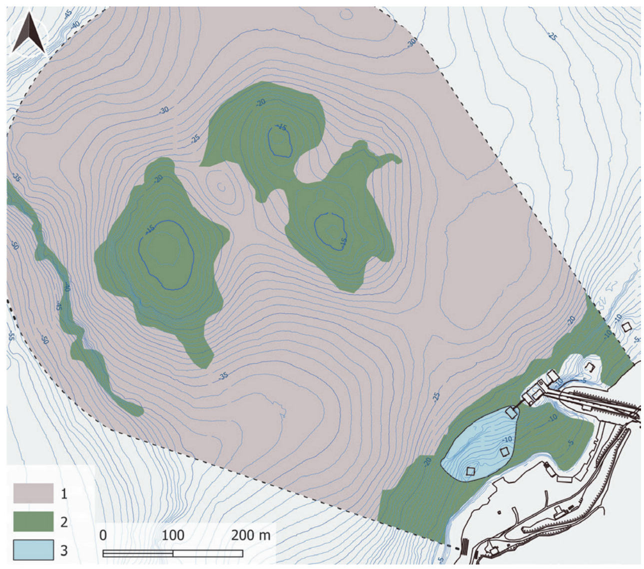

Figure 6. Engineering geological map of the marine part of the LNG terminal, according to [22]: 1 – marine sediments (sand and silt), 2 – carbonate rock visible on the seabed, 3 – embankment (fragments and blocks)

Based on the correlation with the geological fabric of the nearby land, it could be concluded that the carbonate rock mass consists of three lithogenetic units. These are dolomitic limestones and Upper Cretaceous breccias ($K_2^{1,2}$), rudist limestones of the Upper Cretaceous ($K_2^{2,3}$) and Paleogene limestone breccias (E_3Ol_1) [23]. Since the extraction of samples of the rock mass was not planned, it was not possible to determine the geological boundaries between the listed lithostratigraphic units It was visible on the outcrops that the rock mass is in some places extremely fissured and karstified. Based on the results of previous investigation, it was known that the intense karstification reaches several tens of meters below sea level [24].

2.3. Subsequent geotechnical investigations

During the deepening of the seabed, exploratory drilling and laboratory analysis of samples was carried out. Exploratory drilling was performed from a floating platform. The method was rotary drilling with continuous coring. The drilling profile was 101 mm. In shallow no. 1. four boreholes were drilled (BH-1, 2, 3, 4), in shallow no. 2 two boreholes (BH-5, 6), and in the shallow no. 3 no drilling was done (Figure 7). The depth of the boreholes was 3 m into the bedrock. Based on the engineering geological classification, three lithogenetic rock types were established: Paleogene limestone breccias, dolomitic limestones and breccias, as well as rudist limestones of the Upper Cretaceous [25]. Such lithostratigraphic types are also visible on the nearby mainland [22, 23].

Laboratory tests were performed on six rock samples from the core selected from each bore [25]. Dry density was tested on two samples. It was 2.65 g/cm³ (BH-1) and 2.58 g/cm³ (BH-2). Rock strength testing was performed on cores from boreholes BH-1 to BH-5 using the *Point Load Test* (PLS) method. The calculated uniaxial compressive strength value was USC = 70.5 – 86.5 MPa. A standard uniaxial compressive strength test was performed on the core from the BH-6 borehole, and the value obtained was USC = 54 MPa. These are common values for carbonate rocks in the Rijeka Bay area [8].

Figure 7. Photos of the boreholes (B-2 in shallow 1 and B-5 in shallow 2) [25]

3. Excavation and backfilling

Based on the Maritime Study, it was determined that the depth of the seabed should be 14.40 m for safe maneuvering of the ship [18]. Taking into account the expected irregularities that occur during excavation and backfilling in engineering practice, as well as the possible long-term sedimentation of particles due to the action of waves and seawater currents, it was finally determined that the minimum depth should be 15.0 m. In order to harmonize the geodetic maps of land and sea constructions, it was determined in the project that the heights are expressed in the HVRS71 system. Since the difference between the geodetic maps in the HVRS71 system and the hydrographic zero is 32.2 cm [21], it was adopted that the minimum deep of the seabed should be -15.40 m [27].

After the excavation contours were drawn on the 1:2,000 isobath map, it turned out that the most excavations will be in shallow 1, and the least in shallow 2. The total calculated excavation volume for all three shallows was 8,500 m³. Considering the expected working conditions and the inaccuracy of the underwater excavation, the estimated amount of the excavation volume was around 11,000 m³, i.e., 7,500 m³ at the location of shallow 1. The project stipulates that the excavated material will be backfilled in a sufficiently large depression between the shallows. The estimated total volume of the embankment was about 15,000 m³ (Figure 8).

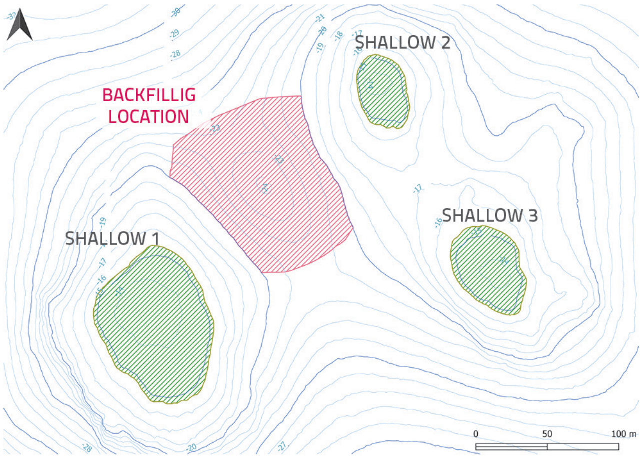

Figure 8. Excavation and backfilling locations, according to [27]

On the basis of the engineering geological map, made on a bathymetric map with a scale of 1:2,000, it was established that excavations for the purpose of deepening the seabed to a depth of 15.4 m according to HVRS 71 will be carried out in a solid carbonate rock mass (Figure 6).

Figure 9. Vessels at the location of shallow 1 [28]

In the preparation phase, the water area was marked by installing temporary navigation marks, and then the geodetic marking of the excavation and backfilling area was carried out, as well as the positioning of the vessel. The works are planned so that the excavation is carried out in one shallow area. After reaching the designed depth, all vessels with equipment will be moved to the next location (Figure 9).

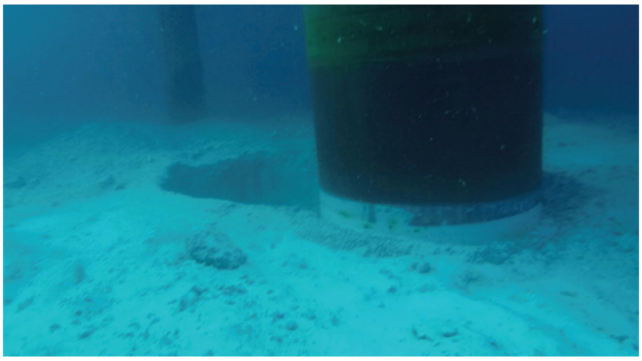

Figure 10. Excavation using a drill [28]

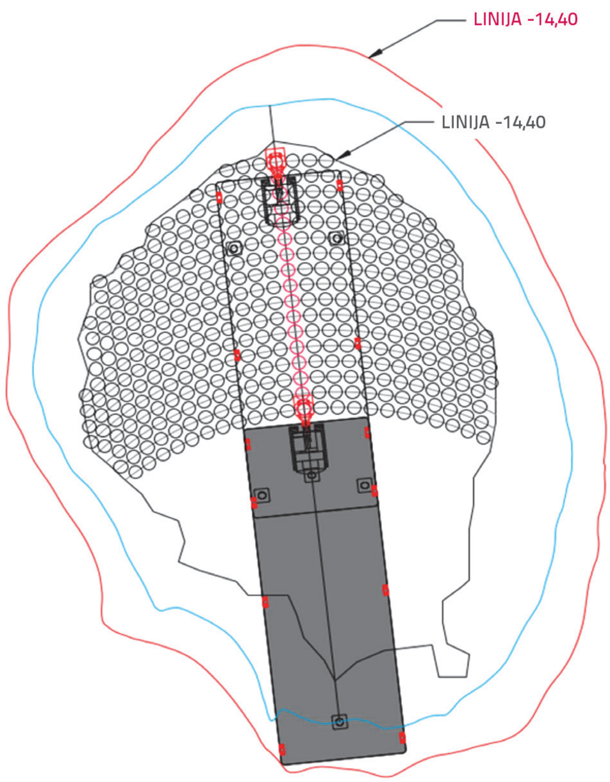

Figure 11. Presentation of the excavation using the drilling method in shallow 1, according to [28]

Since the excavation of the rock mass using explosives was not allowed, based on the results of the exploratory drilling and laboratory analysis of the samples, which is described in chapter 2.3, an excavation methodology was developed using the classic way of breaking and excavating the rock mass using a pneumatic hammer, a heavy mallet with a specially shaped head and hydraulic milling machine [28].

It turned out that at the beginning of the work, the amount of excavation was only 18 m³/day. That is why a new technology was developed using a drill with a diameter of 1,800 mm, whose average drilling speed was 60 cm/h. That machine was intended for pile performance at the LNG terminal pier. Drilling was done 35 cm deeper than the depth required by the project (Figure 10), and according to a precisely determined scheme (Figure 11).

After the completion of the drilling, the rock mass was broken and crushed using a pneumatic hammer and a "rocket" (Figure 12 and 13). After that, the rock mass was additionally crushed using a hydraulic milling machine (Figure 14).

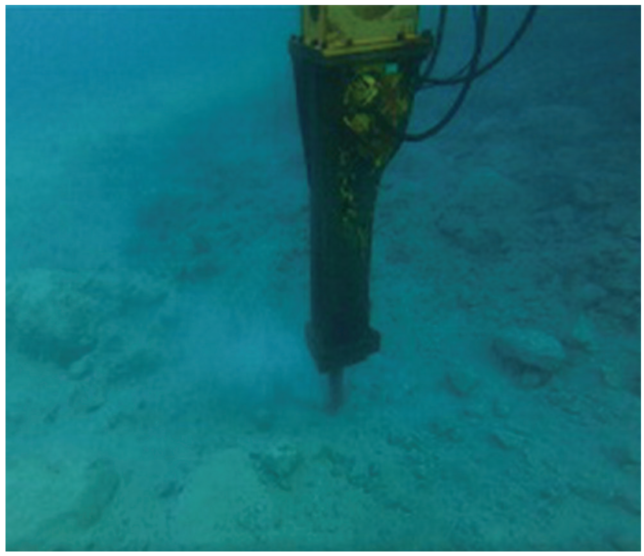

Figure 12. Excavation using a pneumatic hammer [28]

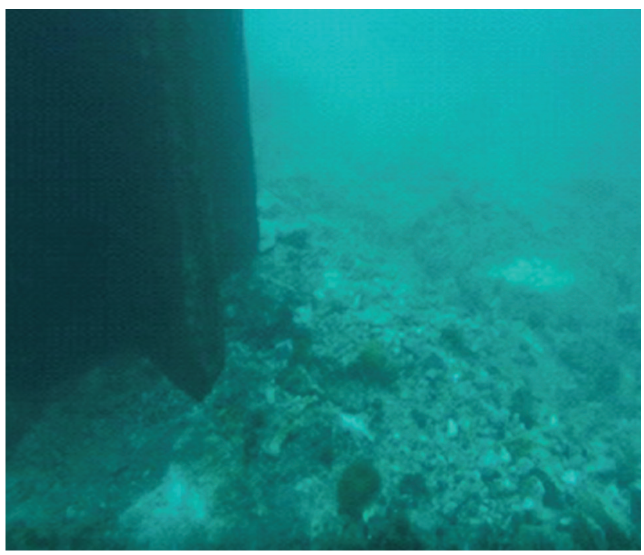

Figure 13. Excavation using a heavy mallet with a specially shaped head, the so-called "rocket" [28]

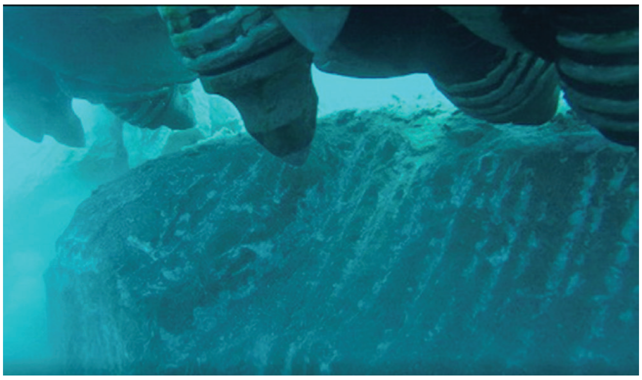

Figure 14. Insufficient efficiency of excavation using a hydraulic milling machinee [28]

With the described change in technology, an average daily excavation of 25 m³/day was achieved, and maximum up to 35 m³/day. In this way, it was possible to complete the works by the agreed deadline. In order to be able to remove the excess excavated material between the bores, drilling was done 35 cm deeper than the planned excavation deep. During excavation with a hydraulic milling machine, part of the material filled the bottom of the bores. Thus, the amount of drilled material was greater than the amount of material removed up to the planned deep.

Backfilling in the depression between the shallows was the optimal solution for disposing of excavated material (Figure 8). Backfilling was carried out so that the excavated material was loaded onto a hopper barge, the bottom of which, after positioning over the required place, opened and discharged the excavated material (Figure 15).

Figure 15. Loading of excavated material in a hopper barge [28]

In addition to the usual expert supervision during construction, divers with scuba diving equipment participated as well. The supervision of the vessels was carried out by the Harbor master's office Rijeka. Due to the application of the described technology, the work on deepening the seabed lasted longer than if the use of explosives had been allowed. The start of the works was in December 2019, and the completion in February 2021. After the completion of the work on the deepening of the seabed in the intervention area, the depth of the seabed was measured and a hydrographic report of the determined state was made, according to which the nautical charts will have to be adjusted.

4. Discussion

Although the shoals were visible on the topographic map of Croatia at a scale of 1:25,000, it was only through hydrographic surveying of the seabed that the exact relief was established at the scale of the map at 1:2,000. Based on the Maritime Study [18], all three shoals were declared dangerous for navigation and therefore had to be excavated to a depth of 15.4 m according to HVRS 71.

It has been shown that using ROV and scuba diving equipment, a sufficiently precise engineering geological map of the seabed can be created. It was then established that the excavation would be performed entirely in a relatively solid carbonate rock mass. As part of the research works, detailed undersea geophysical tests were carried out using the delta-V-t method of shallow seismic in the area of the vertical coast of the mooring. For this reason, these data were used in the assessment of rock mass characteristics such as strength and degree of fissuring. The data obtained from additional research during 2020 from only six shallow boreholes are point-based and may not be representative for designing the optimal excavation method. Namely, the measured RQD index in the boreholes varied from 0 % to 75 %. Based on engineering geological mapping of the excavation area, the distance between fissures is 5 to 100 cm, which is equivalent to RQD = 20 to 95 %. The uniaxial compressive strength test was performed using the PLT method (ASTM D5731) on five samples (72 to 87 MPa) and the uniaxial compressive strength test with the modulus of elasticity (ASTM D7012-14) was performed on one sample (54 MPa), the average value is 75 MPa [26]. Identical tests were performed on a larger number of samples for the needs of the extension of the pier for the LNG terminal in the same lithostratigraphic units and in a zone of similar structural-tectonic fabric. PLT was tested on 27 samples, and the range of estimated uniaxial compressive strength is 59 – 99 MPa (average 80 MPa). Uniaxial compressive strength testing with modulus of elasticity was performed on 11 samples, and the range of uniaxial compressive strength is 45 – 119 MPa (average 77 MPa) [22].

The table for determining the method of excavation based on the data of uniaxial compressive strength and distance between cracks, or RQD index, is very useful [29]. The data obtained based on the examination of a large number of samples show that the carbonate rock mass has such characteristics that the excavation should be partially done by previous blasting, and in other parts by machines and equipment used for heavy digging and light digging. In contrast, the data obtained on the basis of a small number of samples from boreholes in the shallows [25, 26] show that the rock mass can be excavated mostly with light digging equipment, and a smaller part with heavy digging equipment (Figure 16).

However, the described methods and data on the speed of progress when deepening rocky shallows show that these other data were not realistic (Figure 14). Because of this, it was necessary to change the excavation technology by using a drill with a diameter of 1,800 mm to facilitate the breaking of the rock mass.

From the photos taken during and after the excavation, the complete destruction of the biocenosis on the rocky seabed, and the biocenosis of the sandy seabed was also destroyed by backfilling. This is a total area of about 12,500 m^2 (Figure 17).

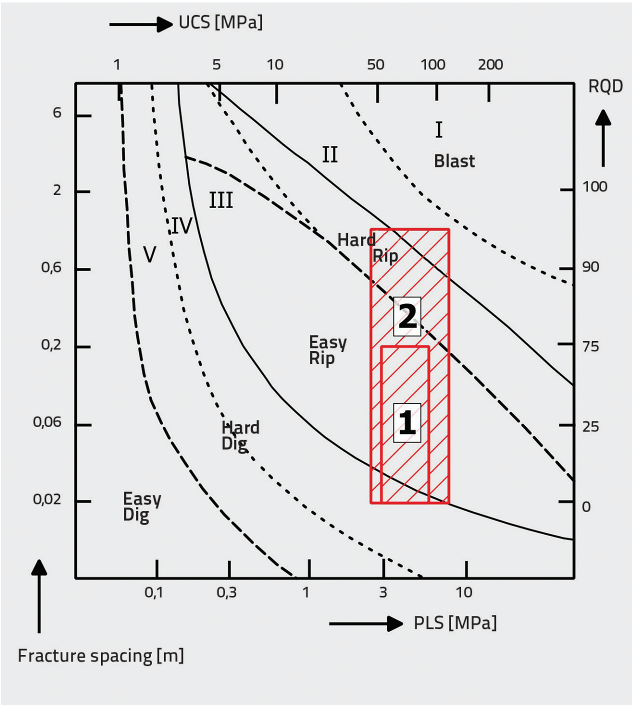

Figure 16. Comparison of rock mass excavation possibilities: 1 – results of laboratory analysis in the narrow excavation area; 2 – results of laboratory analysis on a wider excavation area (according to [29])

Figure 17. Seabed after excavation [28]

In the Non-technical summary of the Environmental impact for assessment report, it is stated: "The impact of shallow deepening and backfilling is not only limited in scope, but also short-lived and reversible. More precisely, immediately after the intervention, a new equilibrium state of restoration will begin, and in 1-2 years at the latest, the marine biocenosis will reach the state resembling the original biocenosis as it was before impact. All this also applies to the material from the excavation, mainly rocky fragments, which will be deposited in a defined location and function as a new attractive substrate for living organism " [30]. From a scientific point of view, it would be interesting to periodically monitor the rate of colonization of organisms. These data can be extremely important for assessing the impact of similar construction interventions on the environment.

5. Conclusion

Geodetic surveying of the seabed established the exact relief at a map scale of 1:2,000. Three shoals dangerous for navigation were determined, which should have been lowered to a depth of 15.4 m according to HVRS 71.

Through engineering geological mapping of the seabed, application of hydroacoustic measurement techniques and inspection using an remote operating underwater vehicle and scuba diving equipment, it was established that the excavation will be carried out entirely in a relatively solid carbonate rock mass. After the excavation contours were drawn on the 1:2,000 isobath map, it turned out that the most excavations will be in shallow 1, and the least in shallow 2. The total calculated volume of excavation in all three shallows was about 11,000 m^3. The project stipulates that the excavated material will be backfilled in a sufficiently large depression between the shallows. A total of about 15,000 m^3 of rocky fragments and blocks was backfilled. It is one of the largest underwater excavations carried out in a rock mass in the area of the Croatian part of the Adriatic Sea.

Excavation using blasting was not allowed. Therefore, based on the results of exploratory drilling, laboratory analysis of samples, as well as the results of geophysical tests using the delta-V-t method of shallow seismic in the area of the mooring, an excavation methodology was developed using the classic method of breaking and excavating the rock mass using a pneumatic hammer, a "rocket" and a hydraulic milling machine. However, it turned out that the strength of the rock mass was greater than predicted, and the result was the slow progress of the works. For this reason, a new technology was developed using a drill with a diameter of 1,800 mm, before the classic way of breaking and excavating the rock mass. This significantly accelerated the work.

Such extensive works in the seabed inevitably caused ecological damage by complete destruction of the biocenosis on the rocky and sandy bottom on the surface of about 12,500 m^2.

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