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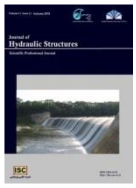

Investigating the settlement of the stone boulders breakwater located on the marine soft fine-grained soil

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Abstract

Stone boulders breakwaters are the most widespread and widely used type of breakwaters. if the foundations of these structures do not have sufficient bearing capacity, large settlements will await the structure. Since the construction of these projects is expensive, and the supply of suitable stone resources are essential for the construction of these projects, a relatively good prediction of the stone materials volume used in the project is important. Therefore, a research project was carried out at Siyadi Port breakwater, (Iran) utilizing geotechnical data and construction observations. The objective was to create a computer model to understand the response of the clay bed to the weight of the rocks. This analysis was done by Lagrangian equations and using FLAC software and led to the selection of characteristic of soil parameters that simulated the subsidence of materials on an elasto-plastic bed. Soil resistance parameters that could not be determined through standard tests were derived through a process of back analysis. The study also investigated the effects of the thickness of the loose layer, variations in sea water levels, and the use of geotextile in the project. A large rise in settling is anticipated as the muddy soil's depth increases. Results also confirms the effectiveness of using geotextiles for settlement management. Moreover, updated characteristics of soil from the previous step in order to comprehend the construction of an entire breakwater section on muddy soil seems crucial. With this method, long-term settlements and the stability of the breakwater section may be reliably predicted.

Keywords: Settlement; Breakwater; Stone Boulders Breakwater; Soft Soil.

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1. Introduction

Marine constructions like breakwaters and coastal walls are crucial human-made structures, particularly in areas with extensive soft and unconsolidated soils along coastlines [1]. An important issue in breakwaters design is the stability [2]. Many researchers have studied behavior of breakwaters like stability and erosion using numerical analysis or experimental studies in laboratory or field [3-10]. The use of stone materials on soft land leads to significant settlements due to the absence of a solid foundation [11]. The soil's shear resistance and its ability to support structures, as well as its settlement capacity, impact the quantity of stones required for breakwaters. This can lead to increased costs, material depletion, and environmental damage. Ghaderi and Rahbani [12] believed that the accretion problem is due to the poor design of the breakwaters' layout.

This matter relates to value engineering, so if suitable geotechnical conditions are not present in non-strategic projects, it may be necessary to consider relocating ports or exploring alternative options. Therefore, it is important to comprehend the response of fine-grained bed materials, typically made up of river or sea sediments, to the loading from the construction of breakwaters. It is crucial to accurately determine the behavior of the soil against the predicted loading of the rock mass and implement appropriate solutions. The presence of rivers and channels that flow into the sea is the primary factor in the formation of fine-grained sediments along the coasts and the seabed adjacent to the coast. Mobarrez et al. [11] conducted an experiment to study the settlement of a breakwater situated on silty soil. They created a simulated sample containing silt with a moisture level exceeding the liquid limit and applied various sizes of aggregates to it. The findings revealed that smaller aggregates resulted in less subsidence, and using smaller aggregates in a thicker layer reduced the overall settlement of the aggregates. Essentially, the infiltration of aggregate material into the soil foundation is directly influenced by the diameter and thickness of the aggregates. In this study, the researchers measured the settlement of soil samples with varying moisture levels and flow limits. The findings indicated that settlement is influenced by soil moisture, with higher levels of moisture leading to greater settlement compared to liquid limit. Nagaraj et al. [13] explained as the liquid limit increases, the shear resistance decreases, and the soil moisture content also plays a role in the penetration of stone materials. According to a study by Fan [14], material subsidence increases as soil moisture reaches three times the liquid limit, leading to an increase in settlement. Beyond that point, the settlement remains constant. In addition, researchers have simulated the breakwater wall using numerical method [15].

The use of geosynthetics to manage the settling of structures has been extensively studied [16]. Many practical experiments and theoretical investigations have explored the impact of geotextiles, leading to the finding that they can reduce settlement in sludgy soil. Numerical simulations of rock penetration in muds have also demonstrated the effectiveness of geotextiles in minimizing settlement.

Additional research has indicated that when sand is poured onto mud, the mud soil acts as a non-Newtonian viscous fluid with shear strength dependent on fluid viscosity. In this scenario, the fluid infiltrates between the sand grains, altering the texture and behavior of the mixture to gradually increase its shear resistance. The extent to which mud particles penetrate the aggregate structure is influenced by particle density, stone aggregate size, and the quantity and size of voids between them [17].

Hence, according to the given information, the stone boulder breakwaters located on unstable, waterlogged clay beds experience significant settling of materials. Consequently, a research project was carried out at Siyadi Port breakwater, in Iran utilizing geotechnical research data and construction observations. The objective was to create a computer model using specialized software to understand the response of the clay bed to the weight of the rocks. Soil resistance parameters that could not be determined through standard tests were derived through a process of back analysis. The study also investigated the effects of the thickness of the loose layer, variations in sea water levels, and the use of geotextile in the project. Additionally, the research explored the behavior of the soil when the soft soil properties during construction is modified due to penetration of the rock through mud soil.

2. Method Analysis

2.1. Project description

This study is based on the ongoing project of constructing a breakwater at the Delwar fishing port on the coast of Delwar city, located on the Persian Gulf. The project involves building a stone boulders breakwater, which has been completed along 60 meters of the total 1300 meters length. Geotechnical studies included drilling three sea boreholes to depths of 30 meters and conducting in situ standard penetration tests and vane shear tests. However, due to the loose upper layer of soil, it was not possible to carry out in-situ or reconstructed tests to measure the soil's resistance parameters. The upper layer of the boreholes, excavated to a depth of 4 to 7 meters, consists of a very soft, gray-colored clay resembling mud. The SPT hammer easily penetrates this layer due to its weight. The gray-colored soft clay layer, containing approximately 50% carbonate, falls under the category of calcareous mud and calcareous, and is classified as lean clay (CL) according to the Unified classification standard. From a depth of 7 meters to the bottom of the borehole, loose to semi-dense silt and sand in a light brown color were observed, becoming very dense beyond 9 meters. These layers are categorized as unified SM and ML. In the BH-3 borehole, a layer of gray SP-SM sand was observed at a depth of 7.5 to 9 meters. Generally, granular layers of suitable density were observed from 8 to 9 meters deep. Crushed shell fragments were observed in the upper layers up to a depth of 7 to 7.5 meters. Table 1 shows the soil characteristics in BH-1 borehole, the closest borehole to the research site.

Table 1. Soil profile sample in BH-1 borehole, the closest borehole to the research site

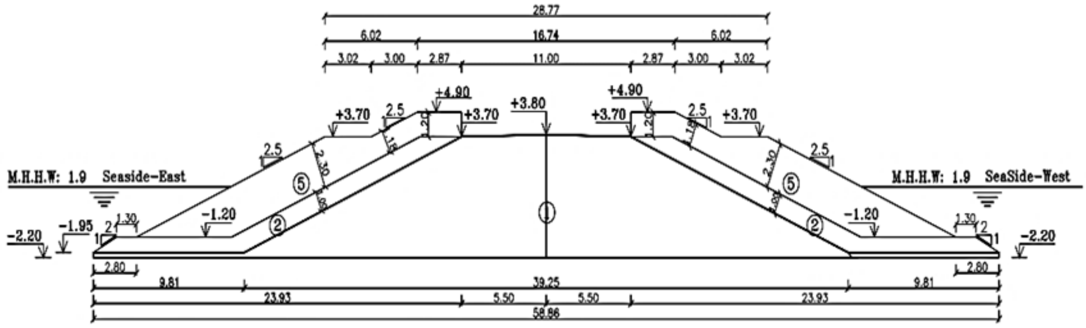
No	Depth(m)	Unified Classification	LL	PI	Cc	Cu	D_{100} mm	D_{60} mm	D_{30} mm	D_{10} mm
Bh-1	2.2-2.5	CL	32	11	-	-	9.51	0.006	-	-
Bh-1	6.7-7.0	CL	35	13	-	-	0.15	0.005	-	-
Bh-1	8.7-9.0	ML	NLL	NPI	-	-	2	0.008	0.001	-

Table 2 displays the properties of the soil in the top two layers of the bed. The extreme softness of the clay made it impractical to conduct in-situ tests or laboratory remolding, so the figures provided are estimates from the consulting company.

Table 2. Consultant's recommended parameters for soil type

Soil properties	Classified soil		
	Very soft clay	Soft clay	Unit
Depth	0-4	4-7	m
Interior friction angle (ϕ)	15-20	20-22	Degree
Cohesion (C_u)	0.07	0.2	kg/cm^2
Elasticity modulus (E)	10-20	30-40	kg/cm^2
Poisson's ratio (μ)	0.45	0.45	-
Density (γ)	1.75-1.85	1.8-1.9	gr/cm^3
OCR	1	1	

The breakwater (Figure 1) being constructed on the seabed close to the shore is made of locally sourced stone materials and is comprised of three layers: core, filter, and armor. The core layer consists of stones weighing between 1 and 100 kg each, the filter layer contains aggregates weighing between 200 and 500 kg, and the armor layer consists of stones weighing between 1500 and 3500 kg. The maximum void space between the stones in the armor layer is 37%, while the other layers have approximately 30% void space between the stone aggregates.



L= 95m	Area(m²)
CORE	157.22
FILTER	41.36
ARMOUR	71.16

TYPE	NAME	WEIGHT	D_{50}	SPECIFICATION
1	CORE	1-100	---	%50>25
2	FILTER	200-500	0.5	%50>350
5	ARMOUR	3000-3500	1.18	%50>3400

SECTION A-A
0+625-0+720 m sc:1/200

Figure 1. Breakwater section

There is no update on the project's progress along the coast up to a distance of 560 meters from the project's starting point. Between this point and a distance of 620 meters, it is evident that the quantity of stone materials utilized in the project exceeded the originally estimated amount outlined in the project plans. Consequently, the contractor raised concerns about significant settling of the bed during execution, prompting the use of settlement measuring devices to verify the bed's settlement. The device, depicted in Figure 2, comprises a 100 x 100 cm metal plate with a perpendicular index rod welded to it. These plates are positioned at various locations on the bed, and the height of each point is measured and recorded at regular intervals using a leveling instrument.

Figure 2. Index of settlement plates and erection at sea

Table 3 and Figure 3 display the longitudinal and transverse placement of the settlement measurement tools, while the transverse arrangement of settlement plates is depicted in Figure 3(a). The outcome of multiple measurements taken at various times is illustrated in Figure 3.

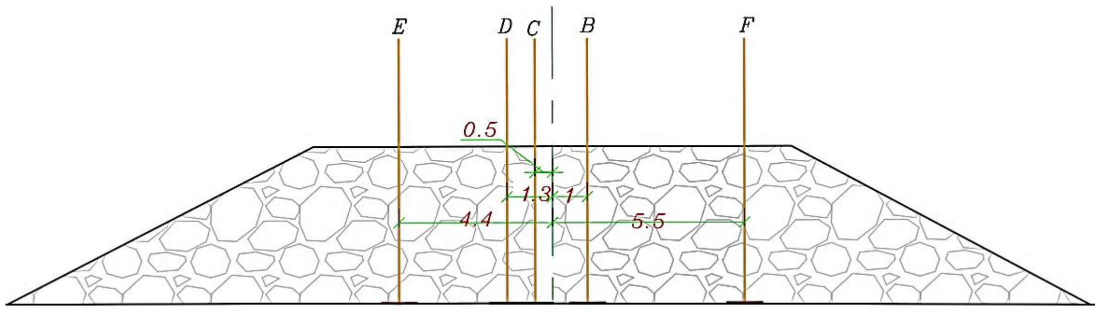
Table 3. The longitudinal and transverse placement of the settlement measurement tools

Gauge	Distance from symmetry axis	Distance from project starting point
B	1	586
C	0.5	597
D	2.3	605
E	4.4	620
F	6.2	622

2.2. Preliminary modeling and back analysis to determine parameters of soft clay layer

The consulting engineers' predicted results were significantly different from the actual observations. As a result, it was determined that the research would involve using the FLAC 2D program to model and assess material settlement, investigate soil behavior under loading, and derive the influential parameters in soil resistance through a back analysis. The Mohr-Coulomb model was employed for this modeling. The settlement measured by settlement plates and the quantity of materials utilized in the project were used as criteria to attain the desired outcomes.

In this simulation, a layer of loose clay measuring 4 meters was placed on top of the soft clay model, with the water level set at mean sea level (M.S.L.). Loading was then gradually and stepwise applied to the soil. The core layer's load was incrementally applied to the soil, and after analyzing and determining the mechanical characteristics of the modeled soil through practical observations, the filter layer was loaded. Following analysis, the armor layer was then applied to the soil. Due to the significant strains experienced by very soft clay elements, when modeling a rock mass embankment on such soil, the software encountered embankment failure and was unable to provide a final answer. Consequently, it was decided to apply loads in the form of uniform and strip loads based on the breakwater's geometry. In this scenario, the soil behaves like a completely viscous substance, and the foundation, which is considered practically flexible with no rigidity, contributes to the deformation of the soil elements independently of the structural deformation above it. The load of the rock mass was calculated considering the porosity of the stone materials, and the specific mass of the pile was determined to be 1700 kg/m^3, accounting for the empty space between the aggregate pieces.



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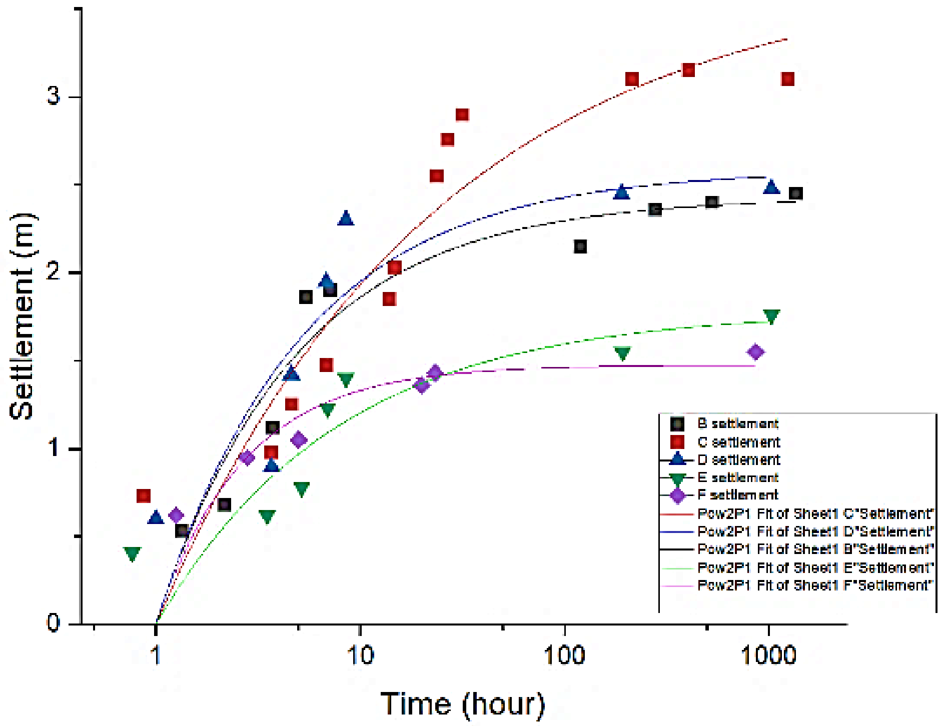


(b)

Figure 3. (a) The position of settlement plates (b) comparison of measured settlement vs time

The graphic representation of the model generated by the software is depicted in Figure 4. To align the software-generated model settlements with the actual measured settlements, the trial-and-error method was employed by adjusting the soil parameters. The initial parameters suggested by the consultant for the very soft clay were the internal friction angle of 15° to 20°, cohesion (c) of 7KN/m^2, and elasticity modulus (E) of 1.0MN/m^2. The investigation involved keeping the cohesion and elasticity modulus constant while varying the internal friction angle parameter to observe the settlement amount.

This process continues until the model fails. At the failure threshold, the settlement value is assessed. When this value does not match the measured settlement on the site, the internal friction angle and modulus of elasticity are kept constant while the cohesion value is adjusted. These adjustments are made until the model reaches the failure threshold, but the threshold does not accurately predict the settlement. Consequently, the modulus of elasticity is reduced until the model reaches the failure threshold, resulting in increased settlement values and ultimately model failure. However, the settlement value is still less than the average observed at the site. The cohesion parameter is then reduced again to match the average observed value. To validate the results, the horizontal and vertical settlements from the analysis are compared with the recorded settlement volume at the construction site.

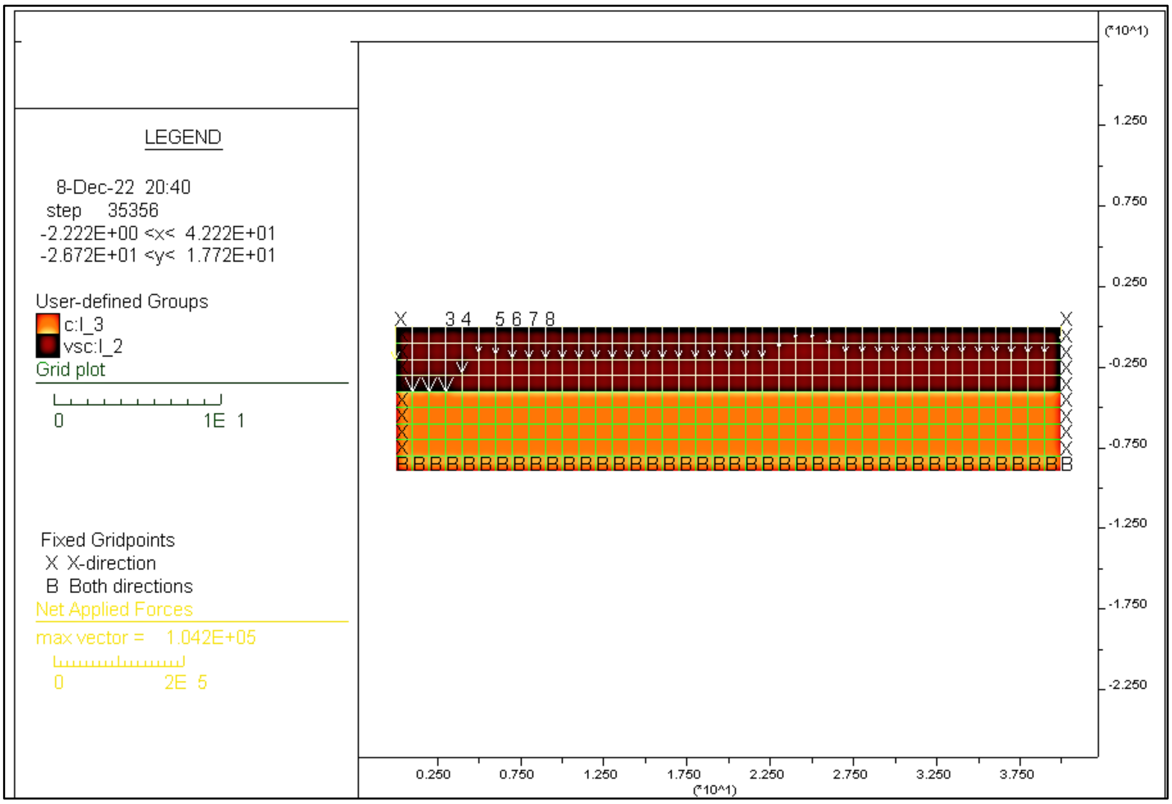


Figure 4. The model designed to apply the primary load during the initial phase of construction.

2.3. Other modeling methods

The question at hand is the potential range for adjusting the parameters selected in the previous step. To address this, a sensitivity analysis was conducted on the parameters obtained from the back analysis to determine the extent of possible changes. This involved keeping two parameters constant, such as the cohesion and the angle of internal friction, while varying the third parameter, modulus of elasticity, until the model reached the breaking threshold. Similarly, the initial parameters were adjusted again by keeping two other parameters constant, such as the modulus of elasticity and cohesion, and varying another parameter, the internal friction angle, to reach the rupture threshold. The potential for adjusting the cohesion was also explored in a similar manner.

To examine the impact of tidal changes in water levels on the breakwater settlement, the modeling process was repeated with adjustments made to the water level and soil pore pressure. Based on findings from geotechnical studies, which identified a sludge layer depth ranging from 4 to 6 meters across the project site, the modeling was updated to account for varying thicknesses of loose soil, and the resulting material subsidence was re-evaluated. The study maintained consistent core uniform load and other parameters. To assess the influence of geotextile on material subsidence, a model was created with the application of a geotextile layer using a cable that lacks bending resistance and only withstands tensile force [18]. The model includes following specifications for these materials: modulus of elasticity: 550 MPa, ultimate tensile strength: 125kPa, ultimate compressive strength: 0 MPa, cross section: 2x10^{-3} m^2, visible perimeter: 2m, internal friction angle: 30°. During the construction, one of the leveling plates experienced stage loadings, causing a 3.75-meter subsidence of the material.

2.4. Complete breakwater modeling

In all the situations mentioned above, the authors of this research attempted to simulate real model conditions. However, the loading has only been carried out with the final height of the dike cross-section during coring and with the upper width of the trapezoidal cross-section of coring. This resulted in settlement, causing a significant portion of the material to sink into the bed soil. When the loading of the final cross-section is added to the same modeling, the modeled environment does not converge, and the amount of deformation becomes infinite, making it impossible for the software to balance the forces.

In many previous studies, the entire cross-section of the breakwater has typically been initially modeled and the displacement of the elements/nodes has been calculated. However, in practical scenarios, the sinking of materials into the mud bed results in the bed reaching a certain level of relative strength, serving as a foundation for the breakwater structure. This means that material subsidence slows down to some extent, and the behavior of the mixed stone and mud materials becomes more akin to the elasto-plastic environment of traditional soils. As a result, a new model was developed, and based on the findings from the previous analysis, a bed with updated properties was defined (Figure 5).

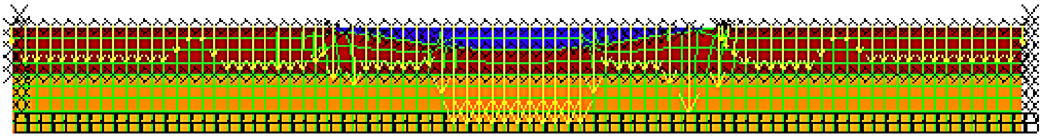


Figure 5. Simulating the impact of a complete breakwater load and updating the mechanical requirements for the settled area in the nearby community.

3. Analysis of the results

When stone materials are poured onto silty soil, the soil breaks up and the materials sink into it, behaving similarly to the suspension of solids in high viscosity fluids [13]. The behavior cannot be accurately represented in the modeling carried out in FLAC software, but a continuous environment with plastic soil flexibility properties is modeled. This study is a case study and cannot be universally applied to all regions. To create a comprehensive model, it is necessary to gather information from similar projects and estimate the mechanical characteristics of their materials so that this type of modeling can be generalized for similar soils.

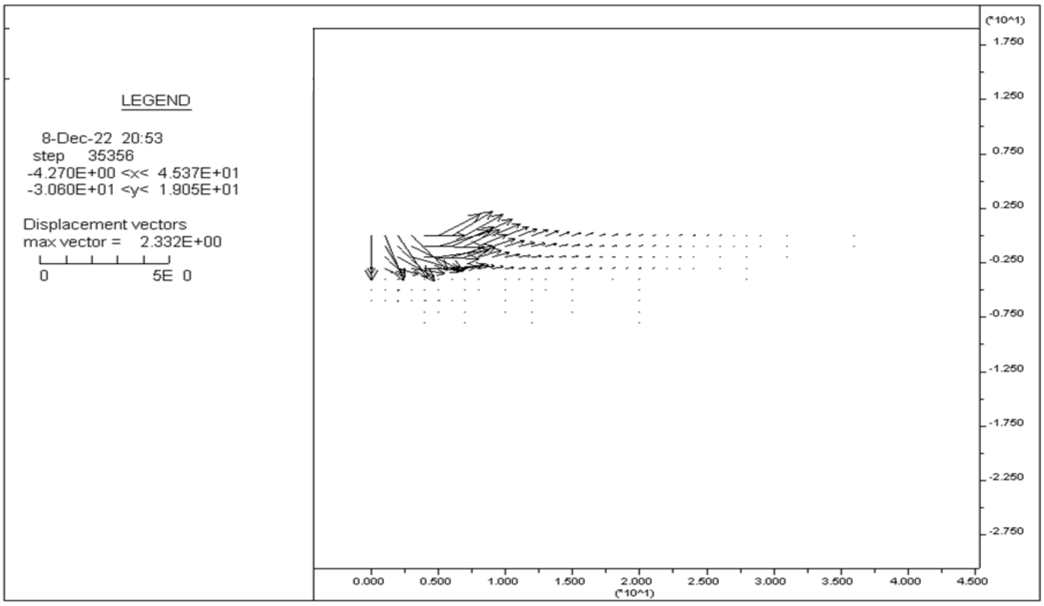
3.1. Comparing the results of the analysis and the actual reports of the site

The findings from the construction of the primary section of the breakwater suggest that settlement increases during the loading of this section. Once the core is finished, the rate of settlement decreases over time and approaches a horizontal line, referring to Figure 3(b). However, the measuring instrument has limitations as it only indicates settlement at one point in the cross-section, and this measurement cannot be extrapolated to the entire loaded cross-section. Furthermore, due to the limited number of measurement plates, comprehensive information about all parts is not available. Therefore, it is essential to integrate the monitoring of the materials used with the measured point settlements to achieve a more precise modeling. To reach such significant deformation, the soil being modeled must have a low modulus of elasticity, as well as low cohesion parameters and internal friction angle to produce the best results. Based on this, the soil resistance parameters were determined as follows: $\phi'=5$, $c=0.11$ kN/m^2, $E=1$ kN/m^2.

Table 4. Comparison of settlement from site measurement and analysis

Length of project	65	m
Average of designed Section	152	m^2
Designed volume	9880	m^3
Built volume from base level	9679	m^3
The volume of materials used according to the site report	13840	m^3
The volume of material settlement according to the site report	4161	m^3
The volume of material settlement according to the analysis report	3533	m^3
Settlement percentage in site	43	%
Settlement percentage by analysis	35.7	%

In Figure 6 and Table 4, the vertical settlement in the coring section during breakwater construction are compared to the settlement obtained from the analysis results. It is hard to say that the settlement curve that was produced by software analysis accurately reflects what actually occurred in practice because of the discontinuity of the data derived from the settlement plates. Based on the results of modeling, the materials are moved horizontally in addition to vertical movement. This can be seen in Figure 6(b). In Table 4, the volume of materials immersed in the sludge from the measurements at the site and the results of the analysis are compared.



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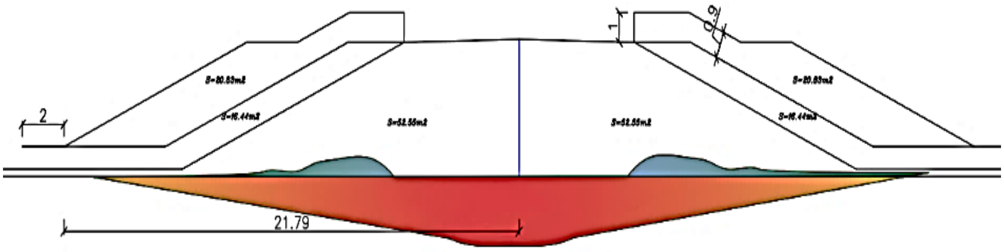

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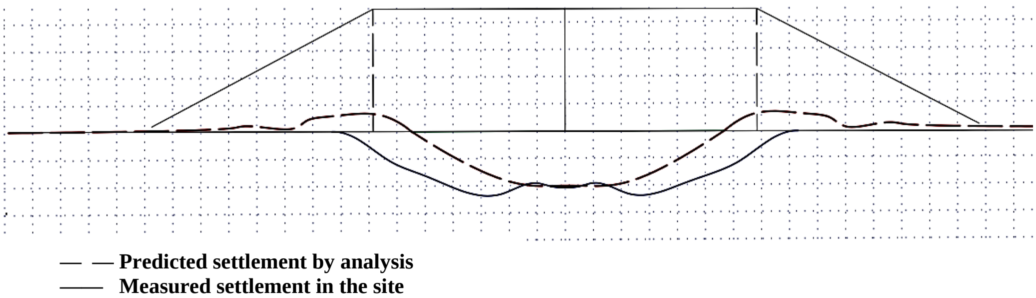


(c)

Figure 6. Measurement of breakwater settlements in modeling (a) displacement of the nodes in the model after completing the core construction phase (b) profile of vertical and horizontal settlement in core with respect to the whole section of the breakwater(c) comparison of vertical settlement measured by settlement plates and settlement obtained from analysis

3.2. Sensitivity analysis

The results of the sensitivity study indicate that the c and φ parameters have a narrow sensitivity range, with just a 2% variation. The modulus of elasticity falls within this sensitivity range of 20%. The coefficient of variation of the modulus of elasticity and the coefficient of variation for the internal friction in this study are in agreement with the findings of [19]. The sensitivity analysis shows that the coefficient of variations of these parameters are as follows: COV(ϕ′) = 2°, COV(c) = 2 kN/m^2, COV(E) = 20 kN/m^2.

3.3. Settlement variation with water surface level variation

During the construction of the project, the difference between the settlement at the time of the tide was not measured because it could not be measured. The results of the analysis show that during the shortest tide (the water level is 2 meters above the bed level), the settlement is a maximum of 2.5 meters. During the highest tide (water height compared to the bed level is 3.8 meters), the settlement is estimated to be 1.4 meters. Such measurement requires the use of specific and accurate tools. But the effect of water level on the amount of settlement was included in the modeling. The findings show that during the shortest tide, the settlement increases. This issue can be explained due to the lower pore water pressure. For this reason, at the time of the highest tide where the water level on the surface of the bed is higher, the settlement decreases. Figure 7 shows the difference in bed level changes. Mud wave tops are getting shorter as a result of the rising water level.

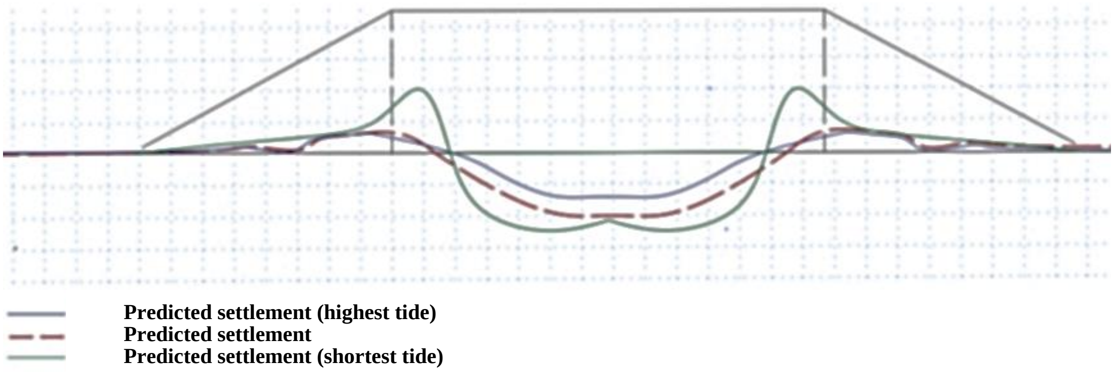


Figure 7. Comparison of bed level changes against water level changes

3.4. Settlement against thickness of loose soil

Measuring the settlement is crucial because the thickness of loose clay fluctuates along the project's longitude profile. The quantity of settlement varies with changes in the loose soil's thickness. Figure 8 demonstrates how the loose layer's thickness increases the settlement. Thus, it can be argued that stone material essentially penetrates to the surface of the second clay layer especially when the thickness of the loose layer exceeds 6 meters. Table 5 displays the settlement figures in this case.

Table 5. Settlement vs the thickness of weak layer

Mud depth(m)	Max settlement(m)
4	2.0
5	4.0
6	5.5

The findings of other studies [20] demonstrate that the bearing capacity of the soil is a function of the thickness of the loose layer, the ratio of the depth of the layer to the width of the foundation and the cohesion ratio of the two consecutive soil layers. By increasing the ratio of the depth of the loose layer to the width of the foundation, the bearing capacity decreases.

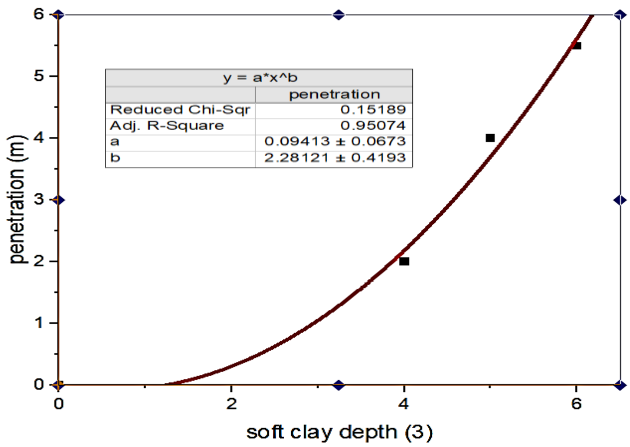


Figure 8. The diagram of settlement variation vs the thickness of the loose layer

3.5. The effect of using geotextile on the settlement

Geotextile is a commonly utilized material in practical works that is approved for its ability to reduce settlement [21]. By applying a sample of geotextile to the model in this study, the quantity of settlement was greatly decreased. Figure 9 illustrates that the maximum settlement is limited to a maximum of 70 cm. In actuality, geotextile is a fabric that, because of its high tensile strength, can withstand the tension in its cross section caused by vertical stress from loading without collapsing the materials.

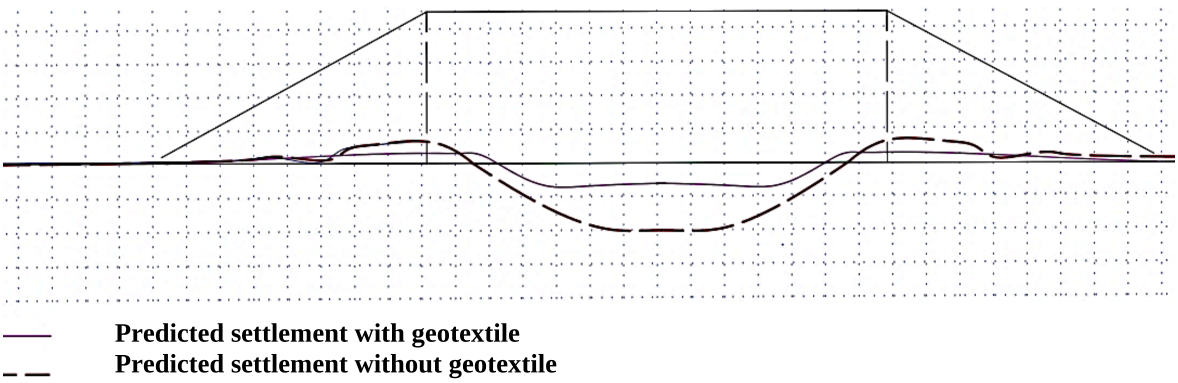


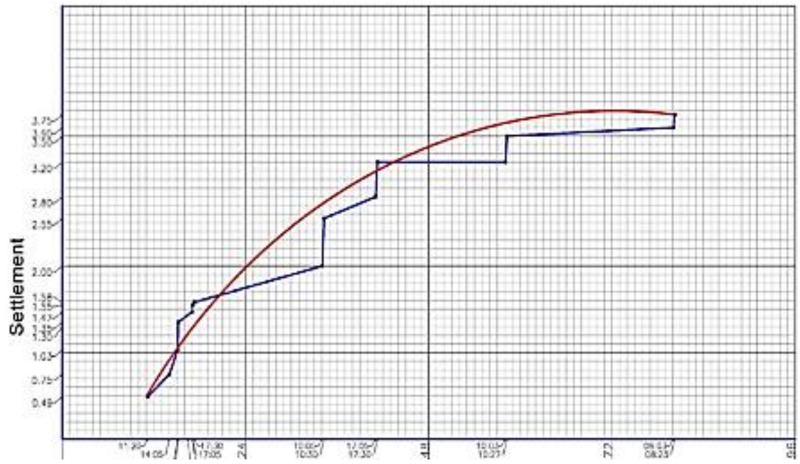
Figure 9. Comparison of settlement with and without geotextile application

3.6. Stage loading

As seen in Figure 3.1, the loading in the present modeling is based on the full height of the breakwater core up to the top of the breakwater and with full width.. There are two methods used to pour stone materials in place during construction: using a truck to pour the materials directly, or using an excavator to move the stone materials from the depot to the construction site. If the materials are poured gradually across the width, we will witness less settlement than if they are poured locally and in a huge volume all at once, as the former scenario causes large settlements. One explanation for this could be that the lateral resistance of the soil increases as the material sinks into the loose layer of mud because the properties of the newly formed material, which is made of both stone and mud, change. Additionally, the loading in the subsequent stages is comparable to the placement of aggregates on a wide flexible foundation. Therefore, a stage loading was modeled according to the data presented in Table 6. The settlement variation diagram measured at the site due to stage loading is depicted in Figure 10(a), while Figure 10(b) displays the analysis conclusion. The final settlement in these figures is comparable and have few differences.

Table 6. Stage settlement recorded in the site

Time	Load step	Sea Level	Water Depth	Gauge	Net Settlement
11:20	0	1.1	3.1	4.51	-0.49
14:05	1	0.54	2.54	4.25	-0.75
15:10	0	0.48	2.48	3.97	-1.03
15:20	2	0.45	2.45	3.65	-1.35
16:45	0	0.6	2.6	3.7	-1.3
17:00	3	0.63	2.63	3.53	-1.47
17:05	0	0.65	2.65	3.45	-1.55
17:30	4	0.72	2.72	3.42	-1.58
10:05	0	1.2	3.2	3	-2
10:30	5	1.15	3.15	2.45	-2.55
17:05	0	0.5	2.5	2.2	-2.8
17:30	6	0.6	2.6	1.8	-3.2
10:03	0	1	3	1.8	-3.2
10:27	7	1.1	3.1	1.5	-3.5
08:03	0	0.7	2.7	1.4	-3.6
08:23	8	0.75	2.75	1.25	-3.75



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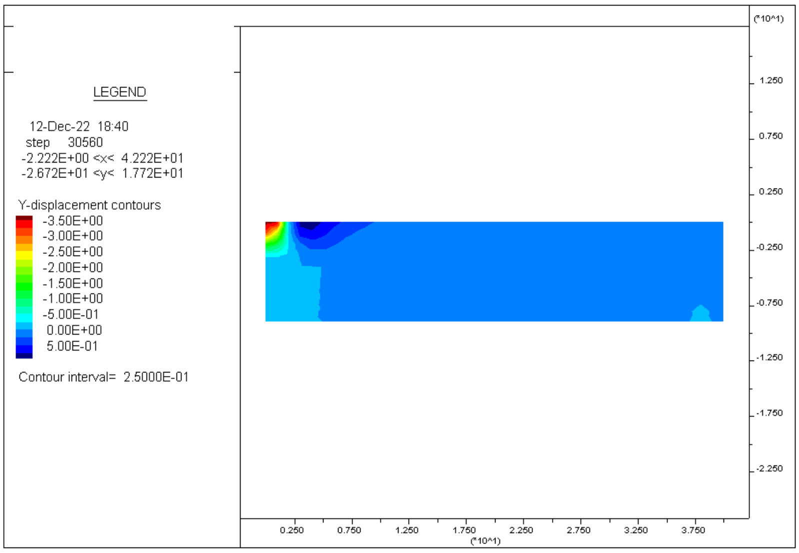

(b)

Figure 10. Settlement diagrams under stage loading (a) Recorded diagram of settlement caused by stage loading in the construction site (b) Settlement diagram resulting from modeling under stage loading

3.7. Modeling using the modification of the soft soil properties during construction

In Figure 6(c), the predicted and measure settlement does nnot coincide except in the middle of the section. In addition, during modeling, if the full load of the breakwater section is applied to the model, the soil will break and the equilibrium equations will not converge. This divergent contradicts what happens in practice. Basically, after the settlement caused by core loading was reduced, the section of the breakwater can be built based on the executive plans and all the stone layers can be implemented in place. This means that the rock material embedded in the mud creates new material that acts as a flexible foundation. During the completing of the work, the changes of the finished surfaces have been taken at different times that the modeling is made separately for this purpose, finding new parameters for the combination of mud and stone soil shows that the resistance parameters of the soil are improved.

With the method of back analysis and trial and error, the main soil parameters were estimated, which are: C=0.4 kPa, φ=30 and E=25 kPa. As shown in Figure 11, based on these parameters, settlement values can be seen in the breakwater, which are consistent with the observations of the breakwater settlement at the time of construction. In this case, the maximum settlement in the toe of the breakwater reaches about 50 cm and in the middle parts it is about 30 cm.

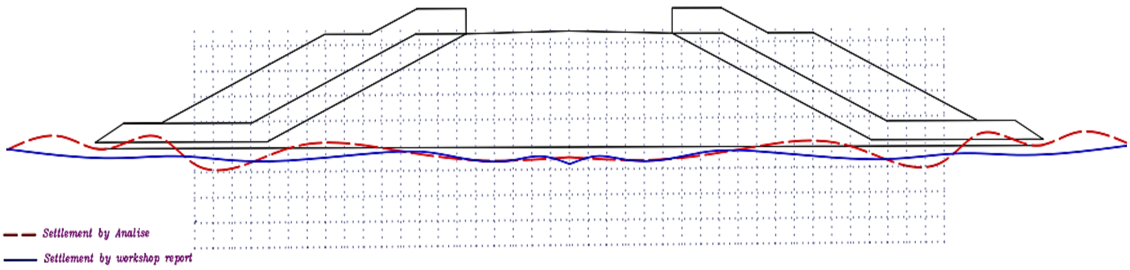

Figure 12. Modeling using the modification of the soft soil properties during construction

4. Conclusions

Installed on loose mud beds, stone boulder breakwaters sink deeply into the mud. Practical, laboratory, and numerical modeling research must be done in order to ascertain the relationship between the mechanical qualities of muddy soil and the quantity of rock material that penetrates it during construction. This must be followed by theoretical relationships. Calculating soil characteristics utilizing experimental data (during project building or laboratory models) and back analysis is required in order to use a more accurate model. Therefore, utilizing information from geotechnical investigations and construction inspections, a research project was conducted on the breakwater at Bandar Siyadi in Iran. The idea was to use specialist software to build a computer model that would show how the clay bed would react to the weight of stones. Through a back-analysis procedure, soil resistance values that are not determinable by normal tests were acquired. The impacts of variations in sea level, the thickness of loose layers, and the project's use of geotextile were also examined in this study. This study also looked at how soil behaves when mud soil infiltration causes rock to seep through soft soil during construction. The modeled soil should have a low modulus of elasticity, low adhesion characteristics, and a low internal friction angle in order to achieve such substantial deformation. According to the sensitivity analysis, these parameters' coefficients of variation are as follows:

$COV(\phi') = 2^{\circ}$, $COV(c) = 2\ kN/m^2$, $COV(E) = 20\ kN/m^2$.

The modeling results also indicate that a large rise in settling is anticipated as the muddy soil's depth increases. Additionally, it is crucial to re-model the settled materials with updated attributes from the previous step in order to comprehend the construction of an entire breakwater section on muddy soil. With this method, long-term settlements and the stability of the breakwater section may be reliably predicted. This study also confirms earlier findings about the effectiveness of using geotextiles for settlement management. Instead of dumping the materials all into one place during building, it is recommended to spread them equally and gradually around the bed using modeling stage construction.

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