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Impact of Rear Slope Variation on Rubble Mound Breakwater Stability Under Seismic Loading

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Abstract

This study aims to enhance the seismic stability of rubble mound breakwaters, crucial maritime structures, by examining how variations in the rear slope angle affect their response to seismic loads. Utilizing the Plaxis 2D software, a finite element method was employed to simulate the behavior of a conventional rubble mound breakwater under different seismic conditions. The analysis considered three different rear slope angles and subjected each to various seismic loads characterized by differing amplitudes and frequencies. Our findings indicate that the rear slope inclination significantly influences the seismic response of the breakwaters, notably affecting the displacements and deformations within the structure. The most optimal angle of inclination was identified, which minimized the seismic-induced deformations, thereby potentially improving the structural integrity and longevity of these maritime defenses. This investigation not only provides valuable insights into the design of more resilient maritime structures but also introduces an approach to optimize breakwater design for better performance under seismic conditions, marking a notable improvement in the field of maritime engineering.

Keywords: Rubble Mound Breakwater; Seismic Loads; Stability; Amplitudes; Frequencies; Rear Slope; Finite Element Method; Displacements.

1. Introduction

The stability of maritime structures is critical to preventing catastrophic damage due to their failure during seismic events [1–10]. These structures, including breakwaters, are designed to incorporate a variety of data types—hydraulic, geotechnical, hydrodynamic, geological, and oceanographic—to enhance their resilience. However, despite considerable efforts to ensure their structural stability, maritime structures remain vulnerable to the destructive forces of earthquakes. Over the past 25 years, seismic activities have led to the failure of numerous port structures worldwide, notably in Los Angeles (1994), Kobe (1995), Kocaeli and Athens (1999), Taiwan (1999), and Southeast Asia (2003). These incidents have significantly contributed to our understanding of the seismic response of port structures, revealing critical insights into their behavior under stress.

Several studies have rigorously investigated the impact of breakwater design on its structural stability, examining various factors such as hydraulic, geotechnical, hydrodynamic, geological, and oceanographic influences [11–17]. These studies have laid a foundational understanding of how different design choices affect the resilience of breakwaters under normal environmental conditions. However, the increased frequency and severity of seismic events globally necessitate a deeper exploration into how these structures withstand such extreme stresses. The existing research highlights the need

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for a focused study on specific design modifications, such as variations in the rear slope angle, to enhance the seismic resilience of rubble mound breakwaters.

The PIANC study [18] on the seismic performance of rubble mound breakwaters provides critical insights into various earthquake-induced failure modes that significantly compromise these structures. The analysis outlines specific failures including crest lowering caused by the settlement of rubble material, leading to differential settlement of superstructure elements (Figure 1-a). Additionally, it reports that crest lowering and lateral spreading may occur due to subsoil settlement or liquefaction, causing further differential settlement of superstructure elements (Figure 1-b). The study also identifies failures arising from subsoil liquefaction, resulting in subsequent crest lowering and the potential displacement of superstructure elements (Figure 1-c). Historically, numerous instances of rubble mound breakwater failures under seismic loading have been well-documented, especially when these structures were built on suboptimal soil conditions. Studies by Yüksel et al. [19] and Sumer et al. [20] have provided detailed analyses of such failures, showing that poor soil conditions significantly exacerbate the vulnerability of these structures during seismic events. Yüksel et al. specifically investigated the seismic response of a rubble mound breakwater in Turkey following an earthquake, revealing how soil quality underpins the structural integrity and performance under stress [19]. Similarly, Sumer et al. explored the broader implications of earthquake-induced liquefaction around marine structures, underscoring the critical impact of soil conditions on the stability and safety of maritime infrastructure [20]. These findings emphasize the necessity for rigorous geotechnical assessments prior to construction, aiming to enhance the design and resilience of breakwaters against earthquakes.

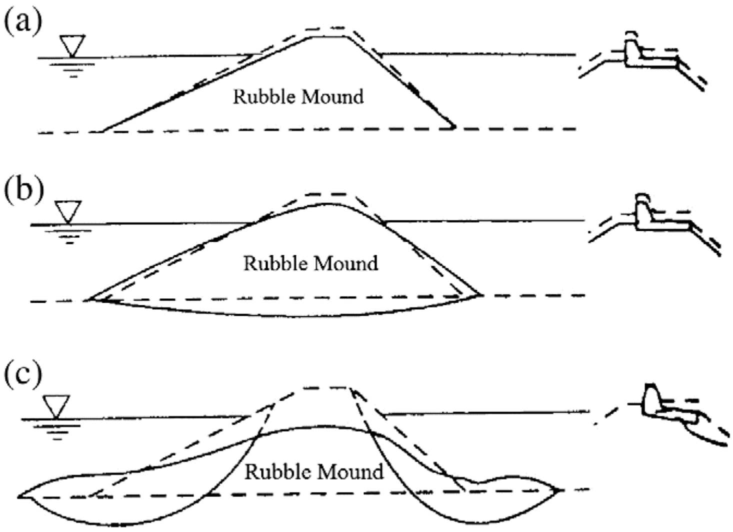

Figure 1. Typical failure modes for rubble-mound breakwaters [18]

Breakwaters serve as vital protective barriers for ports and harbors, shielding them from environmental forces, notably earthquakes. Yüksel et al. [19] delved into the seismic response of a breakwater situated in a fishery port affected by the Kocaeli earthquake in 1999. Through meticulous analysis, the study yielded essential qualitative and quantitative insights (refer to Figures 2 and 3), revealing significant damage marked by settlements of approximately 1.5 meters on the seaside of the structure. The most conspicuous forms of damage included the flattening of cross-sections and slope sliding, with numerical results aligning with physical measurements obtained from liquefied foundation cross-sections. This research not only underscores the profound impact of seismic events on rubble mound breakwaters but also emphasizes the imperative of integrating seismic resilience into their design and construction practices.

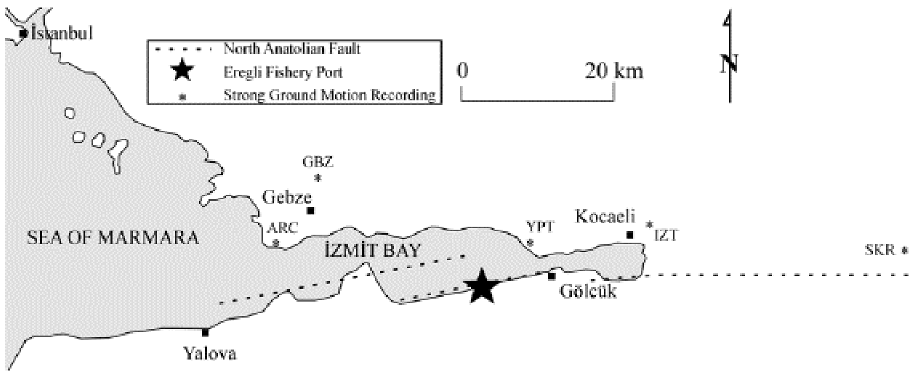

Figure 2. Case history site map and the location of the Eregli Fishery Port Breakwater [19]

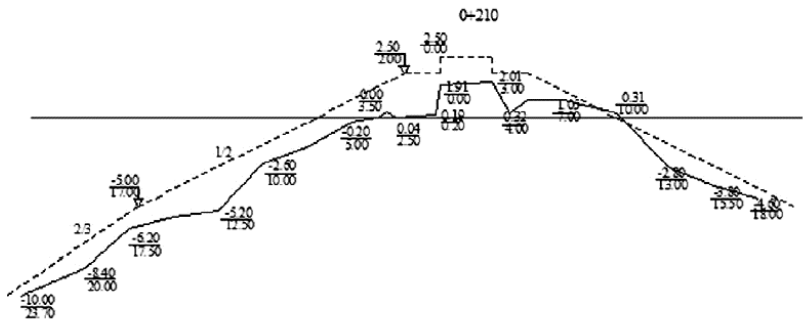

Figure 3. The settlement of breakwaters after the Kocaeli earthquake, Turkey (1999) [19]

Sumer et al. [20] provided a comprehensive review of earthquake-induced liquefaction around marine structures, with a specific focus on rubble mound breakwaters, deriving insights from field observations that highlight the vulnerability of these structures to seismic forces. Following this, Yüksel et al. [21] explored the seismic responses of rubble mound breakwaters using physical models on a rigid foundation. Their study compared failures in homogeneous and conventional mounds, identifying that homogeneous models exhibited greater durability under the tested conditions. This research added depth to our understanding of material and structural responses to seismic activity.

Further expanding on the theme of design-specific impacts, Cihan & Yüksel [22] investigated the role of the toe configuration in enhancing earthquake resistance of rubble mound breakwaters. Their experimental and numerical analyses using Plaxis 2D software underscored the significance of toe protection in structural performance during seismic events. Additionally, Van Gent [23] demonstrated how the integration of a berm with the slope configuration can substantially influence the stability of these breakwaters, further advocating for detailed design considerations.

Recent advancements in the field of coastal engineering have significantly focused on reinforcing the design of rubble mound breakwaters to better withstand environmental challenges and seismic forces. Onyelowe et al. [24] provided an important study titled "Seepage Analysis and Optimization of Reservoir Earthen Embankment with Double Textured HDPE Geo-membrane Barrier." This study has been pivotal in advancing the understanding and application of design modifications to improve the stability of earthen embankments under conditions prone to seepage. By employing a double-textured HDPE geo-membrane barrier, the research addresses traditional challenges of seepage in reservoir earthen embankments and contributes significantly to the development of more resilient infrastructure capable of withstanding diverse environmental stresses. Sajan et al. [25] conducted a comprehensive evaluation of geosynthetic-reinforced rubble mound breakwaters (RMBs) to mitigate tsunami-induced damage, acknowledging the historical challenges faced by traditional RMB designs during severe tsunami events, including foundation failures and inadequate wave energy dissipation. Their research explored innovative approaches, such as integrating geosynthetics and implementing novel design configurations, to enhance RMB resilience against seismic and tsunami forces. These modifications aim to significantly reduce breakwater vulnerability, ensuring better structural integrity and functional performance during tsunami events, thereby providing effective coastal protection. Similarly, Sajan et al. [26] delineated crucial engineering strategies needed to fortify the seismic resilience of rubble mound breakwaters. Their study extensively examined the susceptibility of these structures to earthquakes, scrutinizing conventional and modern design and reinforcement approaches under seismic conditions. The findings underscored the importance of integrating specialized designs, like stone columns, with advanced numerical modeling techniques to assess and improve breakwaters' seismic performance. Akarsh et al. [27] delved into the critical analysis of rubble mound breakwaters under seismic forces, emphasizing the significance of innovative design techniques and advanced numerical models to bolster the structures' seismic resilience. Their findings highlighted the crucial role of specific design adaptations, such as strategically placing geosynthetics and armor units, in enhancing the breakwaters' capacity to withstand seismic loads efficiently. Furthermore, Akarsh et al. [28] conducted a study which provided crucial insights into the seismic resilience of rubble mound breakwaters. The research investigated the structural responses of these breakwaters to seismic forces through shake table tests coupled with numerical analyses, focusing on evaluating the effects of design elements that could enhance stability under seismic loading conditions. Their findings revealed that specific design strategies, including the incorporation of certain geometries and materials, significantly influenced the breakwaters' ability to withstand seismic forces.

The present research on the "Impact of Rear Slope Variation on Rubble Mound Breakwater Stability Under Seismic Loading" aims to address existing knowledge gaps and strengthen solutions for designing breakwaters to better withstand seismic events while minimizing deformations and damages. By conducting a detailed numerical analysis of the effects of varying rear slope angles on breakwater stability under seismic loading conditions, we intend to provide valuable insights into an area that has not been extensively explored in the literature. This research will contribute to a deeper understanding of how specific design modifications, such as adjustments to the rear slope, can significantly impact the resilience of rubble mound breakwaters during seismic events. Ultimately, our findings will offer practical guidance for engineers and designers seeking to enhance the seismic resistance of maritime structures, thereby reducing the risk of damage and improving overall safety and performance.

2. Material and Methods

The assessment framework for rubble mound structures as depicted in Figure 4 was devised by Van Der Meer [29], a recognized authority in coastal engineering and port design. This framework offers a thorough methodology for evaluating how rubble mound structures react to external forces, including those from waves and seismic activities. It involves assessing the stability through the interaction of the armor layer with the core material, and the crest height and wave overtopping by analyzing the hydraulic forces acting on the structure. These forces are affected by wave characteristics and the structural geometry. The foundation's stability is further analyzed by considering soil properties and the foundation-structure interaction.

This framework aims to deliver a methodical and uniform method for evaluating rubble mound structures, aiding engineers and designers in refining their designs. It has gained widespread adoption in the industry and has been utilized in various projects such as breakwaters, revetments, and seawalls. The environmental conditions like currents and waves, along with geotechnical factors, establish the parameters that affect the area around or in front of the structure. These include wave height, distribution, breaking patterns, period, spectral shape, wave angle, foreshore geometry, currents, water depth, water setup, and levels, which are outside the designer's control [29].

Seismic activity represents a specific geotechnical challenge. The relevant parameters are categorized into hydraulics, geotechnics, and structural considerations. Hydraulic parameters detail the wave's impact on the structure, including phenomena like wave overtopping, run-up, rundown, transmission, and reflection. Geotechnical parameters address issues such as liquefaction, dynamic gradients, and excessive pore pressures [29]. Structural parameters define characteristics such as slope, cohesion, porosity, permeability, rock mass, density, shape, surface texture, moduli, and dimensions [29]. Environmental, geotechnical, hydraulic, and structural parameters generate loads affecting the structure, which include external and internal water motion, along with seismic forces.

Structural features such as stone size and shape modify the slope's roughness and permeability, impacting water motion and stability. The structure's ability to withstand waves and earthquakes depends on these parameters. Assessing the structure's response involves comparing its strength against the loads, taking into account the stability of armor layers, filter layers, crests, rear slopes, toe berms, crest walls, and dynamically stable slopes. Geotechnical responses might include slip failure, dynamic response, settlement, liquefaction, internal erosion, and impacts [29]. Additionally, Figure 4 serves as a reference for the physical and numerical modeling of the stability of coastal and shoreline structures.

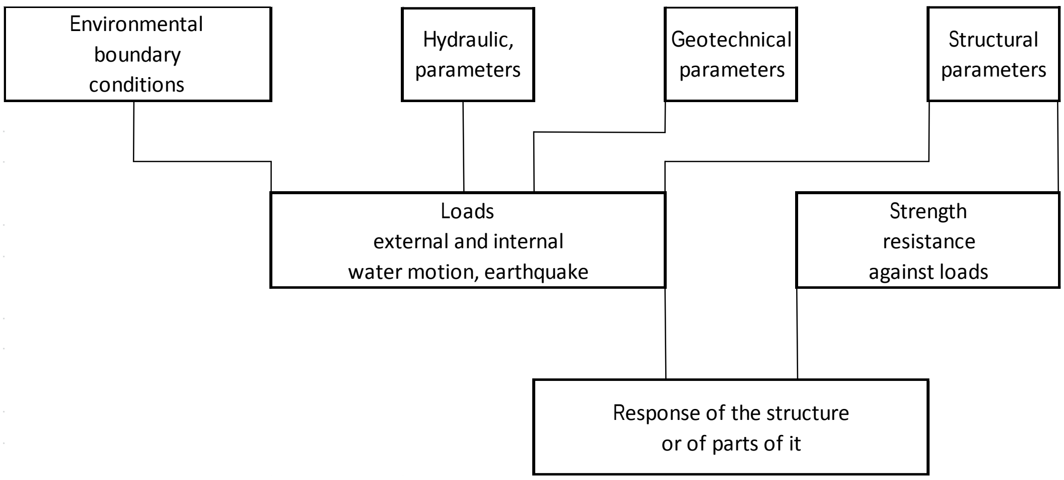

Figure 4. Basic scheme of assessment of rubble mound structure response [29]

This paper deal with numerical study of a conventionnel rubble mound breakwater under seismic loading. Then, not all parameters are treated, but we used the necessary that could lead to the desired results.

2.1. Layer Structure

In the present paper, A conventional rubble mound breakwater consisting of a core, underlayers, and an armor layer was considered. Figure 5 represents the design and the different layers of the rubble mound breakwater that will be studied. A breakwater with specific dimensions was considered, including a height of 6.5 meters, a seawater level of 4 meters, and a crest width of 4 meters as shown in Figure 6. These dimensions are critical to the design and performance of the breakwater and will be taken into account throughout our analysis.

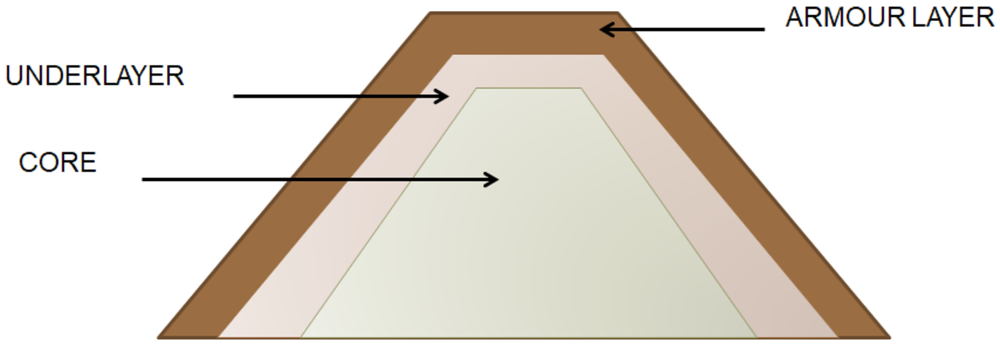

Figure 5. Layer structure of a conventional rubble mound breakwater

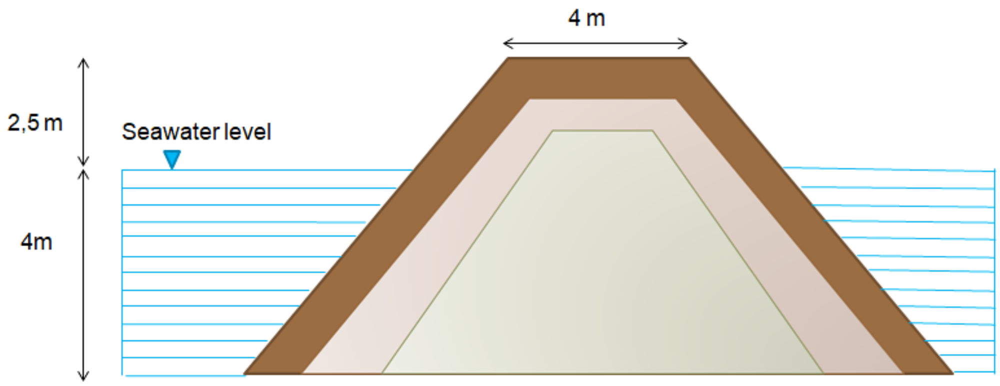

Figure 6. Design of the conventional breakwater

2.2. Breakwater Layers Data

Once the rubble mound breakwater has been modeled in Plaxis 2D, it is necessary to define the various characteristics of the layers that comprise the structure (Table 1). It is important to note that the core and under layer have the same material properties. To ensure the highest level of precision, we utilized empirical data characterizing the recommended materials for constructing rubble mound breakwaters.

Table 1. Numerical-model parameters for breakwater models

Layers	Core and Under layers	Armor layer
Saturated unit weight γ_{sat} ($\mathbf{KN/m^3}$)	18.3	17
Unsaturated unit Weight γ_{unsat} (KN/$\mathbf{m^3}$)	11	10.5
Young's Modulus E (MPa)	2	20
Poisson rate v	0.2	0.3
Expansion ψ (°)	8°	10°
Cohesion c (Kpa)	-	-
Friction angle φ (°)	37°	42°

2.3. Seismic Loads

In order to account for effects of seismic activity on the soil and structure of the breakwater, we conducted a detailed analysis using multiple seismic waves with varying frequencies and amplitudes. To ensure the accuracy and reliability of our model, we relied on the most up-to-date and rigorously validated seismic data available [22]. Our calculations were based on a numerical model, including the dynamic response of soils under seismic loading conditions. The seismic data used in our analysis is presented in Table 2.

Table 2. Seismic data

Seismic wave	Amplitude (mm)	Frequency (Hz)
Wave 1	1	3
Wave 2	1	4
Wave 3	1	5
Wave 4	1	6
Wave 5	1	7
Wave 6	2	3
Wave 7	2	4
Wave 8	2	5
Wave 9	2	6
Wave 10	2	7
Wave 11	3	3
Wave 12	3	4
Wave 13	3	5
Wave 14	3	6
Wave 15	3	7

2.4. Numerical Study

We performed stress-strain simulations on rubble-mound breakwater models using the Plaxis 2D V8 software, which utilizes the finite element method (FEM) [30]. Plaxis 2D is specifically designed for two-dimensional finite element analysis, ideal for deformation and stability evaluations in geotechnical engineering. This software features an intuitive graphical interface, enabling users to efficiently create geometric models and finite element meshes from the vertical cross-sections of the structures under examination. Plaxis includes four subprograms; Input, Calculations, Output, and Curves that streamline the modeling process [30].

In civil engineering applications, both soil and structures often face not only static but dynamic loads. Particularly during earthquakes, these loads can cause significant damage. In our study, we explored the impact of seismic loading on various rubble mound breakwater configurations using Plaxis 2D. For these simulations, we employed fifteen-noded, triangular, 2D plane-strain elements within the FEM framework. The plane strain model, suitable for structures with a consistent cross-section along a certain length, assumes zero displacements and strains in the z-direction, although it accounts for normal stresses in this direction. Typically, earthquake simulations apply dynamic loading along the model's base, generating shear waves that travel upward this is effectively captured in a plane strain model [30].

Plaxis supports several advanced material models, including the Linear Elastic, Mohr Coulomb, Soft Soil, Hardening Soil, Soft Soil Creep, and Jointed Rock models [30]. For this research, we used the Mohr-Coulomb model to simulate the dynamic behavior of the granular materials in the rubble-mound breakwater layers. This model relies on well-established soil parameters commonly used in engineering practice. It serves as an initial approximation of soil behavior, making it suitable for preliminary analysis of geotechnical issues. This approach also allows for the estimation of a constant average soil stiffness, facilitating relatively quick computations and enabling rapid preliminary deformation estimates.

It should be noted that the choice of the slope values of the rear slope and the seaward slope are determined according to the recommendations of Rock Manual [31], which contains the different specifications for the use of embankments and rock fill materials.

For the slope of the rubble mound breakwater on the seaside, the slope is steeper than 3/2; an angle of inclination of 33° is considered. For the rear slope, the slope should be comprised between 4/3 and 2/1; three cases of slope angles were considered:

- In the first case (Slope 1), we considered an angle of 27°.
- In the second case (Slope 2), we considered an angle of 34 °.
- In the third case (Slope 3), we considered an angle of 36°.

In this study, the earthquake simulation involved imposing a specified displacement at the base of the model. The horizontal component of this displacement was set at 0.01 meters (U_X =0.01m), with the vertical component maintained at zero (,U_Y =0). To mitigate the effects of outgoing waves, absorbent boundary conditions were applied along the far vertical boundaries.

We utilized standard earthquake boundary conditions accessible from the loads menu in Plaxis 2D. This feature automatically configures the boundary conditions as described, streamlining the setup process. The depiction of the rubble mound breakwater modeling for each variant is presented in Figure 7. The process begins with defining the geometry model, which is then discretized into finite elements necessary for performing finite element analysis.

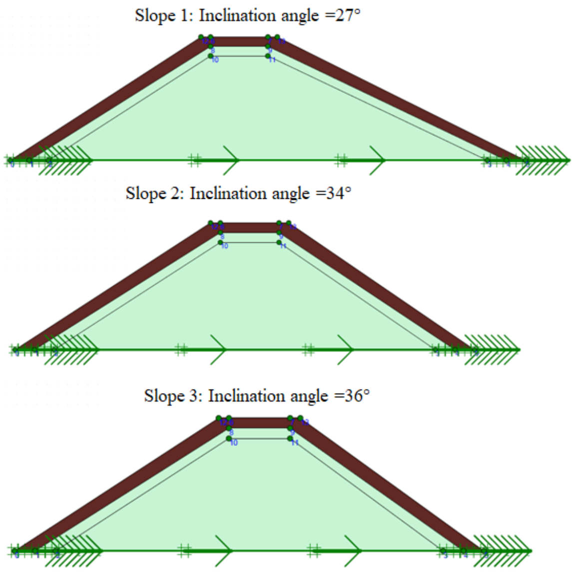

Figure 7. Breakwater model on Plaxis 2D

Mesh generation is a critical step that considers various factors including soil stratigraphy, structural components, loads, and boundary conditions. Plaxis 2D offers mesh coarseness options ranging from fine to very coarse [30]. To achieve precise numerical results, a very fine mesh was chosen for this research, featuring a high density of elements, as detailed in Table 3. The finite element models for slope 1, slope 2, and slope 3 consist of 590, 585, and 600 elements, respectively, as shown in Figure 8. Additionally, the water level was defined at 2.50 meters below the crest to simulate realistic conditions.

Table 3. Predefined values of the element distribution

Element distribution	Elements number
Very coarse	30 - 70 elements
Coarse	50 - 200 elements
Medium	90 - 350 elements
Fine	270 - 700 elements
Very fine	500 - 1250 elements

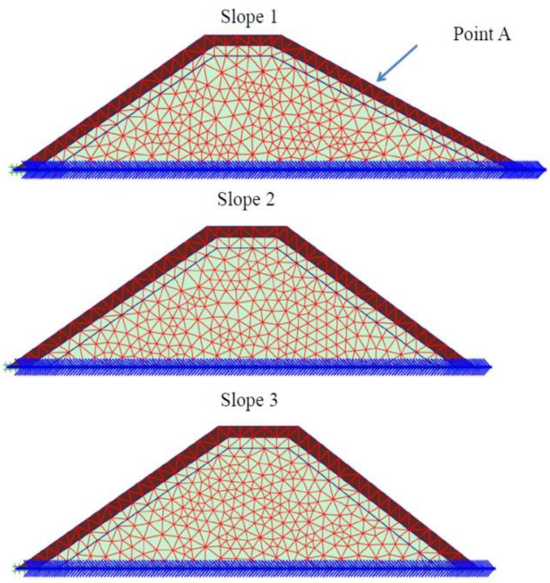

Figure 8. Finite element meshes

In our research, finite element method (FEM) analyses were conducted on each model by subjecting them to horizontal shaking, as detailed in Table 2. Each scenario specified in the table was characterized by distinct displacement amplitudes and frequencies. This paper includes figures that illustrate the models of the three slope variants under a specific case involving an amplitude of 3 mm and a frequency of 7 Hz.

Dynamic loads were applied at the base of the finite-element models, utilizing ten-second acceleration records to simulate the input motions. These dynamic forces were implemented as harmonic loads, characterized by their variation according to sine or cosine functions. Harmonic or sinusoidal loading represents the most basic form of dynamic force and is commonly observed in scenarios involving vibrations from earthquakes and machinery, as depicted in Figure 9. This type of loading is critical for analyzing the structural responses under typical dynamic conditions encountered in real-world environments.

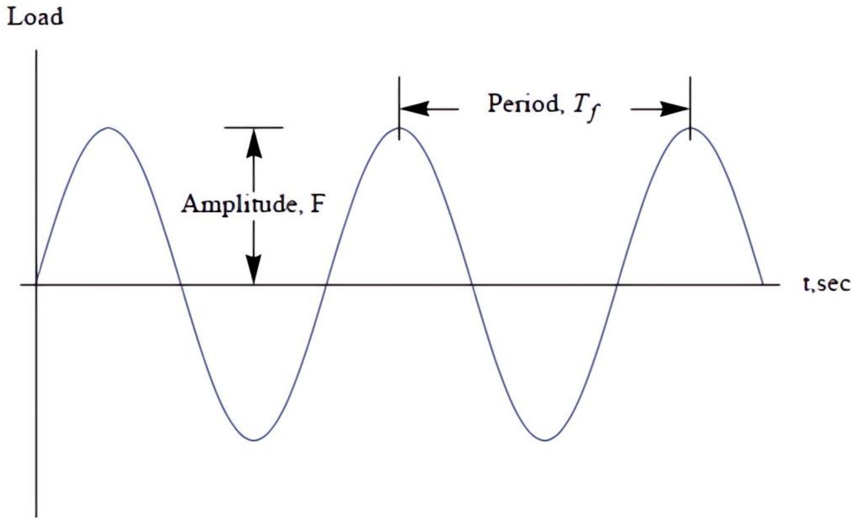

Figure 9. Sinusoidal loading

The nature of the force is defined in terms of amplitude, frequency, shape, as well as duration. It is customary to begin the study of dynamics of structures with this loading. The response of a system to a harmonic excitation (loading) is called harmonic response.

In Plaxis [30], harmonic loads are defined as:

$$F = M' F' \sin(\omega t + \phi_0) \quad (1)$$

in which M' is Amplitude multiplier, F' is Input value of the load, $\omega = 2\pi$ □ is the angular frequency in radians per unit of time, with □ = Frequency (Hz), t is Time and ϕ_0 is The initial phase angle in degrees. (In the current study, we considered an angle of 0°).

3. Results And Discussion

Three varieties of breakwaters were examined to comprehend the behavior of rubble-mound breakwaters when subjected to seismic loads. Employing a numerical approach, the study aimed to ascertain the failure mechanisms of these structures under seismic conditions. Extreme total, horizontal, and vertical displacements were measured for each scenario to validate the findings. The behavior of rubble-mound breakwaters was scrutinized across varying frequencies and amplitudes, specifically focusing on different rear slope configurations. Results from the finite element analysis depicted substantial deformations occurring within the initial 10 seconds of seismic loading, as depicted in Figures 10 to 12.

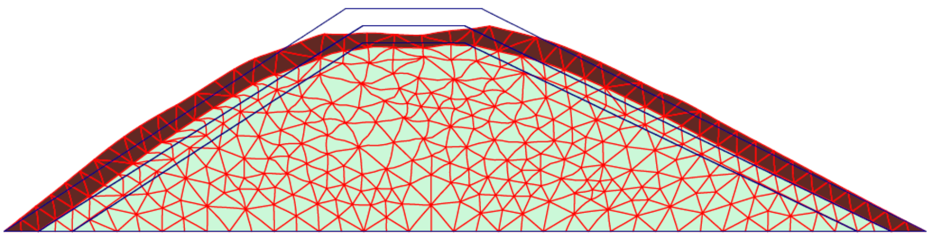

Figure 10. Deformed mesh corresponding to the slope 1

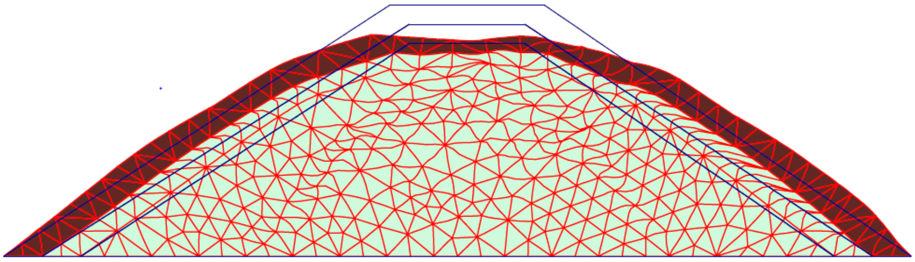

Figure 11. Deformed mesh corresponding to the slope 2

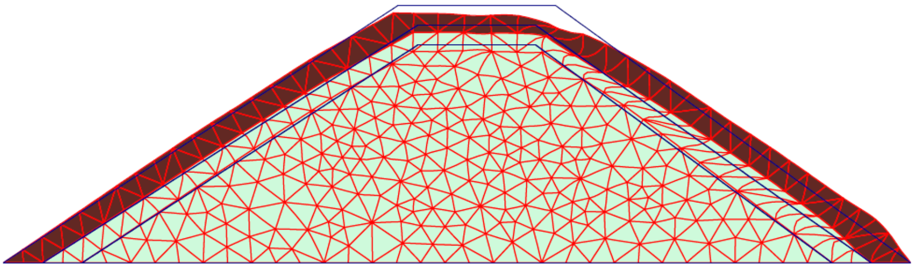

Figure 12. Deformed mesh corresponding to the slope 3

The response of breakwaters to seismic loads can be characterized by various parameters such as total displacement, horizontal displacement, vertical displacement, damage level, and porosity. However, this investigation considered total displacement, horizontal displacement, and vertical displacement. Stability under seismic conditions was delineated through deformed profiles. Figures 13 to 15 illustrate contours of extreme total displacements for the three models. Notably, the magnitude of total displacements amplified at the rear slopes, with the highest deformations observed at the upper sections of these slopes across all three models. The finite element analysis revealed deformations predominantly occurring at the upper portions of slopes and crests, while displacements diminished towards the slope ends. These findings underscore the significance of variations in rear slope inclination, particularly at the upper segments.

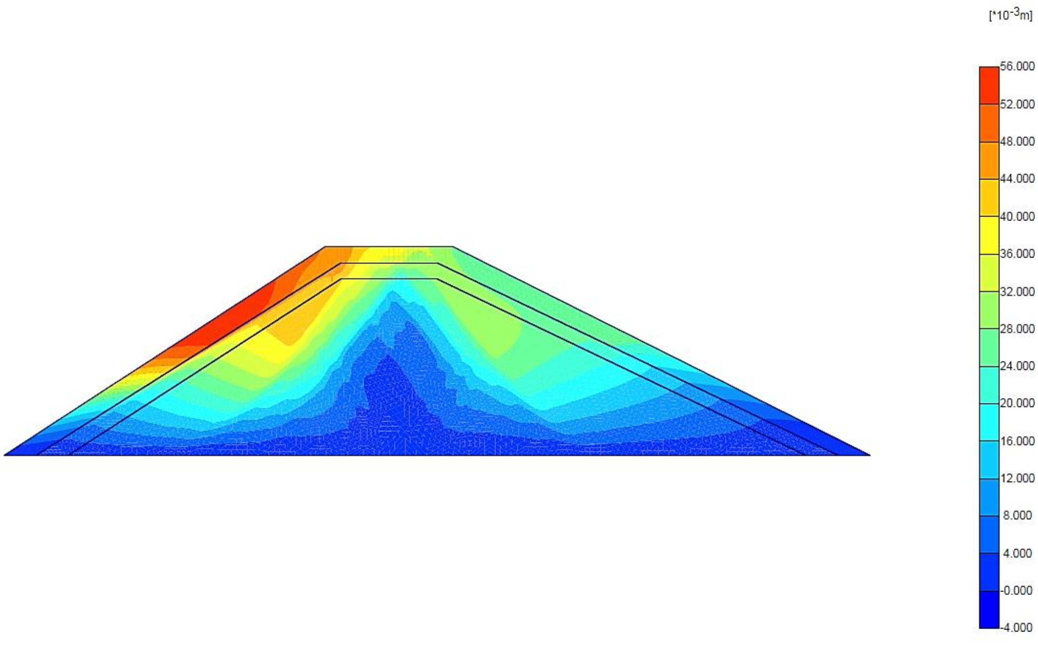

Figure 13. Contours of extreme total displacement corresponding to the slope 1 after 10s

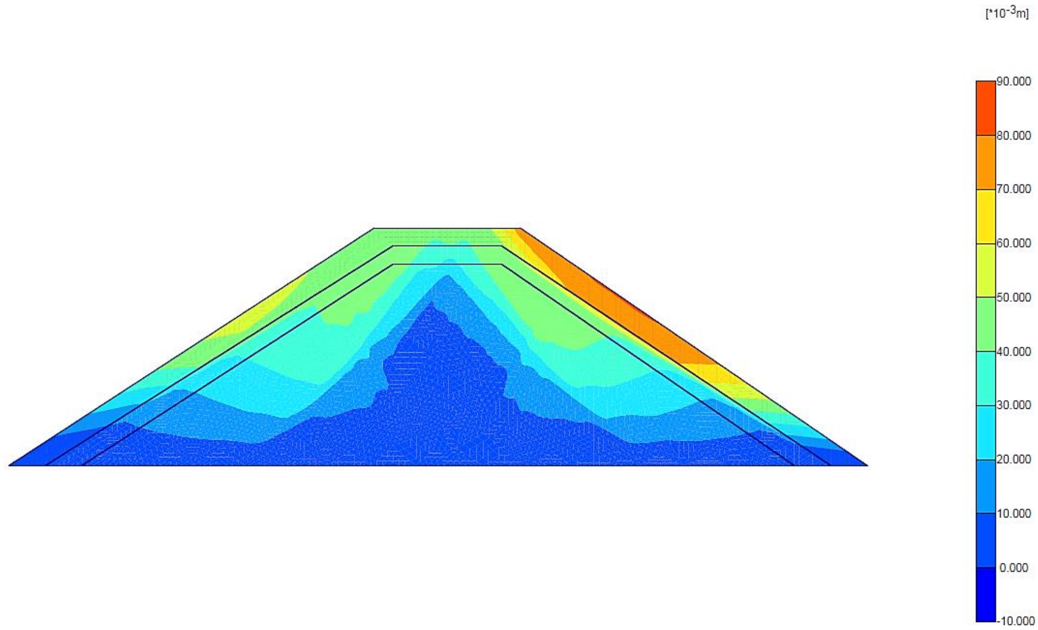

Figure 14. Contours of extreme total displacement corresponding to the slope 2 after 10s

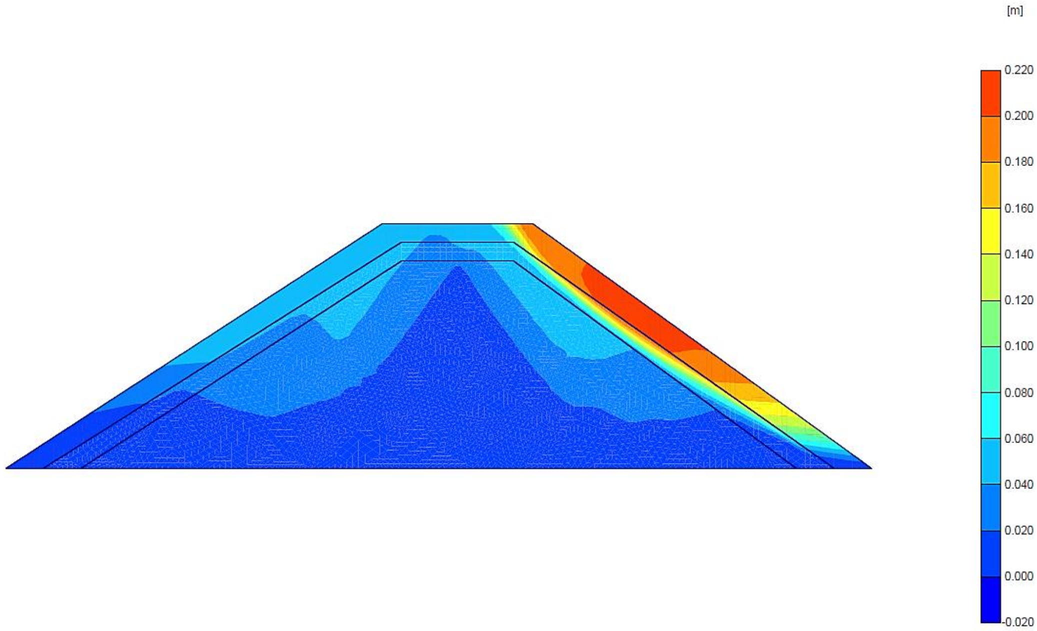

Figure 15. Contours of extreme total displacement corresponding to the slope 3 after 10s

The acceleration and extreme total, horizontal, and vertical displacements were calculated and measured at point A, located on the rear slopes (as shown in Figure 16).

Acceleration is a critical parameter that characterizes the movement of soils subjected to seismic loads. It is closely related to the intensity of the shaking and the soil's response during an earthquake. In the present research, acceleration was used as a key parameter to assess the damage to the breakwaters under seismic loads. The results of the analysis showed that the acceleration values for all three models were high during the initial phase of the seismic event. This indicated that the damage to the breakwaters started early and increased rapidly. However, the acceleration values decreased as the seismic event progressed.

Interestingly, the model corresponding to Slope 3 displayed higher acceleration values compared to Slope 2 and Slope 1, respectively (Figure 16). These differences in acceleration values are expected to result in variations in the degree of damage for each model. The findings of this research demonstrate the importance of considering acceleration as a critical parameter in the design of coastal protection structures that are resilient to seismic loads.

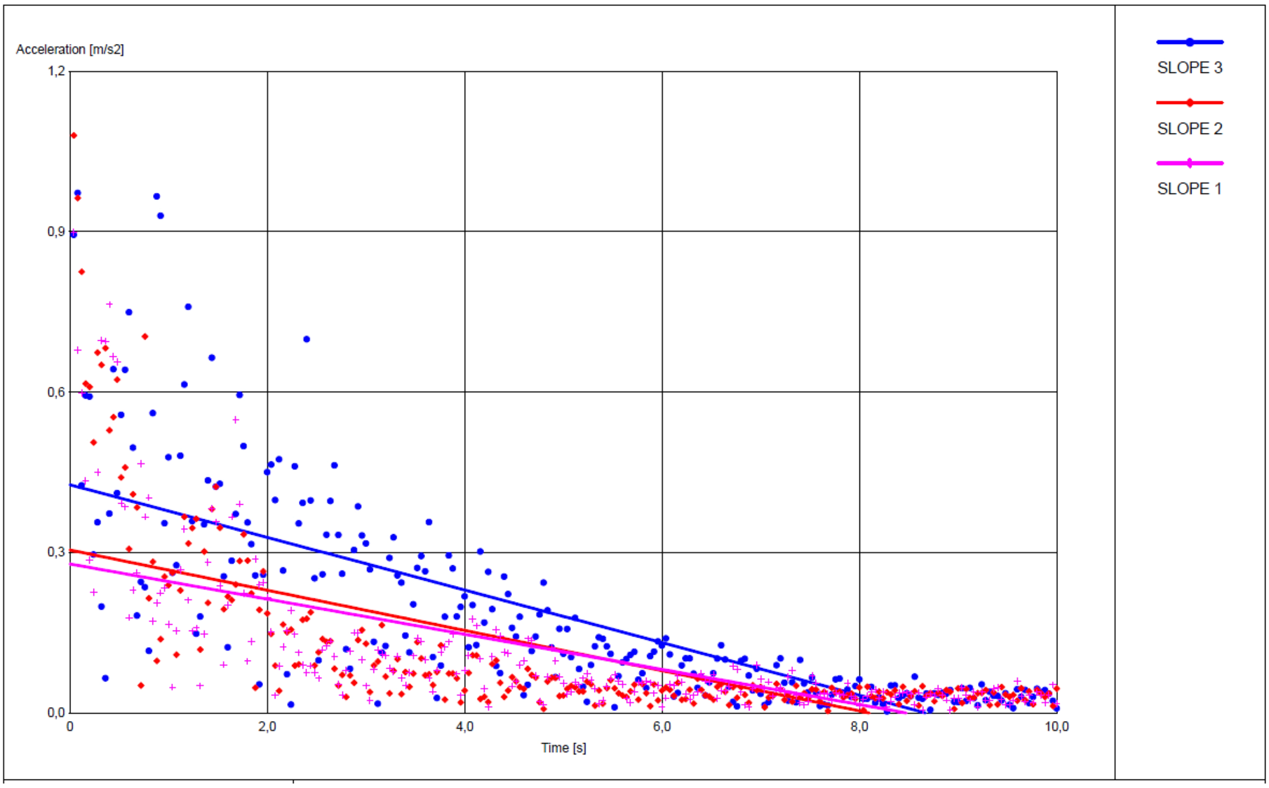

Figure 16. Acceleration time history calculated for the three models of breakwater

The results of numerical analyses for each model were compared to determine the influence of the inclination of the rear slope on the stability of a rubble mound breakwater under seismic loads. Observations showed that significant deformations began to increase early and reached extreme total, horizontal, and vertical displacements for each slope case, as shown in Figures 17 to 19, respectively. Afterward, there was little variation in the values of the displacements for each slope.

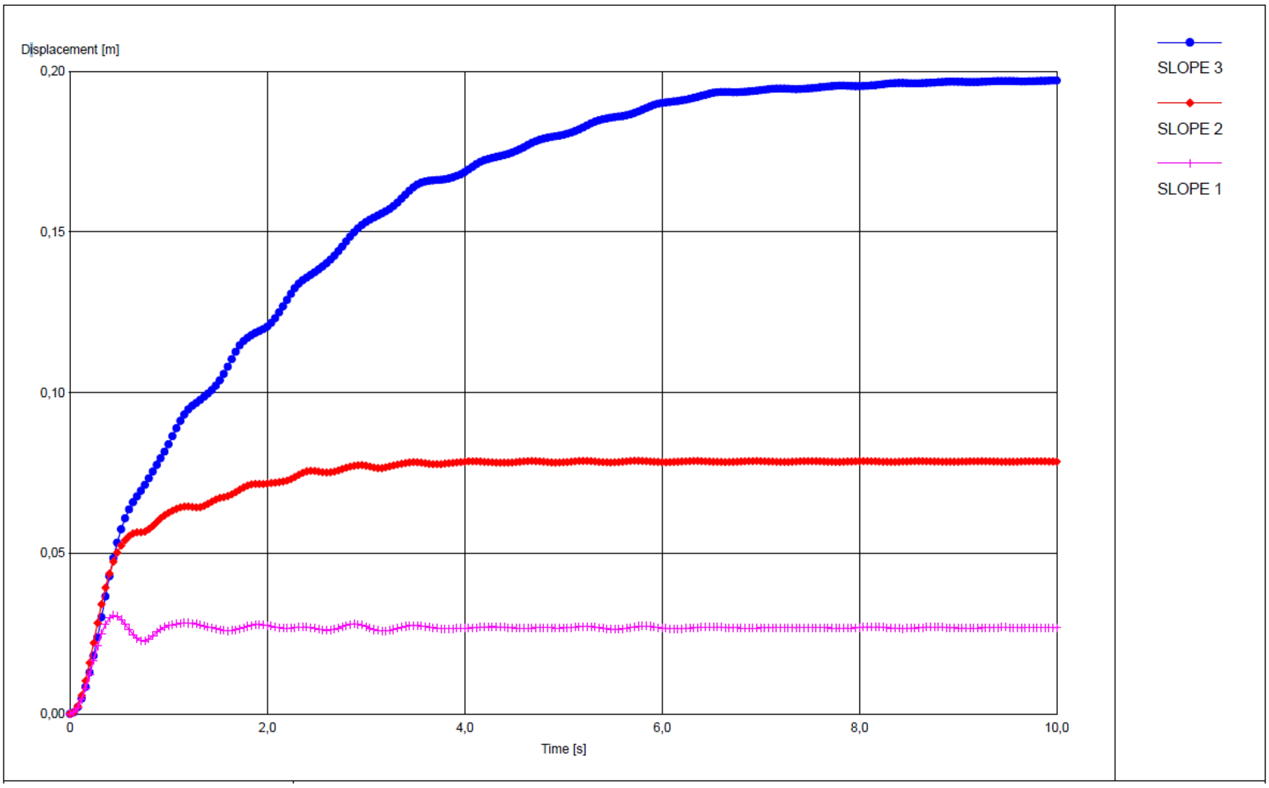

Figure 17. Total displacement time history calculated for the three models of breakwater

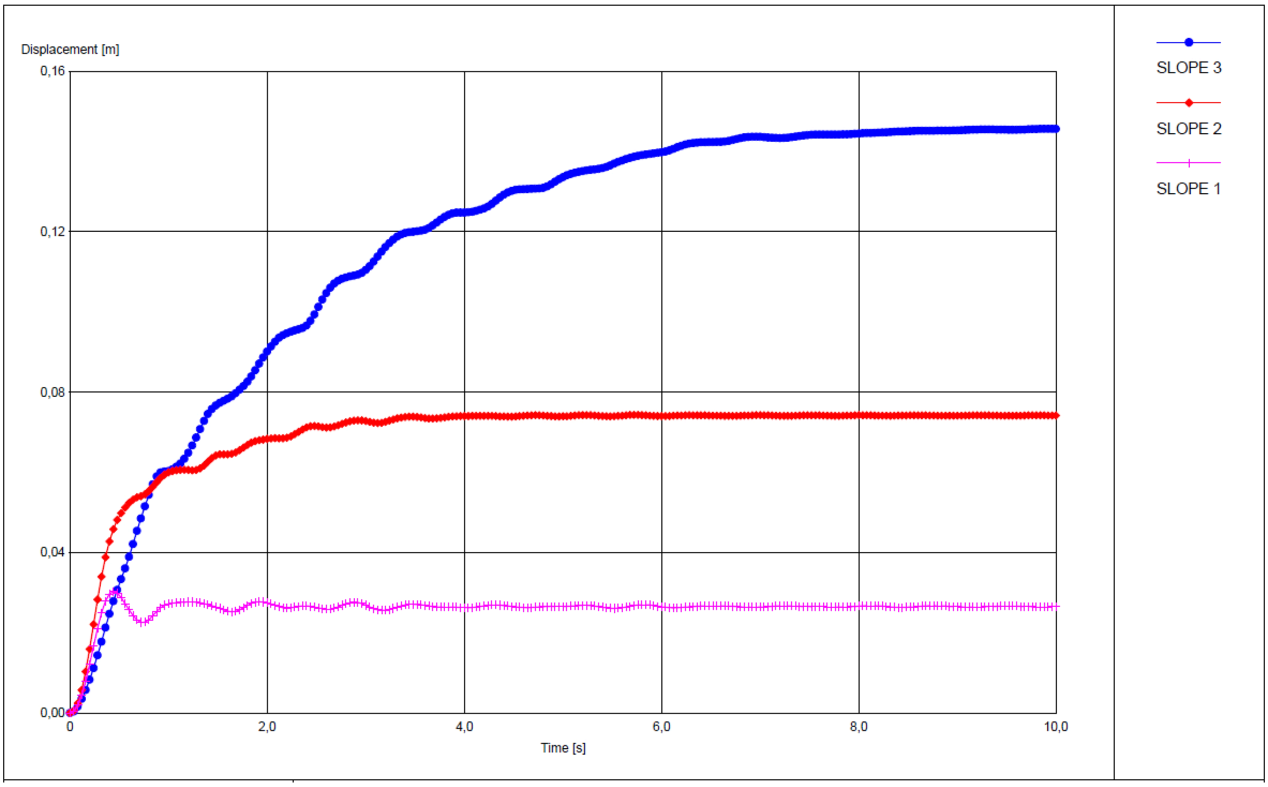

Figure 18. Horizontal displacement time history calculated for the three models of breakwater

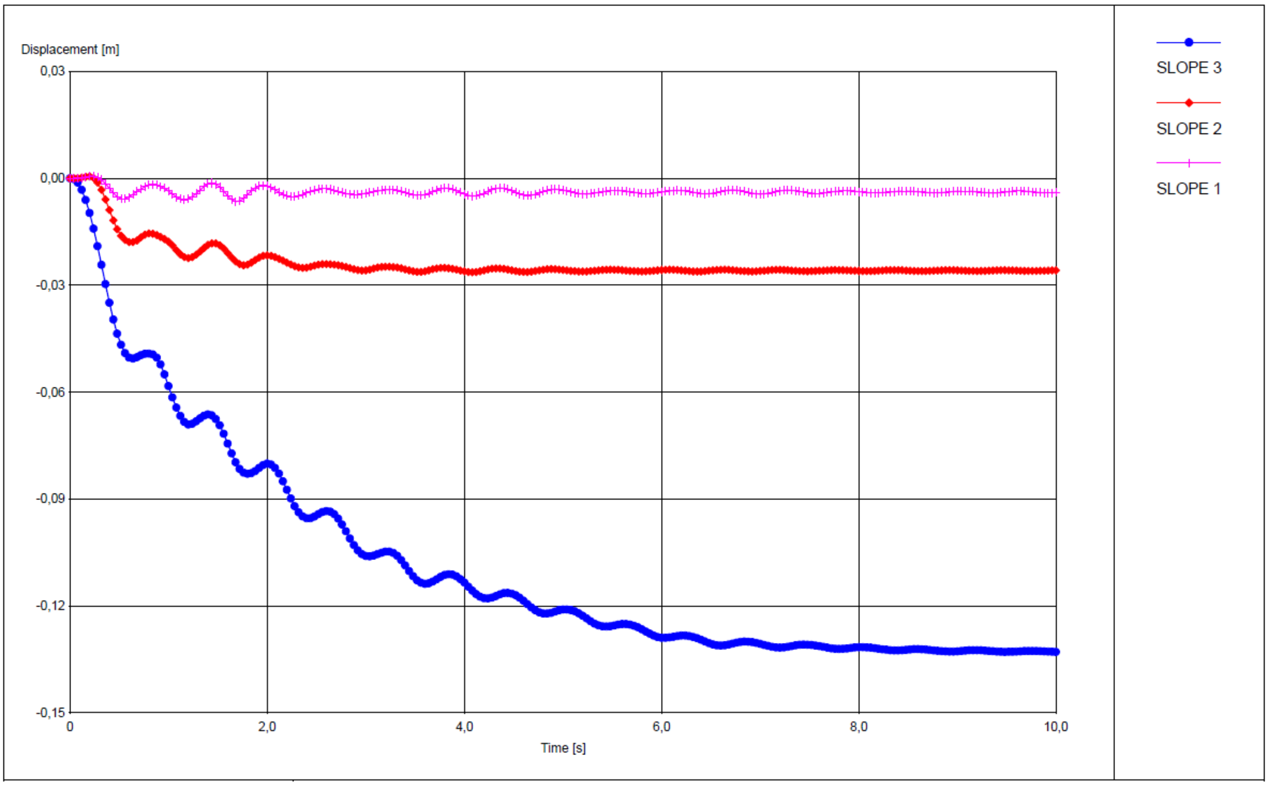

Figure 19. Vertical displacement time history calculated for the three models of breakwater

Figure 17 indicates that the model corresponding to Slope 3 exhibited significantly higher values of total displacement compared to Slopes 2 and 1, respectively. Similarly, Figure 18 indicates that the model corresponding to Slope 3 exhibited significantly higher values of horizontal displacement compared to Slopes 2 and 1, respectively. Figure 19 also shows that the model corresponding to Slope 3 presented significantly higher values of vertical displacement compared to Slopes 2 and 1, respectively.

Rubble mound breakwaters are essential coastal structures that are exposed to significant loads, including seismic loads. In order to evaluate the impact of rear slope inclination and support our earlier findings, we conducted additional numerical analyses on the same models using different amplitudes and frequencies of seismic waves.The results of our analyses are presented in Tables 4 to 6, which provide information on the extreme horizontal, vertical, and total displacements of the three models under different seismic wave scenarios. The findings reveal that the inclination of the rear slope is a critical design factor that can significantly improve the seismic resistance of rubble mound breakwaters. Specifically, decreasing the inclination of the rear slope leads to a reduction in deformations and an improvement in the stability of the breakwater structure.

Table 4. Extreme total displacements corresponding to the slope 1, slope 2 and slope 3

Amplitude (mm)	Frequency (Hz)	Extreme total displacements corresponding to the slope 1 (mm)	Extreme total displacements corresponding to the slope 2 (mm)	Extreme total displacements corresponding to the slope 3 (mm)
1	3	54.68	80.67	201.83
	4	54.73	80.64	202.1
	5	54.73	80.64	201.4
	6	54.78	80.56	203.59
	7	54.82	80.49	201.05
2	3	54.65	80.75	216.86
	4	54.74	80.69	202.35
	5	54.76	80.71	205.18
	6	54.84	80.56	203.31
	7	54.91	80.52	204.47
3	3	54.64	80.86	214.65
	4	54.78	80.76	201.76
	5	54.82	80.81	203.05
	6	54.94	80.62	204.6
	7	55.01	80.60	205.39

Table 5. Extreme horizontal displacements corresponding to the slope 1, slope 2 and slope 3

Amplitude (mm)	Frequency (Hz)	Extreme Horizontal displacements corresponding to the slope 1 (mm)	Extreme Horizontal displacements corresponding to the slope 2 (mm)	Extreme Horizontal displacements corresponding to the slope 3 (mm)
1	3	52.87	76.43	187.16
	4	52.91	76.42	187.33
	5	52.94	76.4	186.52
	6	52.97	76.31	188.7
	7	54.82	76.27	186.2
2	3	52.84	76.48	200.65
	4	54.74	76.47	187.53
	5	54.76	76.47	190.19
	6	53.04	76.3	188.47
	7	54.91	76.3	189.57
3	3	52.84	76.55	198.64
	4	52.96	76.55	186.63
	5	53.06	76.57	188.06
	6	54.94	76.36	189.64
	7	55.01	76.38	190.46

Table 6. Extreme vertical displacements corresponding to the slope 1, slope 2 and slope 3

Amplitude (mm)	Frequency (Hz)	Extreme vertical displacements corresponding to the slope 1 (mm)	Extreme vertical displacements corresponding to the slope 2 (mm)	Extreme vertical displacements corresponding to the slope 3 (mm)
1	3	38.69	53.76	140.82
	4	38.71	53.75	141.08
	5	38.71	53.72	140.73
	6	38.71	53.67	142.37
	7	38.71	53.64	140.49
2	3	38.68	53.80	152.12
	4	38.72	53.79	141.25
	5	38.71	53.76	143.6
	6	38.71	53.67	142.15
	7	38.71	53.66	142.99
3	3	38.67	53.86	150.64
	4	38.74	53.85	141.03
	5	38.72	53.80	141.92
	6	38.72	53.70	143.17
	7	38.72	53.70	143.77

This paper aimed to compare the behavior of the rear slopes of rubble mound breakwaters under seismic loading. To achieve this goal, nine curves were developed to describe the extreme total, horizontal, and vertical displacements of the three slope cases for various frequency values. The amplitude was fixed at 1 mm, 2 mm, and 3 mm, respectively, for each type of displacements. The results, presented in Figures 20 to 28, show significant differences in the response of each model to seismic loading. In particular, the displacements of the model corresponding to the slope 3 were found to be larger than those of the other two cases (slopes 1 and 2), which confirms the previous findings. This study provides important insights into the behavior of rubble mound breakwaters under seismic loading and highlights the importance of considering the rear slope's response in their design.

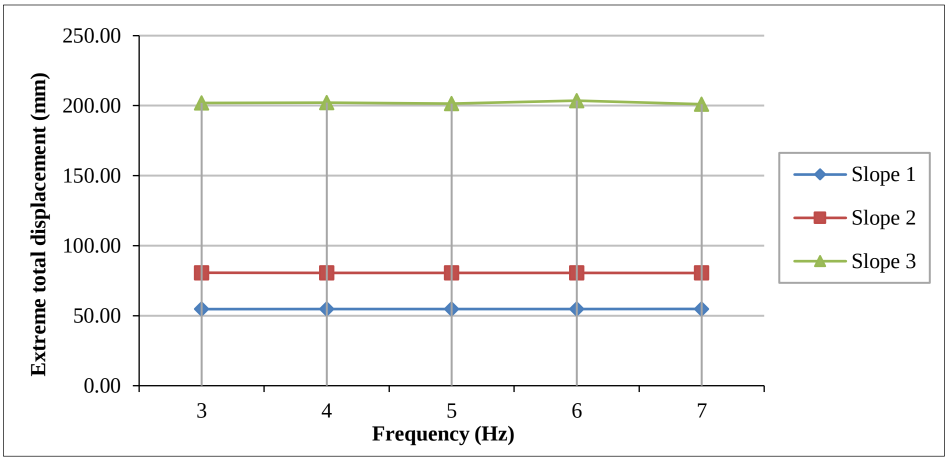

Figure 20. Variation of the extreme total displacement according to an amplitude of 1 mm for the three cases of slope

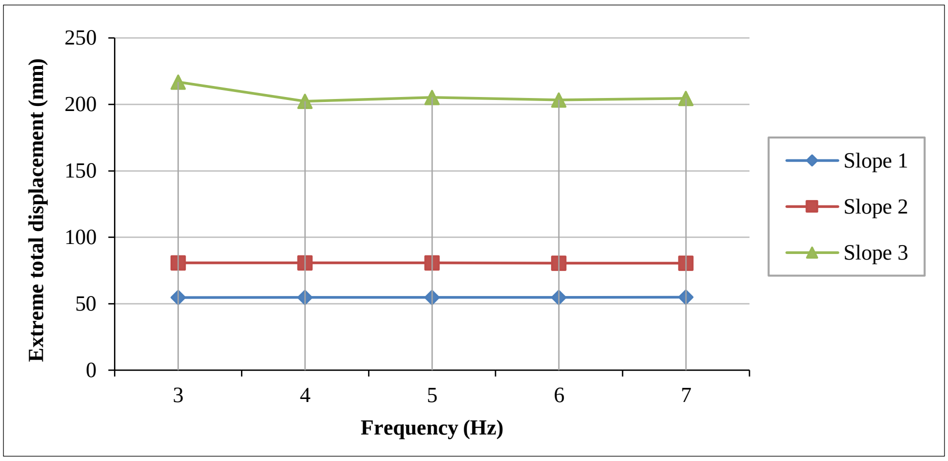

Figure 21. Variation of the extreme total displacement according to an amplitude of 2 mm for the three cases of slope

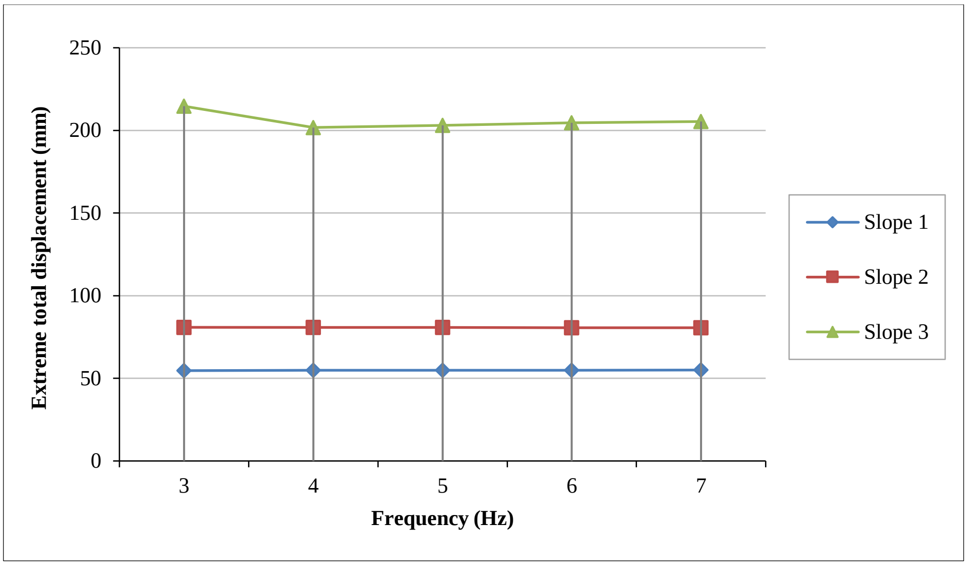

Figure 22. Variation of the extreme total displacement according to an amplitude of 3 mm for the three cases of slope

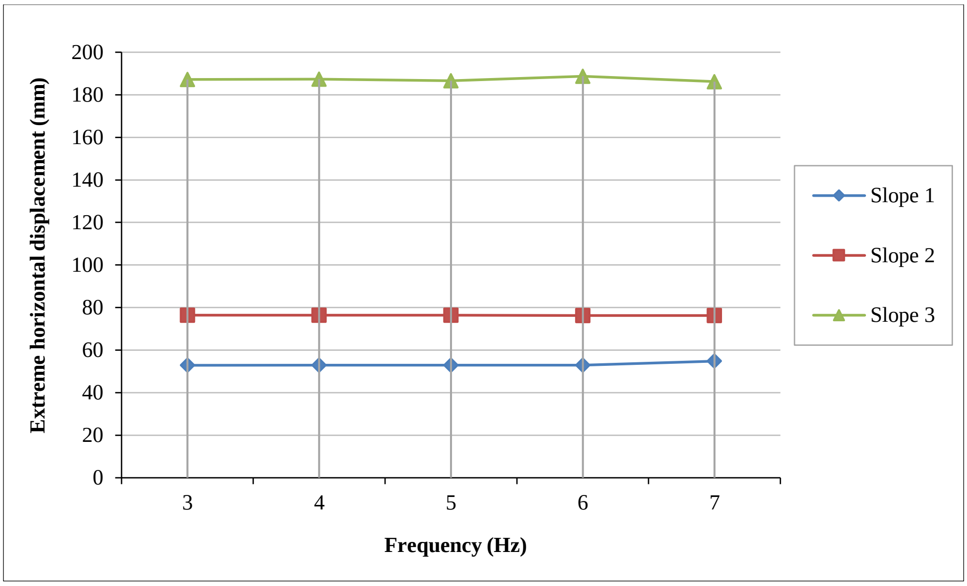

Figure 23. Variation of the extreme horizontal displacement according to an amplitude of 1 mm for the three cases of slope

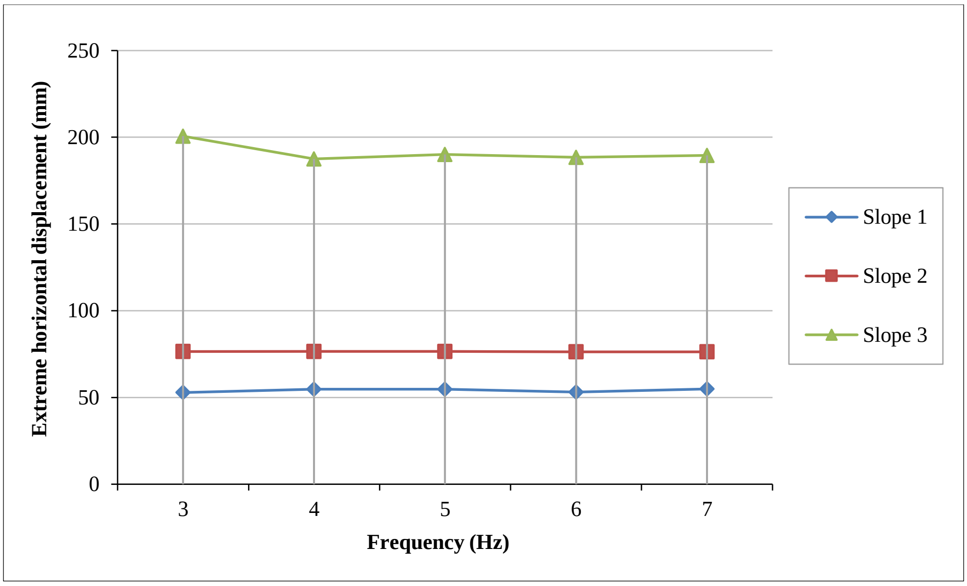

Figure 24. Variation of the extreme horizontal displacement according to an amplitude of 2 mm for the three cases of slope

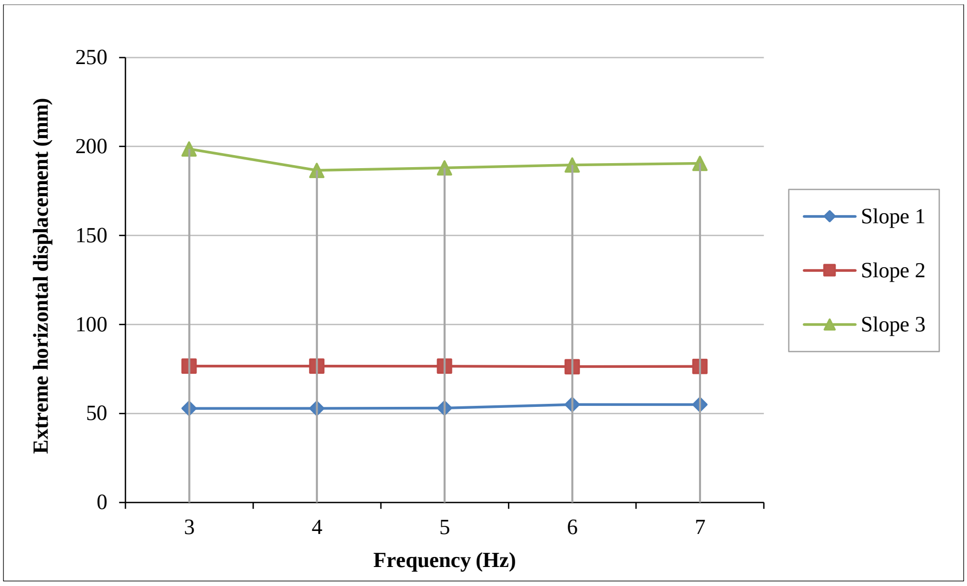

Figure 25. Variation of the extreme horizontal displacement according to an amplitude of 3 mm for the three cases of slope

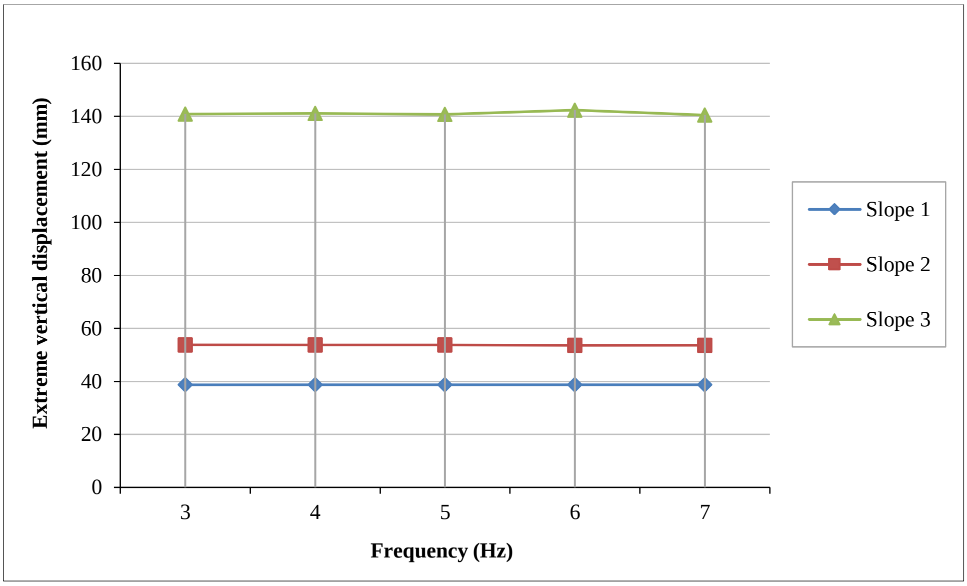

Figure 26. Variation of the extreme vertical displacement according to an amplitude of 1 mm for the three cases of slope

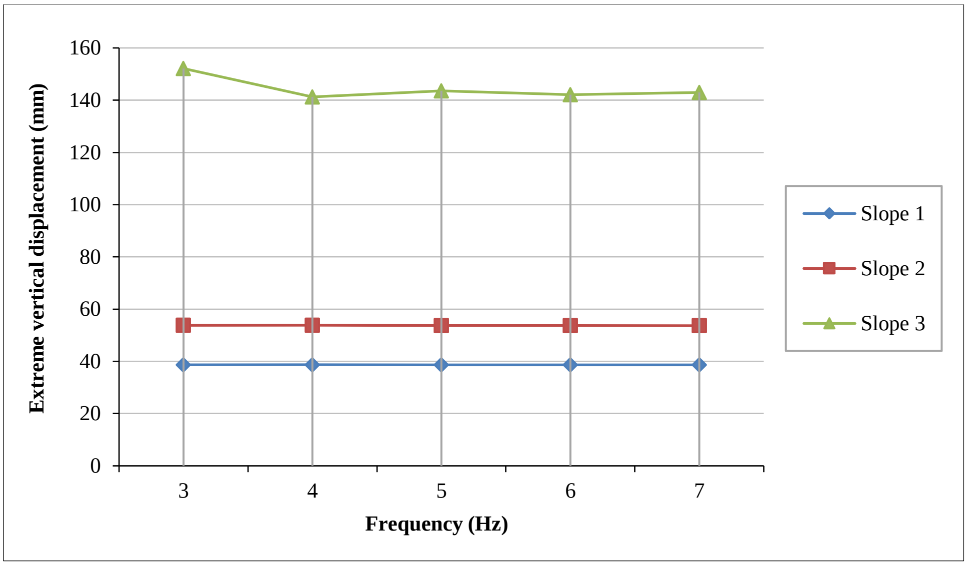

Figure 27. Variation of the extreme vertical displacement according to an amplitude of 2 mm for the three cases of slope

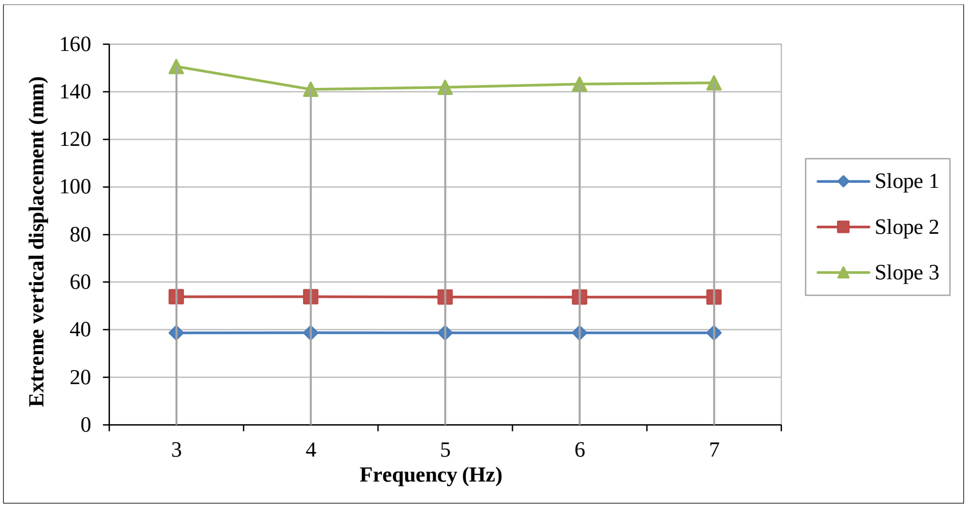

Figure 28. Variation of the extreme vertical displacement according to an amplitude of 3 mm for the three cases of slope

It is noteworthy that, among the three cases with different angles of inclination for the rear slope, the results for slope 3 correspond to the maximum value of deformations. Table 7 provides the extreme displacement values for each slope case under a seismic loading with an amplitude of 3 mm and a frequency of 7 Hz. It can be observed that the slope 3, having a steep angle of inclination, represents the most unstable case, followed by the slope 2 and the slope 1, as illustrated in Figures 29 to 31. Conversely, the slope 1 with a slight angle of inclination represents the most stable case. This finding has important implications for the design and stability assessment of rubble mound breakwaters under seismic loading. It highlights the critical role of the rear slope's angle of inclination in the structure's overall stability and safety. The obtained results demonstrate the need to carefully consider the slope's inclination when designing breakwaters in seismic-prone areas.

Table 7. Extreme displacements representing the three cases of the rear slope corresponding to an amplitude of 3mm and frequency of 7 Hz

Slope	Angle	Amplitude	Frequency	Total Displacements	Horizontal Displacements	Vertical Displacements
SLOPE 1	27°			55.01	55.01	38.72
SLOPE 2	34°	3	7	80.6	76.38	53.7
SLOPE 3	36°			205.39	190.46	143.77

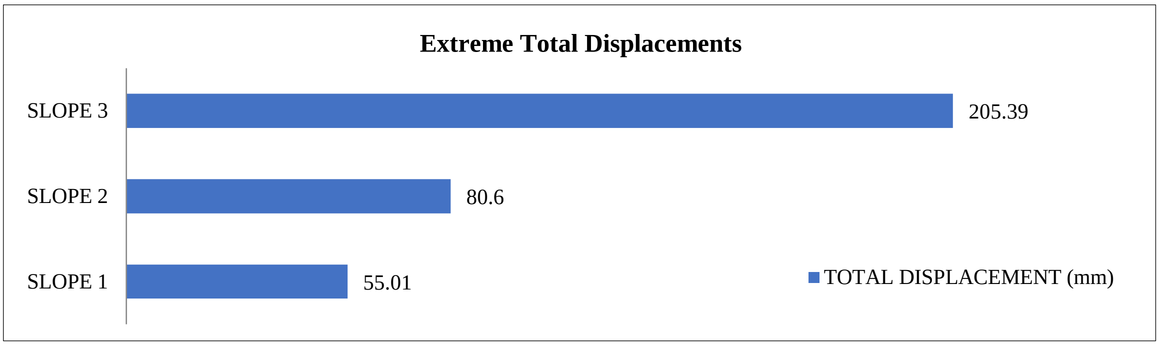

Figure 29. Extreme total displacements of rubble-mound breakwater

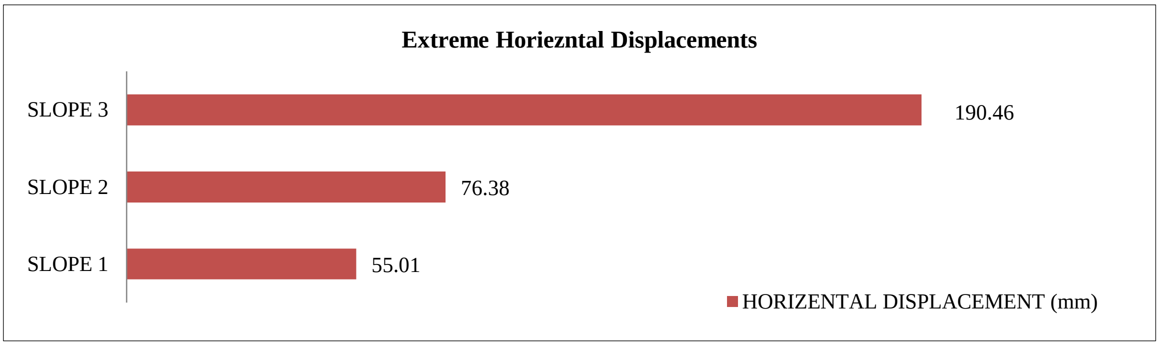

Figure 30. Extreme horizontal displacements of rubble-mound breakwater on seismic's loads

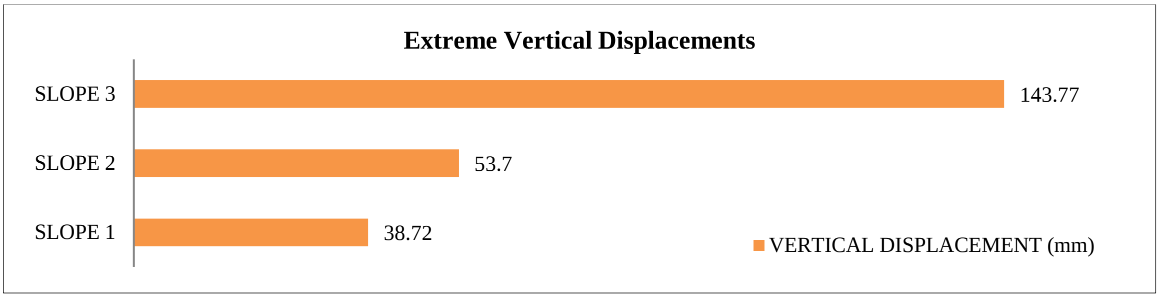

Figure 31. Extreme vertical displacements of rubble-mound breakwater on seismic's loads

The curves depicting the extreme total, horizontal, and vertical displacements for different amplitudes and frequencies corresponding to each slope case illustrate the significant impact of the rear slope's inclination on the structure's stability. As the angle of inclination of the rear slope becomes slighter, the breakwater becomes more stable to earthquakes. Observation and analysis of Figures 32 to 34 suggest that the curves can be divided into three parts. The upper part joins the curves representing the deformations corresponding to the slope 3 model, the lower part joins the curves representing the deformations corresponding to the slope 1 model, and the intermediate part, which is close to the lower part, joins the curves representing the deformations corresponding to the slope 2 model. Based on this observation, a comparison of the different slope cases allowed us to confirm the validity of the previous results. These findings emphasize the critical role of the rear slope's angle of inclination on the stability of rubble mound breakwaters under seismic loading. They provide valuable insights for the design and construction of breakwaters in seismic-prone areas, highlighting the importance of considering the slope's inclination to ensure the structure's stability and safety.

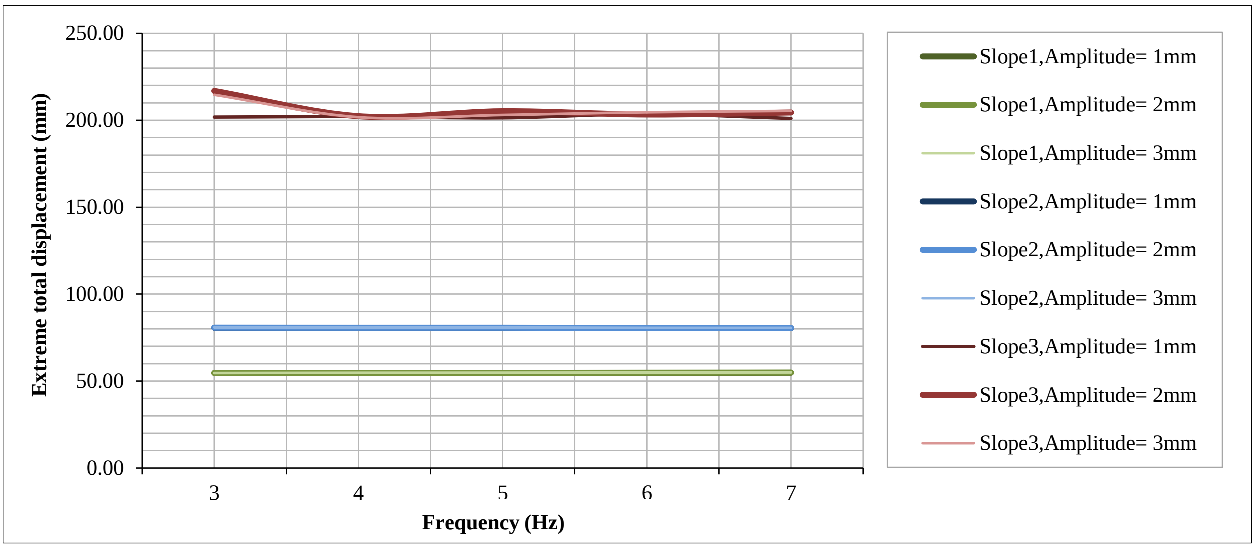

Figure 32. Extreme total displacements corresponding to the three cases for different amplitudes and frequencies

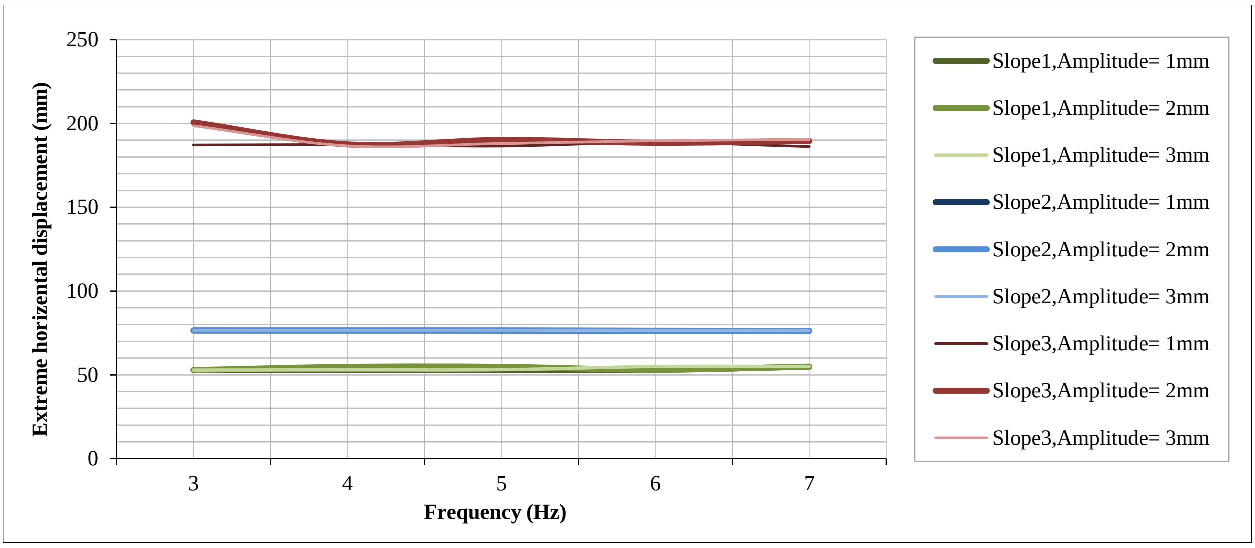

Figure 33. Extreme horizontal displacements corresponding to the three cases for different amplitudes and frequencies

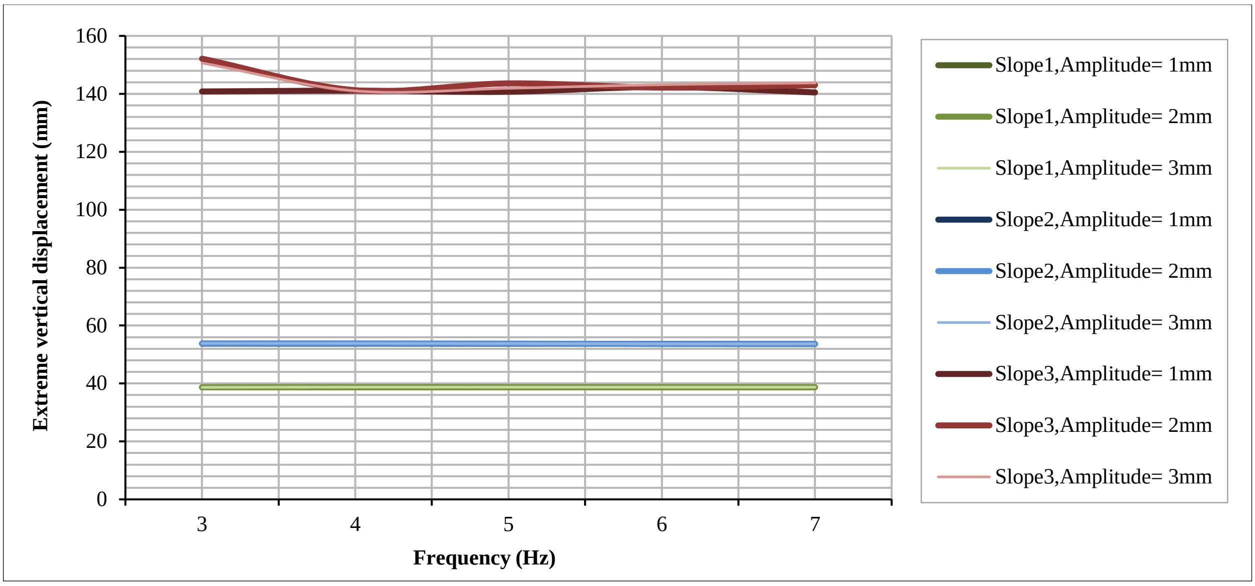

Figure 34. Extreme vertical displacements corresponding to the three cases for different amplitudes and frequencies

4. Conclusions

The present research, based on a numerical study using Plaxis 2D, investigated the seismic response of a conventional rubble mound breakwater seated on a rigid bed, subjected to seismic loads with varying rear slope angles. The study focused on assessing the stability of rubble mound structures across various slope conditions, with particular attention to the variations in frequency and amplitude of the seismic loads, leading to the following conclusions:

- ***Impact of Slope Inclination*:** The responses of breakwater models to seismic loads demonstrated that the slope inclination significantly affects the structure's ability to resist seismic forces. Steeper slopes increase the risk of structural failure, while slopes with a slight inclination enhance seismic stability.
- ***Comparative Displacement Analysis*:** Analysis of displacements under seismic loads revealed that breakwaters with a steeper slope exhibited larger displacements than those with a slight slope across diverse amplitude and frequency ranges. This suggests that optimizing the slope angle could be crucial in design considerations for improving resilience.
- ***Stability Assessment*:** The study concluded that rubble mound breakwaters with slight rear slopes are inherently more stable seismically compared to those with steep rear slopes. This finding is critical for engineering practices, as it directs design optimizations towards slighter slopes to achieve better performance under seismic stress.

In conclusion, our comprehensive numerical analysis suggests that conventional rubble mound breakwaters, when designed with slight rear slopes and seated on a rigid bed, show significantly enhanced resistance to seismic forces when subjected to harmonic loads. These insights are instrumental in advancing the design optimization of rubble mound breakwaters, particularly for enhancing their resilience in regions prone to seismic activities. The study not only contributes to the theoretical understanding of breakwater dynamics under seismic loading but also has practical implications for the construction and retrofitting of coastal defenses, ensuring they are better equipped to handle the challenges posed by earthquakes.

4.1. Limitations

The study's results may lack validation against experimental data or field observations, raising questions about the reliability and accuracy of the numerical model.

4.2. Future Scope

Further research could explore the dynamic behavior of rubble mound breakwaters under seismic loading through advanced numerical methods and field validation studies.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A. and E.A.; methodology, M.A. and E.A.; software, M.A.; validation, M.A. and E.A.; investigation, M.A. and E.A.; resources, M.A. and E.A.; data curation M.A. and E.A.; writing—original draft preparation, M.A. and E.A.; writing—review and editing, M.A. and E.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this research are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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