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Pseudo-static slope stability analysis and numerical settlement assessment of rubble mound breakwater under hydrodynamic conditions

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Abstract

This research focuses on the slope stability analysis of rubble mound breakwaters using the Bishop method, with a specific application to the Chamkhaleh Port in the Caspian Sea region. The study emphasizes the criticality of slope stability in coastal engineering to protect shorelines from erosion and damage caused by waves and currents. The Bishop method is employed in the analysis, allowing a comprehensive assessment of breakwater stability by considering soil properties, slope geometry, and external forces. Sensitivity analysis is conducted to evaluate the impact of various parameters on breakwater stability, enabling optimization of the design and identification of potential failure mechanisms. Additionally, the research addresses numerical settlement analysis using the finite element method. The finite element method proves effective in handling complex geometries and boundary conditions, accurately capturing deformational changes caused by breakwater construction under short-term and long-term conditions. The settlement analysis results indicate acceptable maximum settlements within the project area. To ensure the reliability of the breakwater, geotechnical investigations are conducted to determine the minimum channel slope and allowable distance from the breakwater edge, crucial parameters for achieving acceptable static and pseudo-static safety coefficients. The breakwater's overall stability is assessed, and the factor of safety is quantified to evaluate the probability of slope failure and associated risks. The findings demonstrate the satisfactory stability and settlement performance of the Chamkhaleh breakwater project, affirming its effectiveness in providing coastal protection for the port.

Keywords: Slope Stability; Numerical Analysis; Rubble mound breakwater; Bishop Method; Coastal Structure

1. Introduction

Slope stability is a crucial consideration when evaluating the stability of existing slopes or implementing new ones, especially in the construction of engineering or industrial buildings (1). In coastal zones, where economic development is concentrated and a significant portion of the world's population resides, protecting the coastline from damage and erosion is of paramount importance. Coastal structures like rubble mound breakwaters have been widely used for this purpose. However, the literature reports that many breakwaters are susceptible to liquefaction and shear failure of the seabed foundation (2–6).

Rubble mound embankments are commonly constructed in coastal areas to create access roads or breakwaters. Coastal areas, particularly mudflats, often consist of soft, compressible soil (7–10). Due to the high compressibility of mudflats, significant settlement occurs during the construction of rubble mound breakwaters (11–18).

The slope stability analysis of rubble mound breakwaters using the Bishop method is of utmost importance in coastal engineering. Breakwaters serve as vital structures for protecting shorelines from erosion and damage caused by waves and currents. By applying the Bishop method, engineers can comprehensively assess the stability of these breakwater

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structures, taking into account critical factors such as soil properties (including the compressibility of soft mudflats), slope geometry, and external forces. This rigorous analysis ensures that breakwaters are designed to withstand the complex and dynamic wave forces they will encounter, allowing for long-term stability and effectiveness. Moreover, the Bishop method allows for sensitivity analysis, enabling engineers to evaluate the impact of various parameters such as soil strength, slope angle, wave characteristics, and water levels on the stability of the breakwater. This iterative process empowers engineers to optimize the breakwater design, identify potential failure surfaces or mechanisms, and implement suitable mitigation measures to enhance overall stability and performance. Additionally, the slope stability analysis using the Bishop method plays a critical role in risk assessment by quantifying the factor of safety, which helps evaluate the probability of slope failure and associated risks (19–24). This information is invaluable for decision-making, including determining appropriate safety factors, implementing reinforcement measures, and considering alternative designs to mitigate potential hazards effectively. Through the meticulous application of the Bishop method, engineers can ensure the reliable and resilient performance of rubble mound breakwaters, enhancing coastal protection and safeguarding against adverse effects of wave action in coastal regions (25–28).

2. Bishop method

The Bishop method is closely related to the Swedish Method, but it introduces the consideration of forces between existing slices. In the Bishop method, the landslide base is assumed to have a circular arc shape. To apply this method, one must first determine the slope geometry, the center point of the circular arc, and the position of the shear. The Bishop method is widely used in slope stability analysis due to its simplicity and accurate calculation of the safety factor. It is particularly suitable for automatically identifying the critical failure plane and finding the minimum value of the safety factor. This method calculates the vertical and horizontal forces by ensuring the equilibrium of each slice(29,30).

The formula for safety factor by barrier force moment:

$$R\sum W.sin\alpha = \frac{R}{F}\sum sl$$

$$SF = \frac{\sum sl}{\sum W.sin\alpha}$$

By adjusting the position of the center, it is possible to obtain the minimum safety factor with a critical circle. The presence of water or saturated soil can introduce a lifting force due to a decrease in the normal force acting on the base of the slice. Therefore, when conducting slope stability analysis, it is essential to consider the effective stress conditions. In the Bishop method, the normal force (P) acting on the base of the slice is determined by breaking down the forces acting on the slice, including the downward force (W) and the resultant force on the vertical limit of the slice in the horizontal direction. These calculations are used to determine the safety factor.

So that safety factor equation can be obtained, which is:

$$SF = \frac{1}{\sum W\ sin\alpha}\sum\left(\frac{(c.b + (w - b.u)tan\varphi)sec\alpha}{1 + \frac{tan\varphi tan\alpha}{F}}\right)$$

$$SF = \frac{1}{\sum W\ sin\alpha}\sum\left(\frac{(c.b + (w - b.u)tan\varphi)sec\alpha}{1 + \frac{tan\varphi tan\alpha}{F}}\right)$$

$$Mi = cos\alpha(1 + \frac{tan\varphi tan\alpha}{F})$$

$$SF = \frac{\sum(c.b + (w - u.b)tan\varphi)(\frac{1}{Mi})}{\sum Wsin\alpha}$$

The safety factor (SF) reflects the slope conditions and plays a significant role in assessing slope stability in various studies on slope stability analysis. According to Bowles(31), a safety factor value of less than 1.07 indicates the usual occurrence of slope collapse, FS values between 1.07 and 1.25 suggest slope collapse events that have occurred, and FS values greater than 1.25 indicate rare instances of slope collapse.

3. Study area

The study area for this research is Chamkhaleh Port, which is situated in the southwest region of the Caspian Sea. The port is geographically located at coordinates 37.2155 degrees latitude and 50.2769 degrees longitude. It currently features two rubble mound breakwaters, located at the outlets of the Shalmanrood and Langaroud rivers, with approximate lengths of 530 meters and 430 meters, respectively.

However, both breakwaters have experienced significant sedimentation over time, leading to a reduction in usable land within the water. As a result, the northern breakwater has only 190 meters of available space, while the southern breakwater retains approximately 130 meters of usable land. The sedimentation margin extends for about 2 to 3 kilometers, with a maximum width of 420 meters and a minimum width of 80 meters.

The primary objective of this study is to assess the suitability of the current breakwaters and propose potential solutions for the port's future development. One such option that has been extensively investigated is the reshaping berm breakwater, a specific type of rubble mound structure designed with a berm positioned above the designated water level on its seaward side. When subjected to wave impact, the berm undergoes a dynamic reshaping process, adopting an S-shaped profile that has been proven to be more stable than its original design. Remarkably, the "as-built profile" becomes dynamically stable under intense wave attack and naturally transforms into a more statically stable configuration (32).

Considering the significant advantages of the reshaping berm breakwater, especially in scenarios where quarrying large armor stones is challenging or heavy construction equipment is unavailable, it has emerged as a promising solution for coastal protection in Chamkhaleh Port. Furthermore, the presence of superior rock deposits near the port enhances the stability and durability of the rubble mound breakwater, making it a preferred choice. Additionally, the relatively straightforward construction process of the rubble mound breakwater compared to other types contributes to its selection. Cost-effectiveness further solidifies its position as the optimal option for Chamkhaleh Port.

Ensuring the stability and safety of the breakwater, particularly its interaction with the adjacent navigation channel, is of paramount importance in the design of the Chamkhaleh Port breakwater. Thorough geotechnical investigations were conducted to establish the minimum channel slope and its allowable distance from the breakwater edge. These crucial parameters play a significant role in achieving acceptable static and pseudo-static safety coefficients, essential for the overall performance of the breakwater.

4. Hydrodynamic condition

During wind blowing over the water surface, shear stress generated by the friction between the air flow and the water surface creates an inclined surface in the free water, resulting in an increase in water level near the coastline. Storm surges, including the phenomenon of wind-induced run-up, can cause damages in coastal areas. Storms contribute to water level rise through the formation of shear stresses induced by wind on the free water surface or the generation and propagation of waves, leading to coastal water level elevations, which can result in flooding and the creation of stagnant water areas that persist long after the storm has passed.

To prepare the bathymetric file and bed information, essential data was obtained based on existing hydrographic maps of the Caspian Sea. The depth mapping file is represented as an irregular triangular mesh with 1187 nodes and 2036 elements. The simulation area's grid refinement, as shown in Figure 2, was designed to achieve higher accuracy and resolution for obtaining more precise results within the project area.

4.1. Wind Data

To conduct wind-induced flow modeling, comprehensive time series wind data covering the entire Caspian Sea is necessary. Higher accuracy in this data within the study area will yield more precise results. However, since the reference wind data was available only in the Chamkhaleh region, it was extended to cover the entire Caspian Sea for the analysis.

4.2. Computational Grid

One of the crucial aspects of modeling hydrodynamic phenomena is the hydrographic data and the grid used in computations. Figure 1 illustrates the grid employed for modeling the wind-induced flows. As an irregular grid is used in this model, refining the grid dimensions in the study area enables a better estimation of flow characteristics in the vicinity of this region. The interpolated data, derived from the available hydrographic data of the Caspian Sea, is depicted in Figure 1.

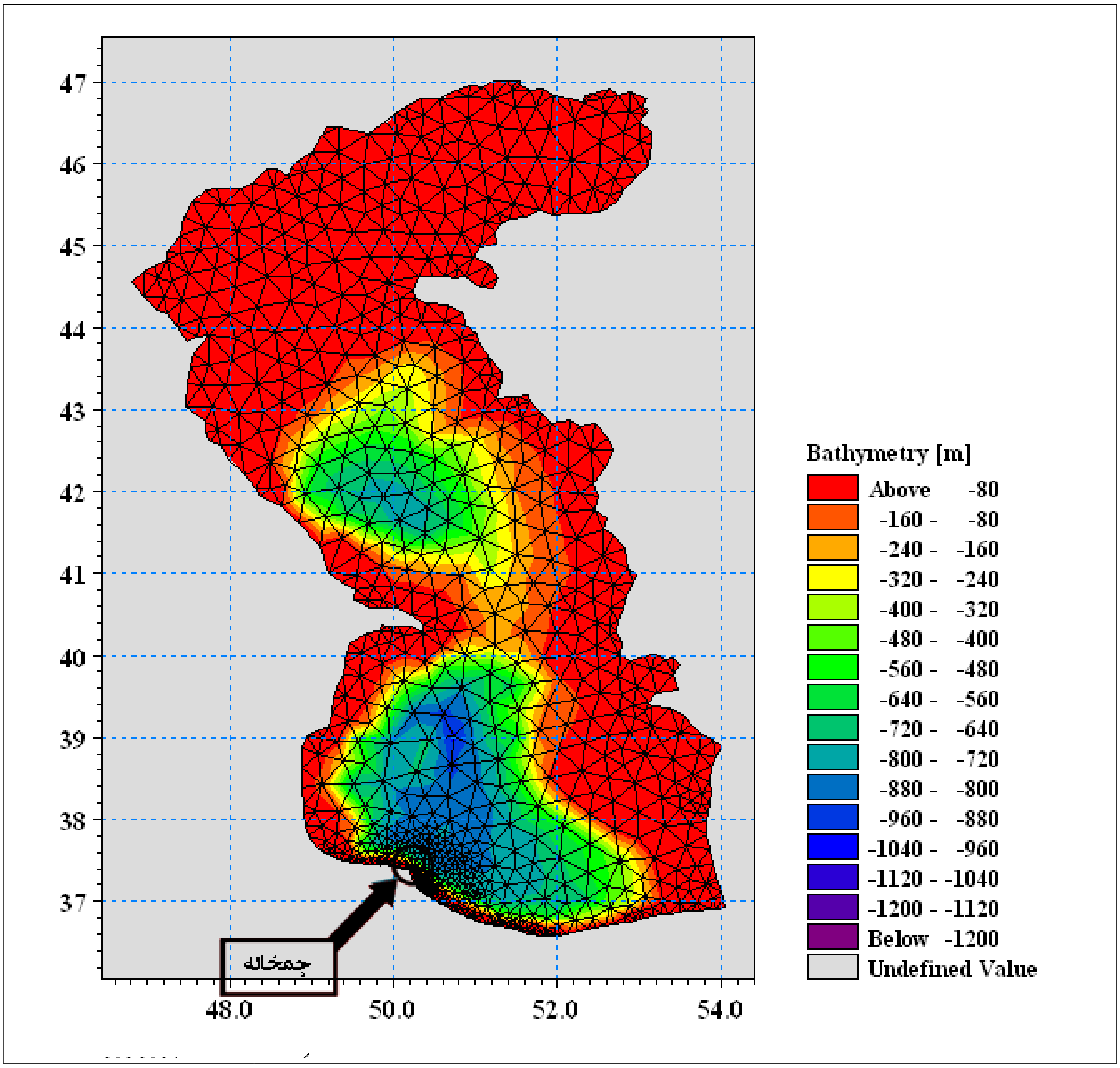

Figure 1 The modeling domain utilized for simulating wind-induced flow in the study area.

4.3. Time Step for Equation Solver

As mentioned earlier, the hydrodynamic model used for simulating wind-induced flows is an explicit finite volume model, and therefore, the choice of discretization parameters, including the triangular element size and the time step for solving equations, is of special importance. The element size used in each modeling area is determined based on the required accuracy for providing flow characteristics. Consequently, a finer grid is employed in the vicinity of the study area. After determining the grid arrangement, the time step for solving equations is obtained based on the stability criteria of the model. The critical CFL number used in this study for enhanced simulation and model stability is set to 0.08. It is worth noting that whenever possible, the time and space steps should be chosen to be similar. For the mentioned grid in the study area, a time step of 60 seconds is considered to avoid instability in the surrounding regions.

4.4. Calibration Coefficients

These coefficients include the bed roughness coefficient, eddy viscosity coefficient, and the coefficient in the equation for wind-induced shear stress. Depending on the type of flow studies performed, these coefficients can be utilized as adjustable parameters in the calibration process. As there are no measured data available for calibrating runoff and wind-induced flows in the Chamkhaleh region, calibration of the model in the project area is not feasible. Therefore, the recommended values for calibration parameters in the model are used, which generally provide a reasonable estimation of the flow conditions in the area.

4.5. Results of Simulating Wind-Driven Sea Currents

After setting up the model, the HD model was used to simulate wind-induced flow and water level changes for a period of 12 years. The purpose was to better understand the hydrodynamics of the study area. Figure 2 presents a sample of water level changes across the entire Caspian Sea at a specific time. In Figure 3, the water level changes due to wind at a location with coordinates 37.235°N and 50.2986°E, and at a depth of 10 meters, are shown as a time series extracted from the modeling results. The maximum water level changes during the simulated period were around 30 centimeters.

Another output of this modeling is determining the wind-induced flow rates. Figure 4 illustrates the calculated velocity vectors at the specified point, indicating that the wind-induced flow mainly aligns with the coastal direction within the project area. Moreover, it can be observed that the wind-induced flow velocities are generally very low, with approximately 71% of the velocities being less than 1.0 meter per second. The predominant flow direction is from the northwest to the southeast.

For estimating the design water levels induced by wind, the Extreme Value Analysis (EVA) method was utilized. By applying this method and considering different return periods, the increase in water levels was calculated for the simulated period. The results, as depicted in Figure 5, indicate that the most appropriate probability distribution was the modified Gumbel distribution, with the estimated wind-induced water level for a 25-year return period being approximately 26 centimeters.

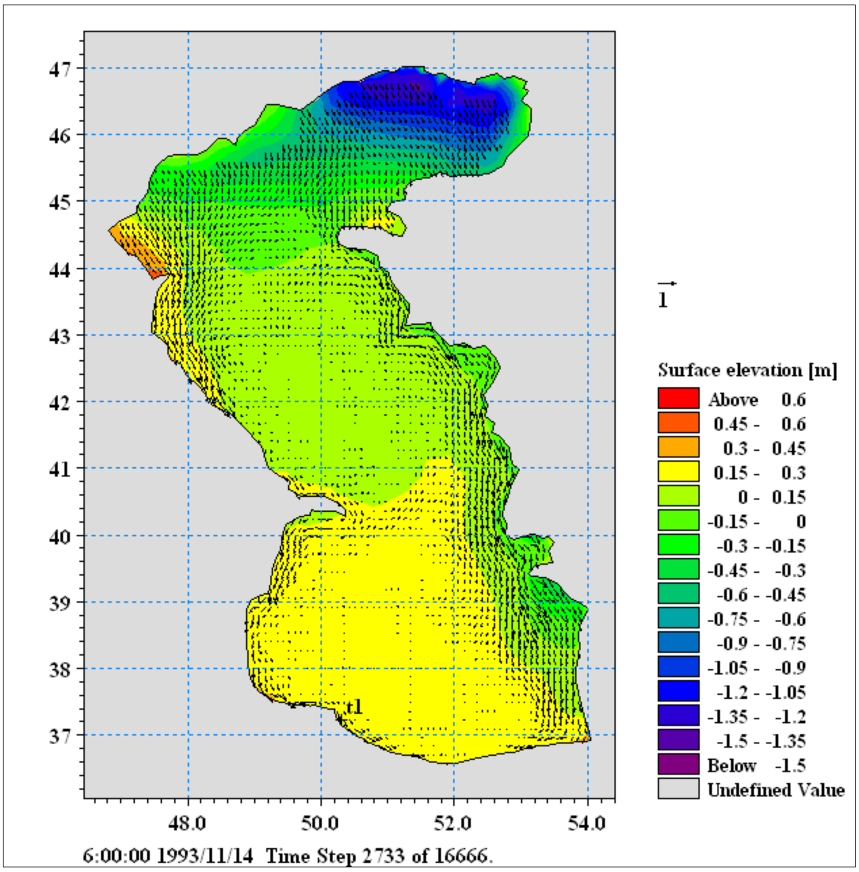

Figure 2 Water Level Fluctuations Across the Caspian Sea at a Specific Time

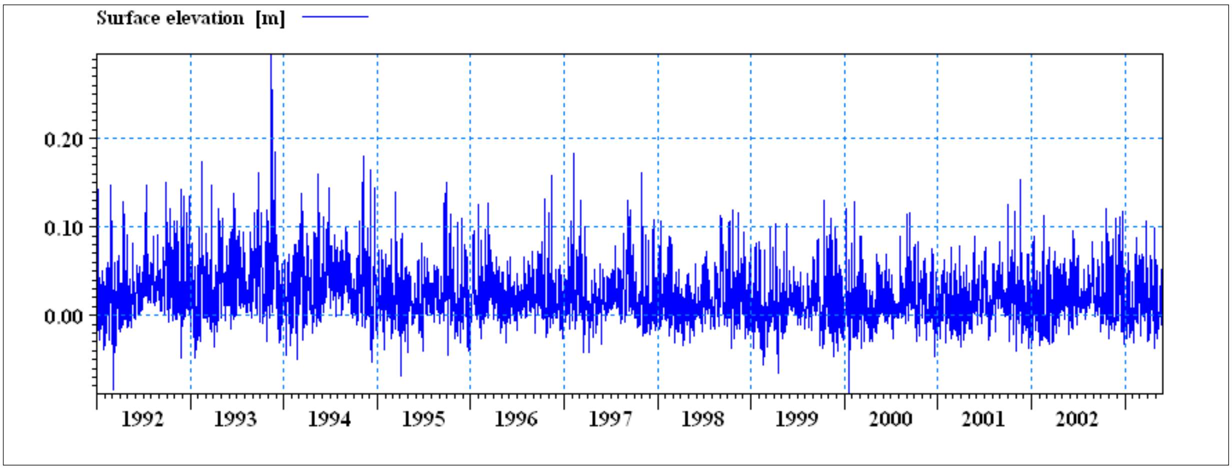

Figure 3 Wind-Induced Water Level Changes in the Study Area

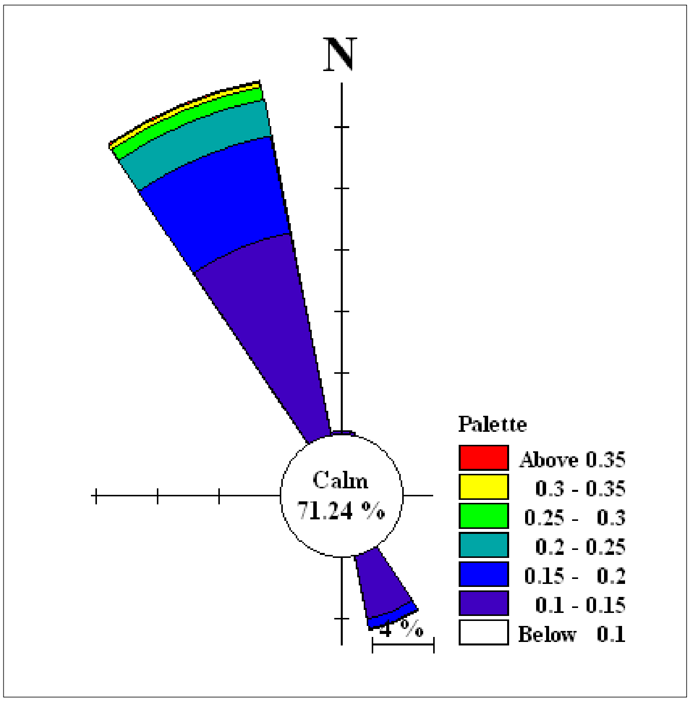

Figure 4 Flow Pattern Resulting from Mathematical Wind Modeling in the Study Area

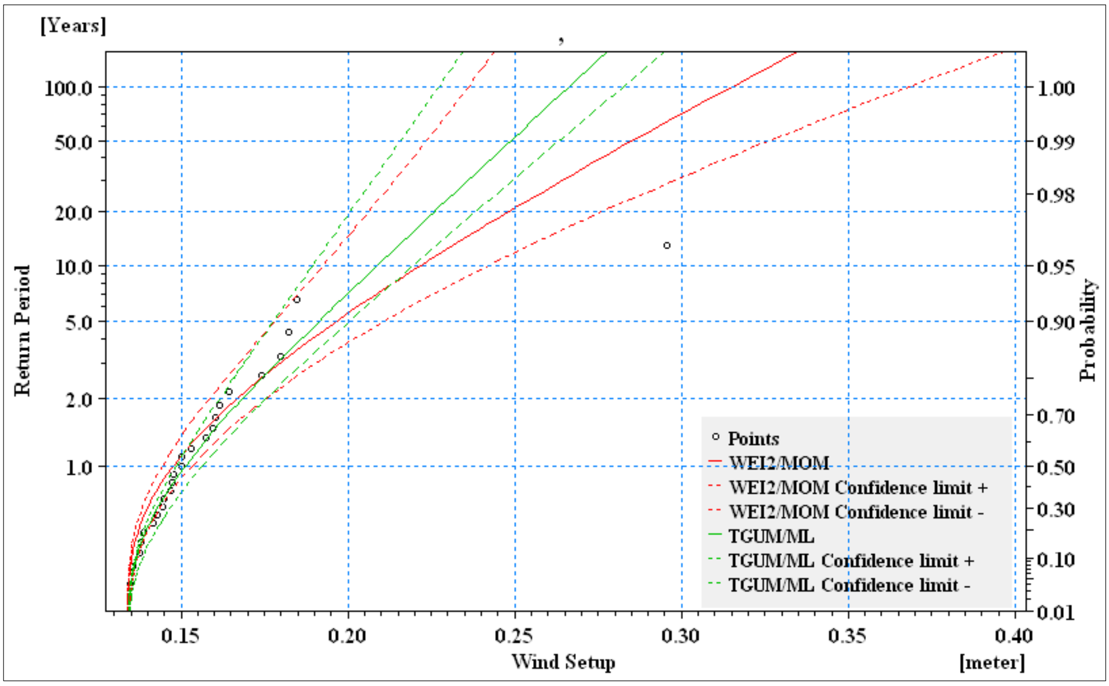

Figure 5 Probability Distribution and Magnitude of Wind-Induced Wave Runup for Various Return Periods

4.6. Total Design Level

the total water level in the Chamkhaleh region is estimated for various return periods for design purposes. Firstly, the maximum wave-induced setup in all effective directions is determined for each return period. Then, the maximum wave setup and wind setup values for each return period are directly summed with long-term changes in the water level, as shown in Table 1. For example, the total design level for a 25-year return period in the Chamkhaleh area is obtained as 1.1 meters.

Table 1 Design Water Level Values for Various Return Periods in Chamkhaleh Area

Return period [yr]	**2**	**5**	**25**	**50**	**100**
Maximum Wave Setup [m]	0.29	0.29	032	0.32	0.32
Maximum Wind Setup [m]	0.71	0.22	0.26	0.29	0.32
Maximum Long-term Level [m]	0.52	0.52	0.52	0.52	0.52
Maximum Total Level [m]	0.98	1.03	1.1	1.13	1.16

5. Characteristics of the Breakwater and Geotechnical Conditions

sections of the breakwater have been initially designed as shown in Figure 6 for the wave-ward side and Figure 7 for the lee-ward side. Furthermore, an average unit weight of 2.2 t/m^3 has been assumed for the breakwater to facilitate geotechnical analyses.

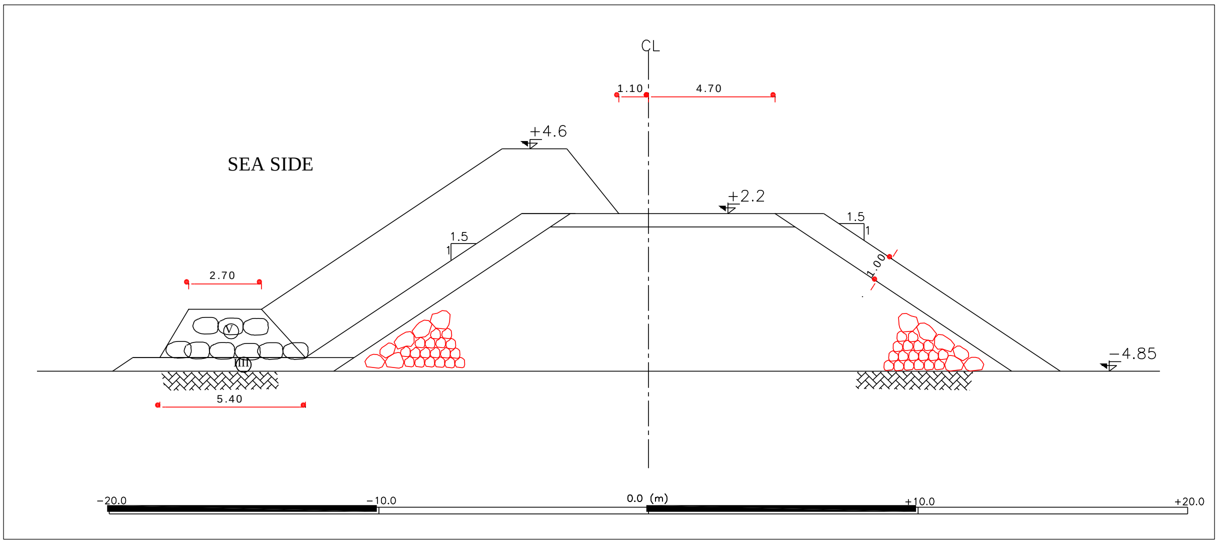

Figure 6 Cross-Section of the Breakwater (Section 1)

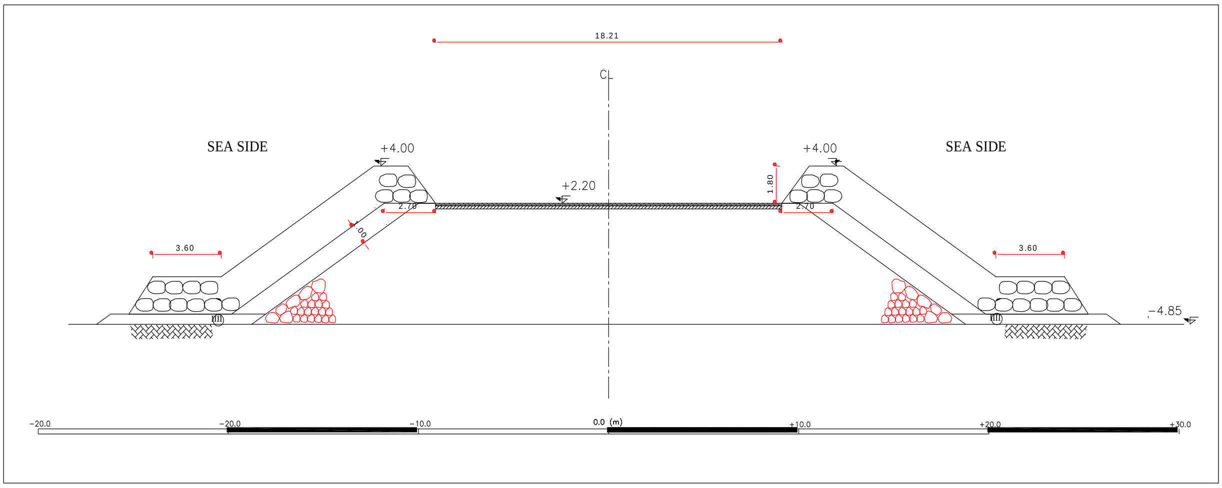

Figure 7 Cross-Section of the Breakwater in the Head (section 2)

The overall soil composition in the project area can be classified into layers of cohesive and non-cohesive sediments, accompanied by sand with varying densities from firm to hard. Based on this classification, the assumed geotechnical parameters for long-term and short-term conditions are presented in table 2:

Table 2 Subsurface Geotechnical Parameters

style	γ_{sat} (kN/m3)	c' (kN/m2)	ϕ' (deg)	c (kN/m2)	ϕ (deg)
Long Term	20	10	28	-	-
Short Term	20	-	-	100	5

6. Stability Analysis

For the slope stability analyses, the models were created using the Slide limit equilibrium software and the Bishop method, considering a distance of 10 meters from the toe of the slope to the breakwater section and a slope ratio of 1:3

(vertical: horizontal). The analyses were conducted in both static and pseudo-static states to determine the stability factors for potential sliding surfaces. By comparing the calculated minimum sliding factors with the allowable safety factors, the slope stability condition can be assessed. (33)

According to the Port and Maritime Structures Design Guideline Code, the minimum allowable static safety factor is 1.5, and the minimum allowable pseudo-static safety factor is 1.15 (34,35).

Since the main objective of this study is to investigate the overall stability and sliding behavior of the breakwater in relation to the adjacent slope, rather than the internal stability of breakwater elements, the models were configured with the breakwater represented as applied loading surfaces. In the pseudo-static analyses, the horizontal acceleration coefficient was assumed to be 2.3, and the design acceleration coefficient was set to 0.2. The results obtained from both short-term and long-term static conditions, as well as short-term pseudo-static conditions, are presented in figures 8 to 13.

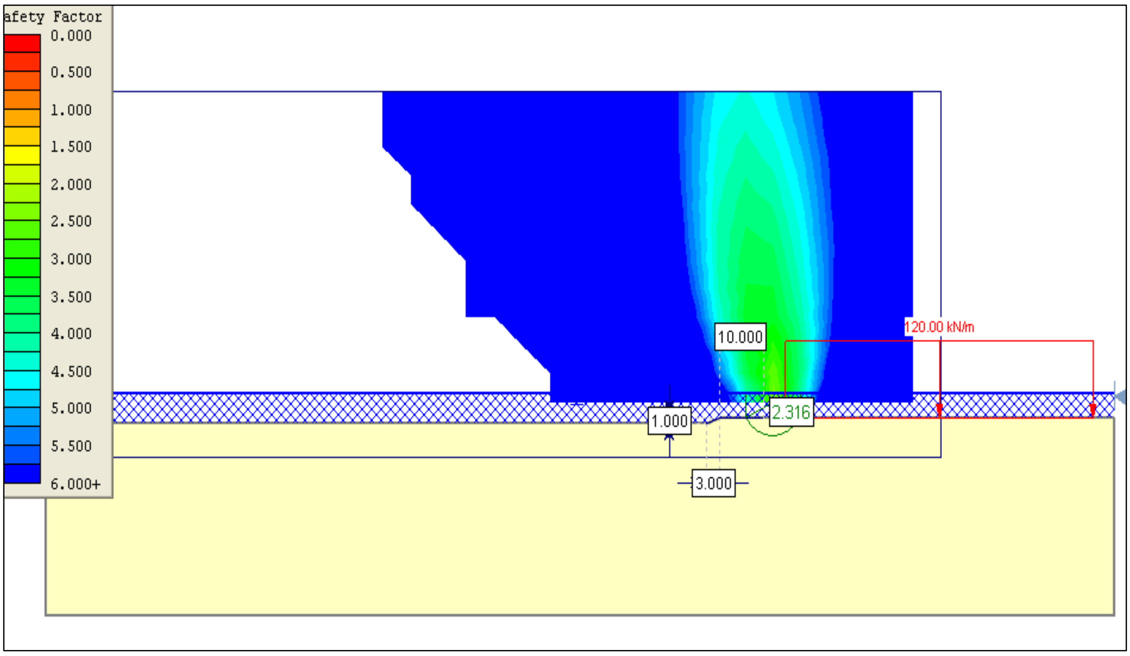

Figure 8 Cross-Section 1 Model in Static State and Long-Term Geotechnical Parameters

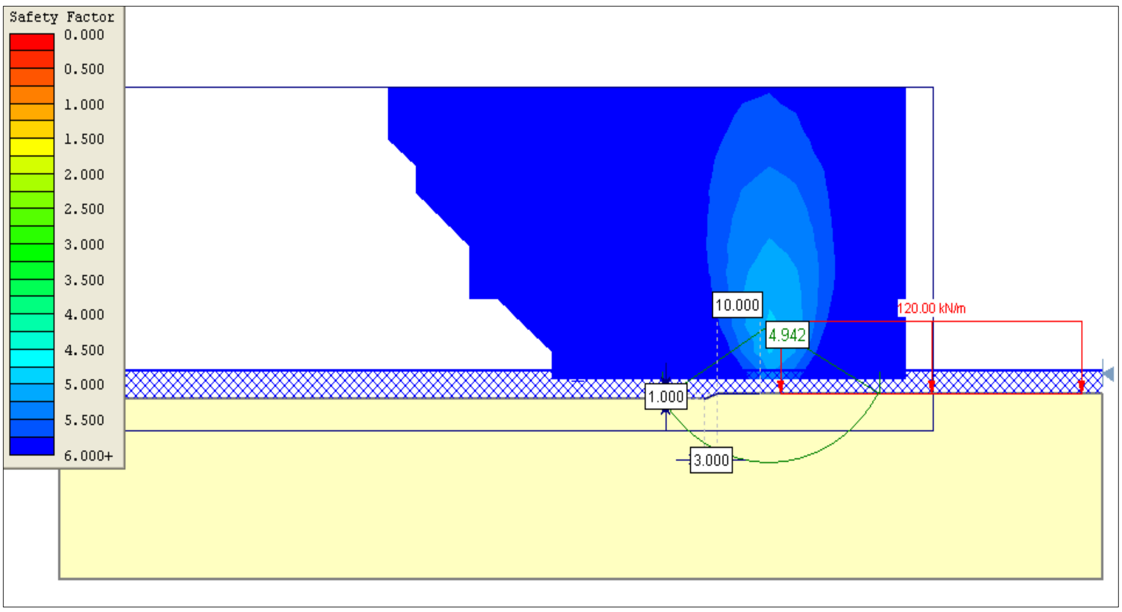

Figure 9 Cross-Section 1 Model in Static State and Short-Term Geotechnical Parameters

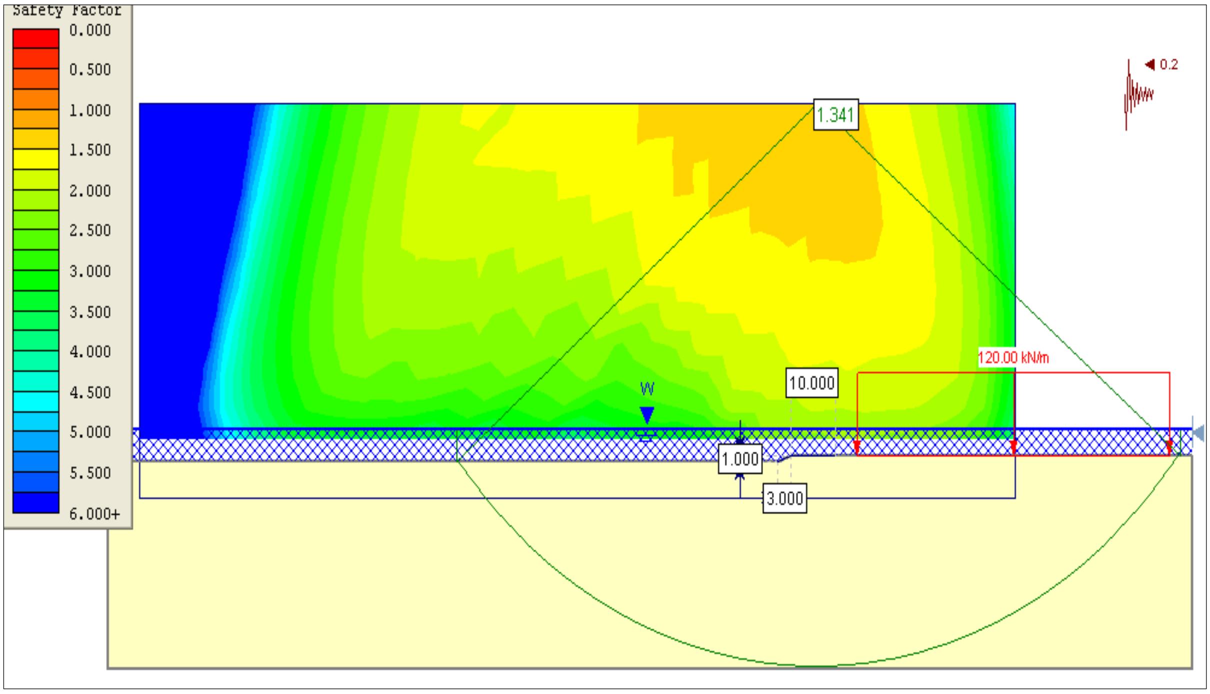

Figure 10 Cross-Section 1 Model in Pseudo-Static State and Short-Term Geotechnical Parameters

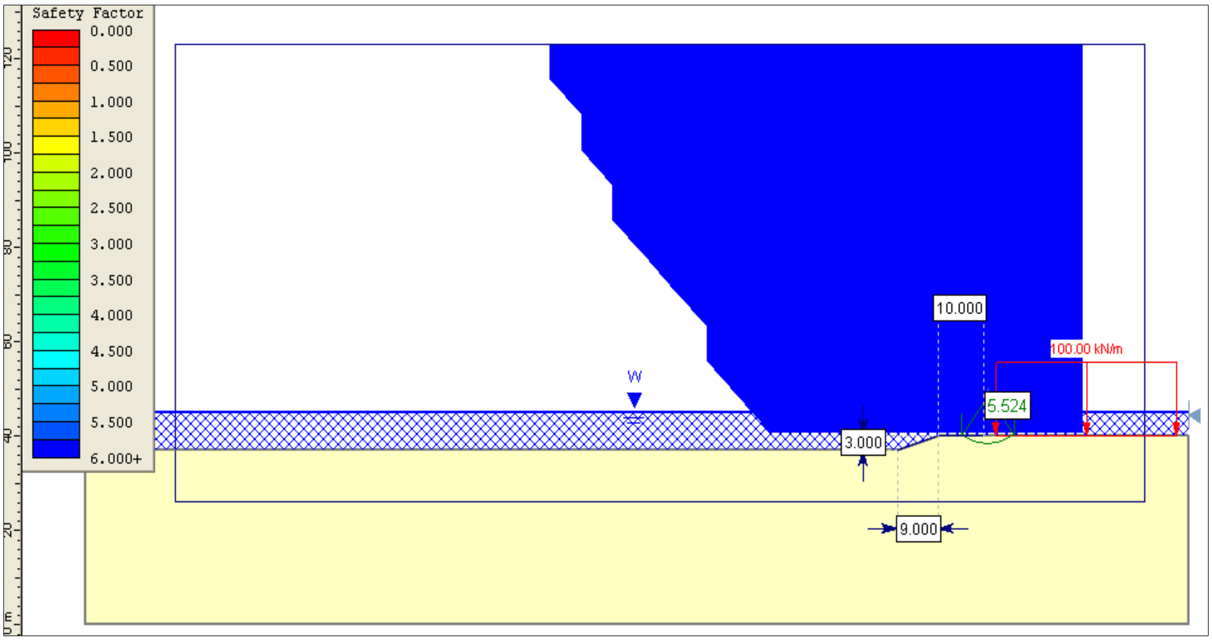

Figure 11 Cross-Section 2 Model in Static State and Long-Term Geotechnical Parameters

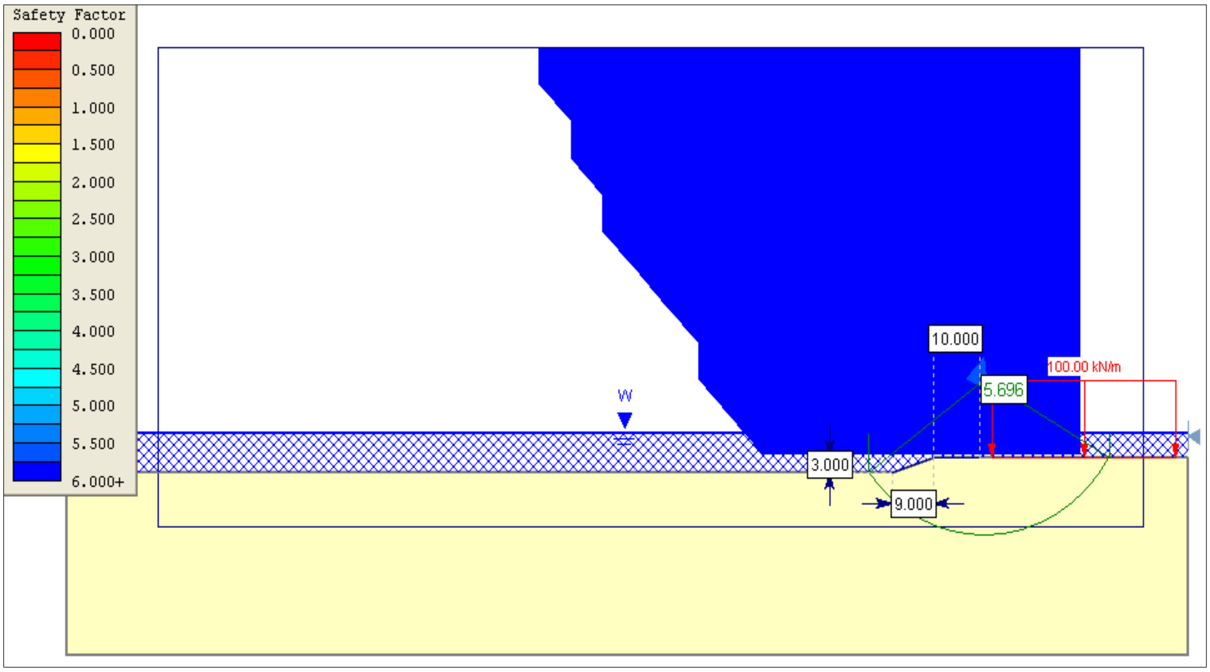

Figure 12 Cross-Section 2 Model in Static State and Short-Term Geotechnical Parameters

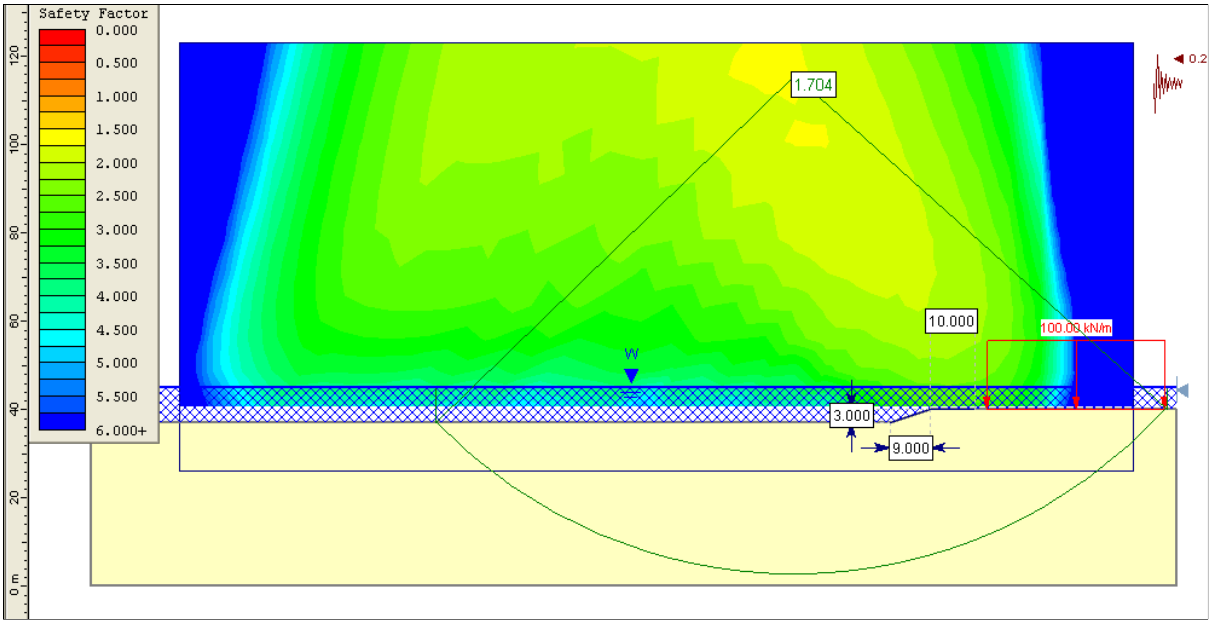

Figure 13 Cross-Section 2 Model in Pseudo-Static State and Short-Term Geotechnical Parameters

7. Numerical settlement analysis

The analysis was conducted using the finite element method, which is a numerical solution approach. Numerical methods, particularly the finite element method, offer several advantages, such as effectiveness in handling complex geometries where exact solutions may be impractical. Additionally, the finite element method can address systems with intricate boundaries and initial conditions.

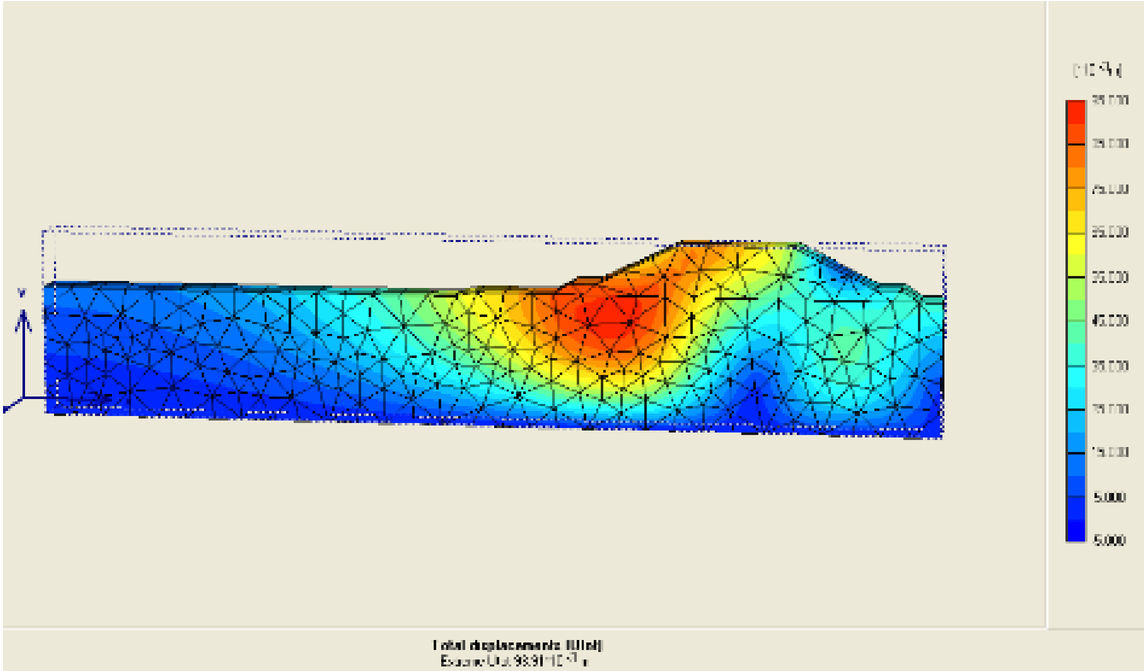

Figure 14 Deformation Zone of Cross-Section 2 under Short-Term Conditions

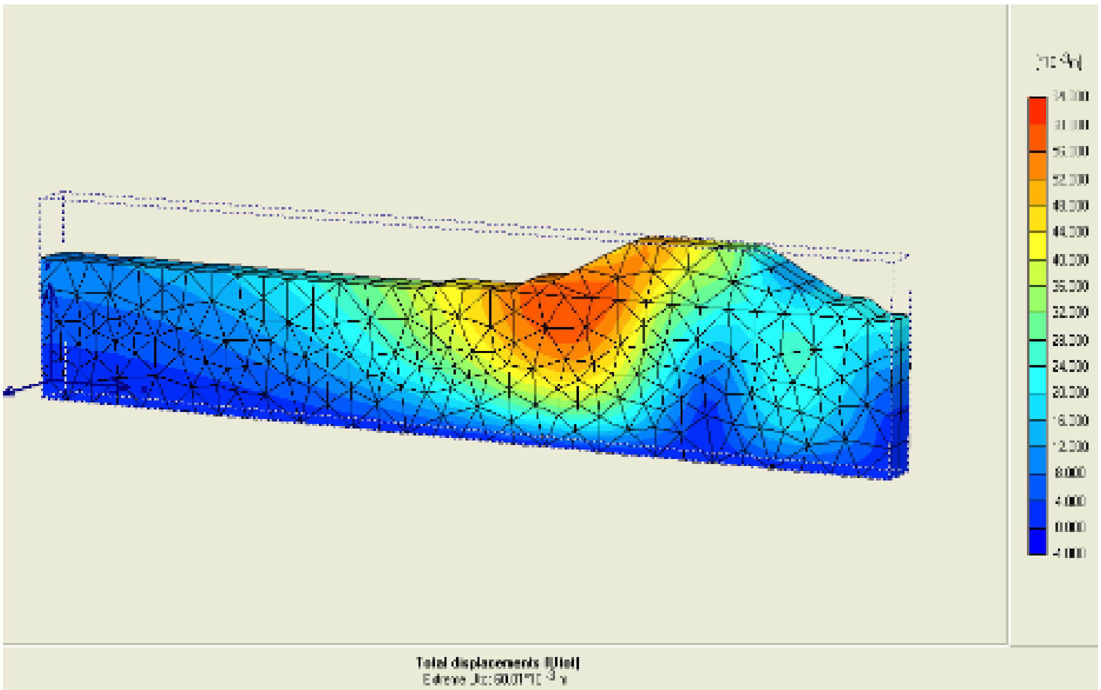

Figure 15 Deformation Zone of Cross-Section 2 under long-Term Conditions

In the finite element method, the geometric model is discretized into smaller components called elements, and the analysis is performed based on these elements distributed across the model. Each element comprises nodes, which can be linear (first-degree) or nonlinear (second-degree or higher).

When applying the finite element method for analysis, solving a large number of equations simultaneously becomes necessary. The total number of equations is directly influenced by the number of nodes and elements employed in the model. Consequently, it is crucial to use an appropriate number of nodes and elements during modeling to maintain the accuracy of the output results without unnecessary computational overhead. Achieving this requires a sound understanding of the problem, enabling the user to properly mesh the geometric model considering various factors such as problem type, model degrees of freedom, boundary conditions, initial conditions, loading, and other specifications.

The settlement analysis of the Chamkhaleh breakwater involved a phased construction of cross-section 2, with special consideration given to its proximity to the toe of the slope, which presented a more critical condition when compared to cross-section 1. The primary objective of the modeling process was to accurately capture the deformational changes caused by the construction of the breakwater under both short-term (figure 14) and long-term (figure 15) conditions.

8. Conclusion

The performance of protective structures in ports includes ensuring port tranquility, maintaining water depth, preventing shoreline erosion, and controlling water level rise behind the breakwater during storm surges and tsunamis. In many cases, it is expected that protective structures fulfill multiple functions over their service life. In the case of the Chamkhaleh breakwater project, based on the results obtained from the conducted modeling and settlement evaluation considering slope conditions and distance to the toe under short-term and long-term static as well as short-term pseudo-static conditions, the maximum settlement under short-term conditions is 9.3 centimeters, and under long-term conditions, it is 6 centimeters, both of which fall within the acceptable range.

Furthermore, the factor of safety for the overall stability of the breakwater slope in cross-section 1 under long-term and short-term static conditions is 4.942 and 2.316, respectively. In the pseudo-static analysis, this factor decreases to 1.341 but remains within the design allowable range.

For cross-section 2, the factor of safety under long-term and short-term static conditions is 5.524 and 5.696, respectively. In the pseudo-static analysis, this factor decreases to 1.704, which, similar to cross-section 1, falls within the design allowable range. These findings indicate that the Chamkhaleh breakwater project exhibits satisfactory stability and settlement performance under the analyzed conditions, providing effective protection for the port.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

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