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Effects of Berms on Rubble Mound Breakwater Stability under Seismic Loading

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ABSTRACT

For rubble mound breakwaters, incorporating a berm in the seaward slope can be very effective in reducing wave overtopping and mitigating wave loads acting on the breakwater armor elements. This research aims to investigate the effect of horizontal berm on the seismic response of conventional rubble mound breakwaters, considering various amplitudes and frequencies characterizing seismic loads. Finite element models of conventional rubble mound breakwaters, with and without berm, are developed using Plaxis 2D software for this purpose. Additionally, the stability of rubble mound breakwaters with berms is studied through various numerical models, considering different lengths and height levels of the berm. A comparative analysis of the results shows that rubble mound breakwaters incorporating berms exhibit lower deformation characteristics compared to those without berm. The numerical study results suggest that berms can significantly enhance the stability and reduce displacements of rubble mound breakwaters under seismic loading compared to breakwaters without berm.

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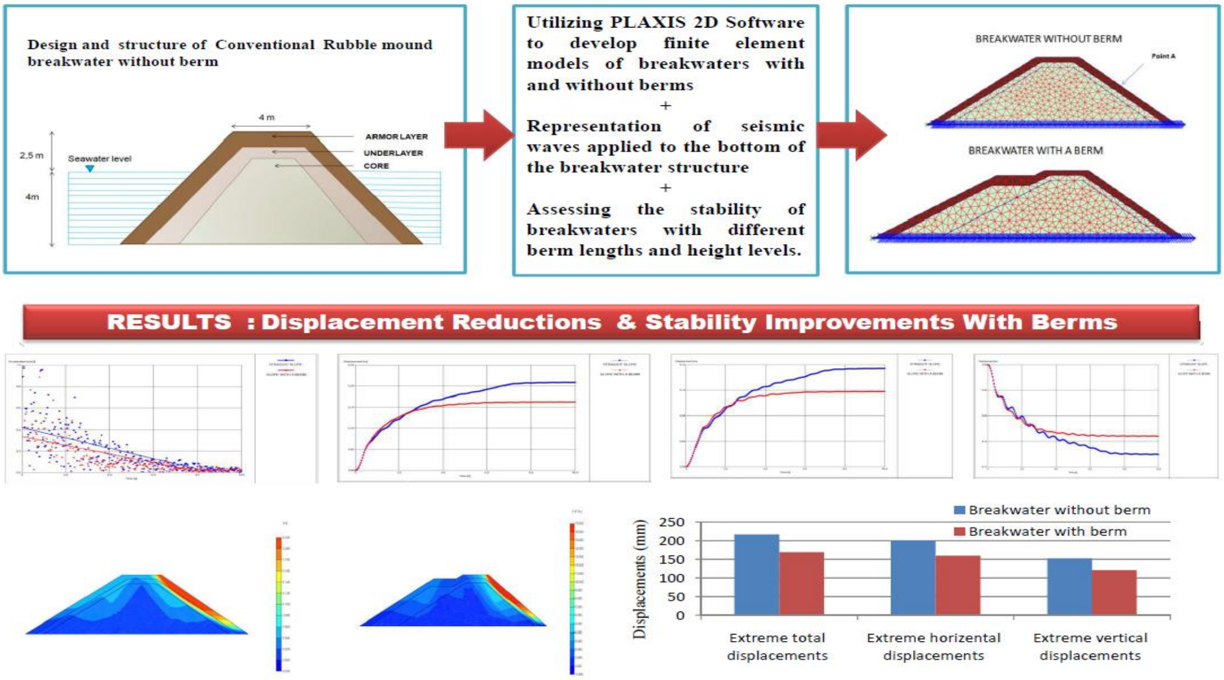
Graphical Abstract



Utilizing PLAXIS 2D Software to develop finite element models of breakwaters with and without berms
+
Representation of seismic waves applied to the bottom of the breakwater structure
+
Assessing the stability of breakwaters with different berm lengths and height levels.

RESULTS : Displacement Reductions & Stability Improvements With Berms

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1. INTRODUCTION

Earthquakes pose a serious threat to civil engineering structures, potentially resulting in severe structural damage, collapses, and loss of life. In recent years, numerous studies have focused on understanding the seismic vulnerability of civil engineering structure (1, 2). These studies aimed to comprehend the underlying mechanisms and propose risk mitigation solutions (3, 4). Recent research has investigated the seismic vulnerability of coastal structures. Reis et al. (5) underscore the need to address coastal structural vulnerability to earthquakes and resulting tsunamis because of the uneven distribution of the world population in coastal regions**.** Mohammed (6) attempted to develop a Coastal Vulnerability Index (CVI) for the coastal areas of Alexandria and Behera governorates in the Nile delta region using nine relative vulnerability variables.

Furthermore, numerous studies have assessed damages in rubble mound breakwaters. Campos et al. (7) provided a historical review of damage models for rubble mound structures. Almeida et al. (8) explored characterizing damage in rock slopes, which is relevant to evaluating bermed breakwater stability under various loading conditions. Aniel-Quiroga et al. (9) conducted laboratory experiments to anlyze damages in rubble mound breakwaters under tsunami impact, and proposed the necessity to conduct more laboratory experiments, varying the geometries. Hofland et al. (10) explored measuring damage in physical model tests of rubble mound breakwaters.

A significant amount of research has been conducted on the design of rubble mound breakwaters to minimize failures and enhance their stability. Karapa et al. (11) Investigated the importance of slope reinforcement by installing X-block concrete supports to strengthen the gravity wall construction and prevent failure. Onyelowe et al. (12) focused on conducting a steady state seepage analysis and optimizing the downstream slope factor of safety in a poorly compacted earthen embankment, using the Modified Bishops method and a double-textured High-Density Polyethylene (HDPE) Geo-membrane barrier, resulting in improved stability. Mousavi et al. (13) evaluated by using the physical modeling of the breakwater and different tests the stability level of antifer concrete blocks considering the decrease of the armor weight. Yamini et al. (14) investigated and enhanced Articulated Concrete Block Mattress (ACB Mat) design for coastal protection through laboratory-scale experimentation and formulation of modified equations and design charts.

Incorporating a berm on the seaward slope of rubble mound breakwaters has been the subject of numerous previous research, which have elaborated on how this variation can enhance the stability of rubble mound breakwaters. To evaluate the impact of a berm on wave overtopping discharge, neural network technique has been developed to demonstrate how wave overtopping diminishes due to the presence of a berm (15). Vermeer (16) explores the stability of rubble mound breakwaters with berm through a literature survey and model investigation. Dijkstra (17) investigated the stability of armor layers on a rubble mound breakwater with berm. Van Gent (18) has shown the influence of a berm in combination with the upper and lower slope on the stability of the rubble mound breakwater. Celli et al. (19) provided a new stability formula aimed to be used when relative low berms are foreseen at the toe of conventional rubble mound breakwaters. Sasikumar et al. (20) have employed numerical simulations to explore wave kinematics within berm breakwaters, assessing the impact of varying berm geometry. Chen et al. (21) have contributed insights into wave overtopping at breakwaters with berms, considering their influence on wave dynamics. Burcharth (22) delves into the front slope stability of berm breakwaters, offering valuable insights into the structural aspects of berms. Van Der Meer (23) provides a fundamental understanding of breakwater construction.

In the context of investigating the stability of breakwaters, it is imperative to consider previous research on the seismic response of rubble mound breakwaters subjected to seismic loads as an important criterion for designing these types of structures. Recently, Akarsh et al. (24) attempted to demonstrate the seismic responses of rubble mound breakwaters through a series of shake table tests and numerical simulations, revealing that higher acceleration amplitudes resulted in significant settlements and horizontal displacements of the breakwater. Cihan and Yuksel (25) demonstrated the importance of the toe of a rubble mound breakwater face to seismic resistance by using an experimental approach, supported by a numerical method based on PLAXIS 2D software, and they focused on the deformation of breakwater armored units under cyclic loading (26).

This paper presents a numerical study investigating the seismic response of a rubble mound breakwater with a high berm compared to a rubble mound breakwater without a berm, evaluating different heights and lengths of the berm. Subsequently, we will analyze the influence of this variation on the stability of the structure under seismic loading for different values of frequencies and amplitudes characterizing the seismic waves. To achieve this, the data regarding the design of the breakwater considered in this research and the numerical calculation method were presented in section 2. Results of the analysis, including main observations from numerical simulations, were detailed in section 3. Lastly, section 4 presented the conclusions drawn from this research, highlighting the implications of the findings, study limitations, and suggestions for future research.

2. MATERIALS AND METHODS

This paper treats a conventional rubble mound breakwater consisting of a core, underlayer, and an armor layer. Figure 1 illustrates the design and layers of a typical conventional rubble mound breakwater.

We considered a breakwater with a height of 6.5 meters, seawater level of 4 meters, and crest width of 4 meters. These dimensions will be taken into account throughout our analysis. Based on the model mentioned above of the rubble mound breakwater, we define the characteristics of the layers that comprise the structure. It is noteworthy to mention that the core and under layer have the same properties. Furthermore, we used empirical data that describes the the materials used for the construction of the rubble mound breakwaters. In order to consider the diverse impacts of seismic events on both the soil and the structural integrity of the breakwater, we conducted an extensive analysis using multiple seismic waves characterized by different frequencies and amplitudes. To establish the precision of our model, we relied upon the most current and meticulously verified seismic data that was available (25). By considering these factors, our objective was to offer a thorough and scientifically well-founded assessment of how the breakwater structure would perform under seismic conditions. The seismic data utilized in our analysis is presented in Table 2 (25).

We executed stress-strain simulations on models of rubble mound breakwaters using the Plaxis 2D V8 software (27), which employs the finite element method (FEM). This method, has been used in several researchs to analyze the stability of civil engineering structures under seismic loads (25, 28, 29). In this paper, the Finite Element Method was employed to analyze the seismic response of a rubble mound breakwater with a berm, considering different berm height levels and lengths, and comparing it to a breakwater without a berm.

Plaxis 2D is a two dimensional finite element program developed to perform deformation and stability analyses for different types of geotechnical applications. The program uses a convenient graphical interface that allows users to generate a geometric model and a finite element mesh based on the vertical cross section of the structure to be studied. The interface for using Plaxis 2D software consists of four subprograms (Input, Calculations, Output and Curves). Soil and structures are subjected to static and dynamic loads. If the loads are severe, as in earthquakes, they may cause significant damages. Using Plaxis 2D Software we analyzed the effects of seismic loads in the different models of rubble mound breakwater used in the present research.

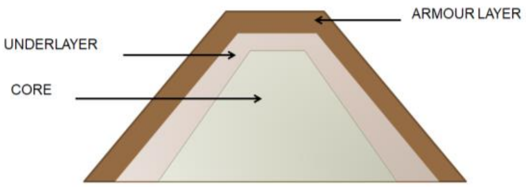

Figure 1. Layer structure of a conventional rubble mound breakwater

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
E (Mpa)	2	20
Poisson rate v	0.2	0.3
Expansion ψ (°)	8°	10°
Cohesion c (kPa)	0	0
Friction angle φ (°)	37°	42°

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

To simulate the models of the present research, fifteen noded, triangular, 2D plane-strain elements were used in the FEM model. A Plane strain model is used for geometries with an uniform cross section and corresponding stress state and loading scheme over a certain length perpendicular to the cross section (z direction). Displacements and strains in z direction are assumed to be zero. However, normal stresses in z direction are fully taken into account. In earthquake problems the dynamic loading source is applied along the bottom of the model resulting in shear waves that propagate upwards. This type of problem is generally simulated utilizing a plane strain model (27). We used a Mohr-Coulomb model for modeling the dynamic behavior of the granular materials constituting the rubble mound breakwater. This model is based on soil parameters that are well known in engineering practice. It should be noted that the choice of the slope values of the back slope , the seaward slope , the height level and the length of the berm are determined according to the recommendations of The Rock Manual, which contains the specifications for the use of breakwaters and rock fill materials. On the seaside, the slope is steeper than 3/2; We considered an angle of 33°. For the rear slope of the breakwater, the slope should be comprised between 4/3 and 2/1; We considered an angle of inclinaison of 36°. Two cases of berm height levels and two cases of berm length were considered.: A height level of 5 m, a height level of 6 m, a length of 2.5 m and a length of 3.5 m.

The earthquake is simulated by applying a predetermined displacement at the bottom boundary. Therefore, the input value of the horizontal prescribed displacements is set to 0.01m. The vertical component of the prescribed displacement is kept zero (U_X=0.01m, U_y =0). At the far vertical boundaries, absorbent boundary conditions are applied to absorb outgoing waves. In this research we used Standard earthquake boundaries, this option is selected from the loads menu. The boundary conditions as described above are automatically generated. The modeling of the rubble mound breakwater representing each case of variants on Plaxis 2D Software is presented in Figure 2. Once the geometry model was defined , it is necessary to discretize the geometry into finite elements to carry out finite element calculations. The mesh generation process takes into account several factors such as soil stratigraphy, structural objects, loads, and boundary conditions. PLAXIS 2D presents five modes of mesh coarseness: Fine, very fine, medium, coarse, and very coarse. To ensure the accuracy of the numerical results, the mesh must be sufficiently fine. For the present research, a very fine mesh was employed with a high density of elements, as summarized in Table 3 (27).

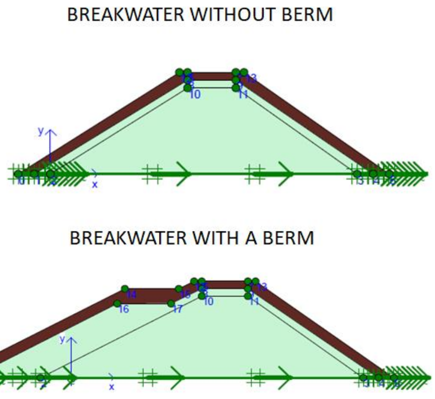

Figure 2. Rubble mound breakwater models on Plaxis 2D

The FEM models corresponding to the breakwater with berm (berm hight of 6 m and a length of 3.5 m) and without berm have 594, and 600 elements, respectively (see Figure 3). The parameters required for the granular materials comprising the rubble-mound breakwater include the internal friction angle ϕ, cohesion c, and dilatancy angle ψ.

For each model test, FEM analyses were performed for horizontal shaking of the different cases shown in Table 2. In this article, we will present the figures of the models of the variants of the breakwater which corresponds to the case of amplitude of 2 mm and a

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	250 – 700 elements
Very fine	500 - 1250 elements

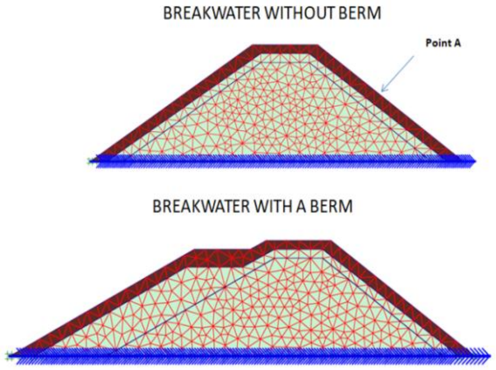

Figure 3. Finite element meshes

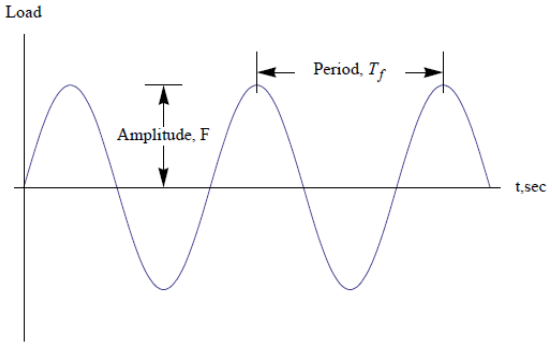

Figure 4. Sinusoidal loading

frequency of 3 Hz. Dynamic loads were applied at the bottom of the finite element model. Ten second acceleration records were used as input motions. The acceleration and extreme total, horizontal, and vertical displacements were calculated and measured during the dynamic time at point A, located on the rear slopes (as shown in Figure 3). In the present research we represented the dynamic loads by harmonic loads. A harmonic loading or sinusoidal loading is the simplest dynamic force and frequently used in vibrations due to earthquakes and machines (Figure 4).The characteristics of the force are defined by their amplitude, frequency, shape, and duration. In Plaxis (27), harmonic loads are defined as:

$$F=M' F' \sin(\omega t + \Phi_0) \quad (1)$$

In which

M’: Amplitude multiplier.

F’: Input value of the load.

ω : 2 π f, with f=Frequency in cycles per unit of dynamic time (Hz).

Φ_0: Initial phase angle in degrees in the sine function. (In this research, we considered an angle of 0°).

3. RESULTS AND DISCUSSIONS

In this article, we considered models of the rubble mound breakwater with a berm and a breakwater without a berm. In order to justify the effect of this variation, we examined two levels of berm height (5 meters and 6 meters) and two lengths of the berm (2.5 meters and 3.5 meters). The numerical study investigated the seismic response of all cases for various values of amplitudes and frequencies as specified in Table 2. Firstly, we presented the results of the numerical computation for the conventional model of the rubble mound breakwater without a berm, considering various values of frequencies and amplitudes. These results manifest in extreme total displacements, extreme horizontal displacements, and extreme vertical displacements, as shown in Table 4. The results of the numerical study, using the finite element method, indicated an important deformations under seismic loads within the 10 seconds, as shown in Figures 5 and 6. The contours of the extreme total displacements for the model of the rubble mound breakwater without berm are illustrated in Figure 7. Based on the results of the finite element analysis, it is observed that the magnitude of total displacements increased at the rear slope (specifically in the vicinity of pointA).

3. 1. The Impact of Height Level of Berm

The incorporation of a berm into the rubble mound breakwater depends on several parameters. This research evaluated the effect of the berm analysing two parameters: the height level of the berm and the length of the berm. In order to assess the impact of the berm height level on the stability of the rubble mound breakwater in response to seismic loads, the seismic response of the

TABLE 4. Extreme total, horizontal and vertical displacements corresponding to the breakwater without berm

Amplitude (mm)	Frequency (Hz)	Extreme total displacements (mm)	Extreme horizontal displacements (mm)	Extreme vertical displacements (mm)
1	3	201,23	187,16	140,82
	4	202,1	187,33	141,08
	5	201,4	186,52	140,73
	6	203,59	188,7	142,37
	7	201,05	186,2	140,49
2	3	216,86	200,65	152,12
	4	202,35	187,53	141,25
	5	205,18	190,19	143,6
	6	203,31	188,47	142,15
	7	204,47	189,57	142,99
3	3	214,65	198,64	150,64
	4	201,46	186,63	141,03
	5	203,05	188,06	141,92
	6	203,31	188,47	142,15
	7	205,39	190,46	143,77

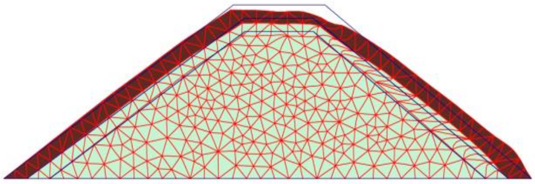

Figure 1. Deformed mesh corresponding to the breakwater without a berm for an amplitude of 2 mm and a frequency of 3 Hz

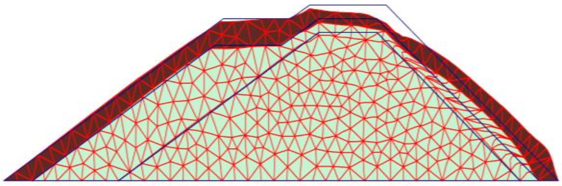

Figure 6. Deformed mesh corresponding to the breakwater with a berm hight of 6 m and a length of 3.5 m for an amplitude of 2 mm and a frequency of 3 Hz

breakwater will be compared for two berm height levels : 5 meters and 6 meters for various values of amplitudes and frequencies, while keeping the length of the berm constant at 2.5 meters. After modeling in the Plaxis 2D software and performing numerical calculations based on the finite element method, the results were obtained as shown in Tables 5 and 6. Comparing the results from Tables 5 and 6, it is observed that the rubble mound breakwater with a berm height of 6 meters exhibits less significant deformations compared to the one with a 5-meter berm height, indicating that the former model is more stable than the latter.

The behavior of these two breakwater models was studied under a seismic load with an amplitude of 2mm and a frequency of 3 Hz for a dynamic duration of 10 seconds. Figures 9, 10, 11 and 12 represent the variation in acceleration, extreme total displacements, extreme horizontal displacements, and extreme vertical displacements for each berm height level case in a dynamic duration of 10 second.

Based on these results, Figure 13 has been constructed to illustrate the extreme displacements for each model of the rubble mound breakwater height level. It highlights the differences in deformation among the

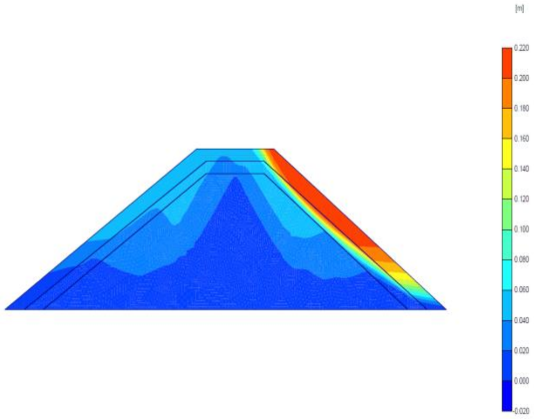

Figure 7. Contours of extreme total displacements corresponding to the breakwater without berm for an amplitude of 2 mm and a frequency of 3 Hz after 10s

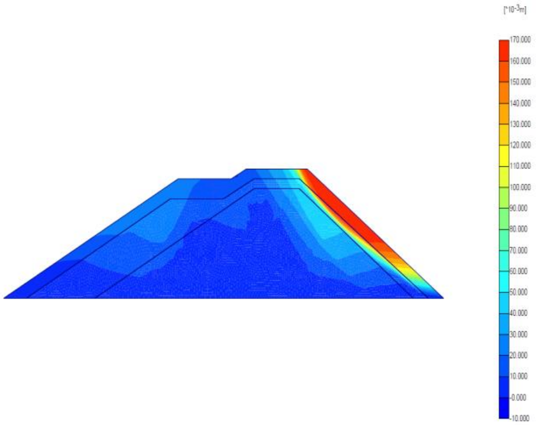

Figure 8. Contours of extreme total displacements corresponding to the breakwater with berm hight of 6 m and a length of 3.5 m for an amplitude of 2 mm and a frequency of 3 Hz after 10s

TABLE 5. Extreme total, horizontal and vertical displacements corresponding to the breakwater with a berm of 5m height level

Amplitude (mm)	Frequency (Hz)	Extreme total displacements (mm)	Extreme horizontal displacements (mm)	Extreme vertical displacements (mm)
1	3	200,31	186,33	140,09
	4	199,97	186,06	139,86
	5	200,9	186,86	140,46
	6	200,06	186,1	139,89
	7	200,4	186,42	140,17

	3	200,82	186,74	140,5
	4	200,25	186,37	140,14
2	5	200,29	186,25	140,04
	6	200,69	186,63	140,28
	7	201,46	187,38	140,94
	3	201,85	187,64	141,28
	4	195,55	182,02	136,67
3	5	198,89	184,9	138,92
	6	201,42	187,24	140,8
	7	199,1	185,18	139,04

TABLE 6. Extreme total, horizontal and vertical displacements corresponding to the breakwater with a berm of 6m height level

Amplitude (mm)	Frequency (Hz)	Extreme total displacements (mm)	Extreme horizontal displacements (mm)	Extreme vertical displacements (mm)
	3	180,45	168,88	126,88
	4	180,35	168,82	126,86
1	5	180,5	168,94	126,87
	6	180,5	168,89	126,83
	7	181,04	169,34	127,32
	3	180,39	168,87	126,87
	4	180,13	168,6	126,68
2	5	180,99	169,34	127,11
	6	181,24	169,51	127,31
	7	181,52	169,84	127,53
	3	179,93	168,49	126,86
	4	180,65	169,15	127,34
3	5	181,72	170,05	127,7
	6	182,66	170,77	128,28
	7	179,59	167,71	126,45

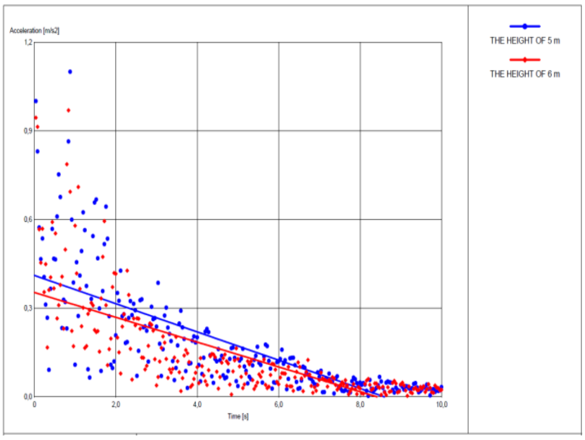

Figure 9. Slope-acceleration time history calculated for the two models of the height of berm

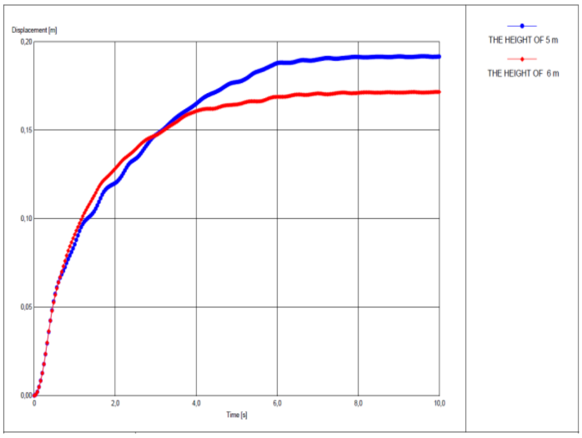

Figure 10. Slope- total displacement time history calculated for the two models of the height of the berm

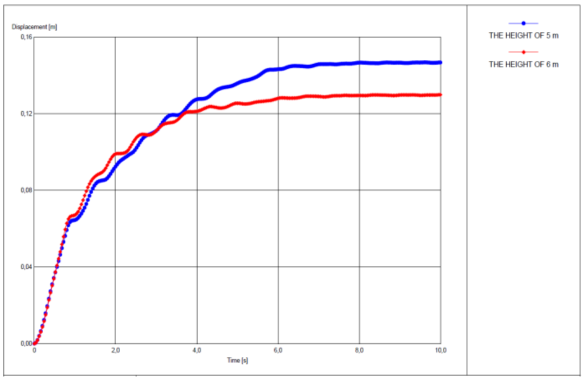

Figure 11. Slope- horizontal displacement time history calculated for the two models of the height of the berm

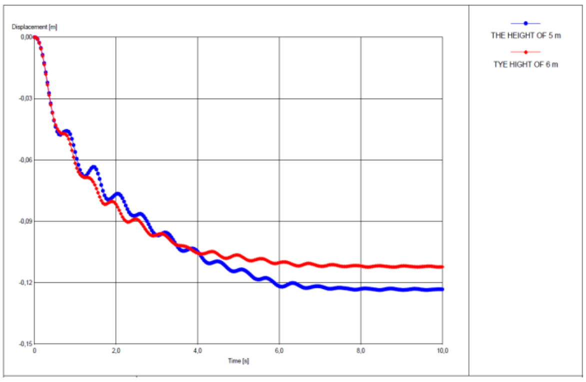

Figure 12. Slope- vertical displacement time history calculated for the two models of the height of the berm

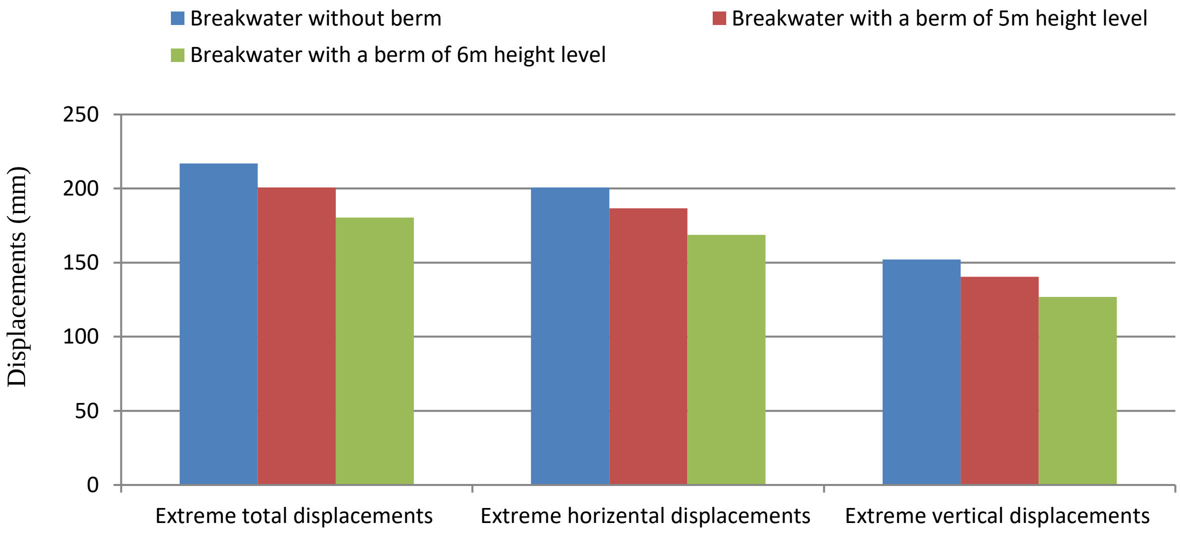

Figure 13. Comparison of the extreme displacements among the models of breakwaters, without a berm and with berm heights of 5m and 6m

breakwater with a berm height level of 5 meters, a height level of 6 meters, and the breakwater without a berm, which exhibits the most significant deformations. The analysis of these results leads to the conclusion that the higher the value of the berm height level, the more extreme displacements decrease at the rubble mound breakwater under seismic loading.

3. 2. The Impact of Length of Berm

To evaluate the influence of berm length on the seismic stability of the rubble mound breakwater, A comparative analysis of its seismic response for two berm lengths was conducted: 2.5 meters and 3.5 meters, across varying amplitudes and frequencies, while maintaining a constant berm height of 6 meters. The results illustrated in Tables 6 and 7 were obtained. Analyzing the results in Tables 6 and 7, it is observed that the rubble mound breakwater with a 3.5-meter berm is less deformed compared to the one with a 2.5-meter berm, indicating that the first model is more stable. In order to validate these results, we examined how the two breakwater models responded to a seismic load with a 2mm amplitude and a 3 Hz frequency over a dynamic time of 10 seconds. Figures 14, 15, 16 and 17 show variations in acceleration, extreme total displacements, extreme horizontal displacements, and extreme vertical displacements, for each berm length case during this 10 second dynamic analysis.

The results corresponding to a seismic load with a 2 mm amplitude and a 3 Hz frequency show the effects of varying the length of the berm on the seismic response of

TABLE 7. Extreme total, horizontal, and vertical displacements corresponding to the breakwater having a berm height of 6 meters and a length of 3.5 meters

Amplitude (mm)	Frequency (Hz)	Extreme total displacements (mm)	Extreme horizontal displacements (mm)	Extreme vertical displacements (mm)
1	3	169,37	159,56	121,05
	4	168,55	158,54	120,44
	5	167,57	157,89	119,7
	6	168,5	158,7	120,41
	7	168,77	158,92	120,58
2	3	169,31	159,53	120,86
	4	169,04	159,29	120,88
	5	171,22	160,96	122,81
	6	168,69	158,79	120,68
	7	170,39	160,16	122,03
3	3	170,24	160,4	121,53
	4	171,23	161,23	122,58
	5	176,04	165,03	126,93
	6	174,81	164,02	125,86
	7	171,43	160,62	122,9

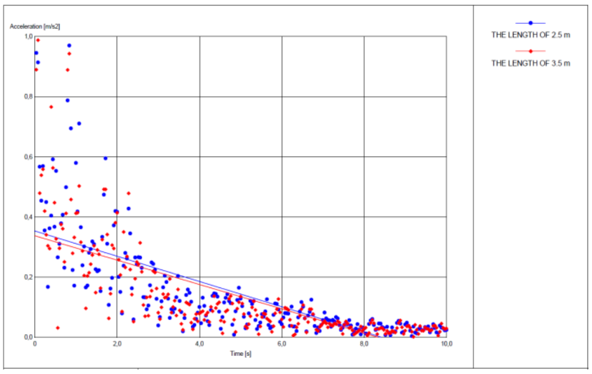

Figure 14. Slope-acceleration time history calculated for the two models of the length of berm

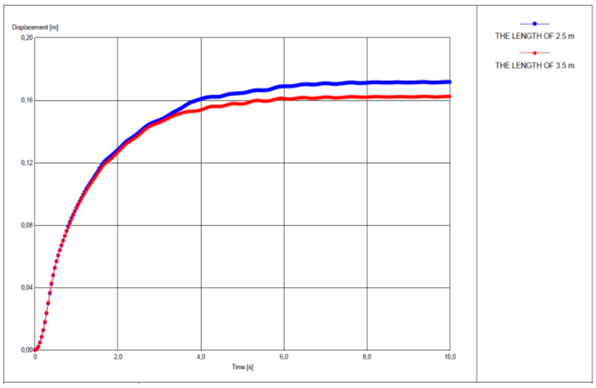

Figure 15. Slope- total displacement time history calculated for the two models of the length of the berm

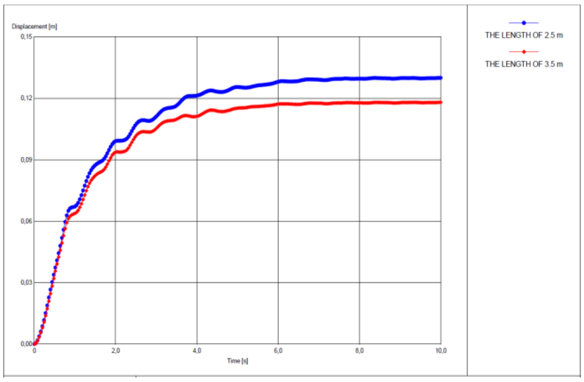

Figure 16. Slope- horizontal displacement time history calculated for the two models of the length of the berm

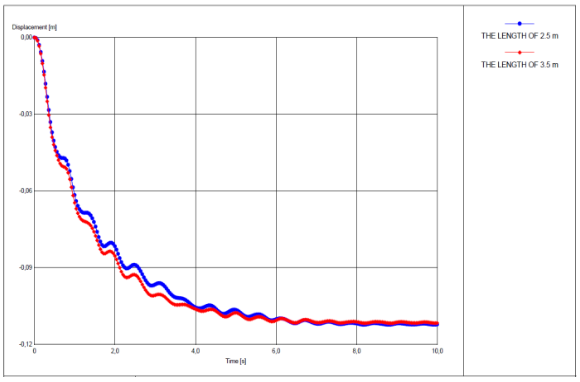

Figure 17. Slope- vertical displacement time history calculated for the two models of the length of the berm

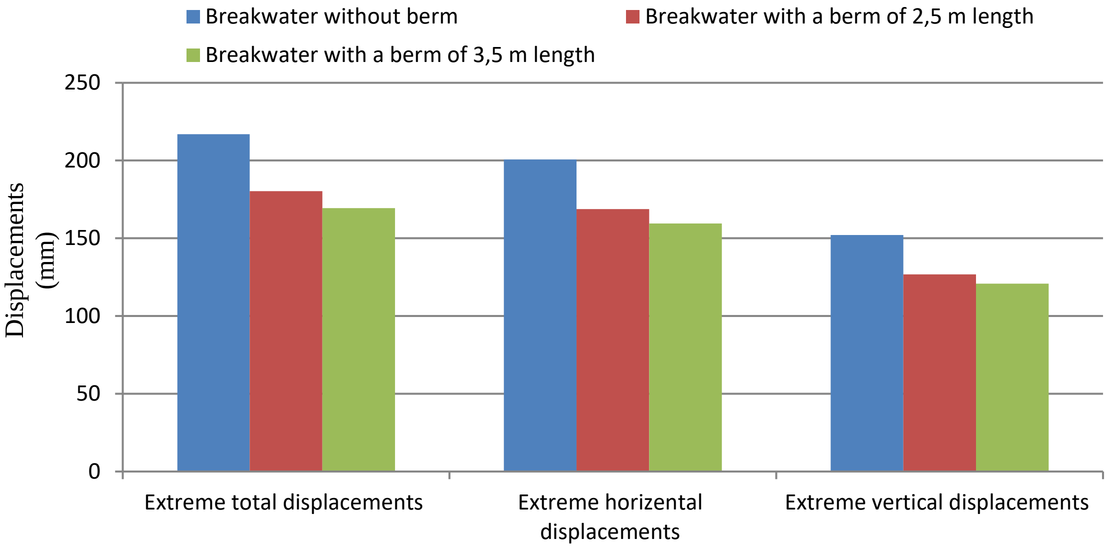

Figure 18. Comparison of the extreme displacements among the models of breakwaters, without a berm and with berm lengths of 2.5m and 3.5m

the rubble mound breakwater. Based on these results, Figure 18 has been constructed, illustrating the extreme displacements for each model of the rubble mound breakwater berm length and highlighting the differences in deformation for the breakwater with a berm length of 3.5 meters, a length of 2.5 meters, and the breakwater without berm, which exhibits the most significant deformations. The analysis of these results leads to the conclusion that the higher the value of the berm length, the more extreme displacements at the rubble mound breakwater decrease under seismic loading.

3. 3. The Impact of Incorporation of a Berm Into the Rubble Mound Breakwater

After demonstrating the impact of both the height and length of the berm on the seismic response of the rubble mound breakwater, The effect of integrating this variation into a conventional model without a berm was examined. To demonstrate the significance of this variation, we choosed the most stable model of the rubble mound breakwater with a berm among those studied previously. Subsequently, the seismic response was compared to that of the model without a berm for various values of amplitudes and frequencies. Through a comparative analysis of the results in Table 7 corresponding to the breakwater having a berm height of 6 meters and a length of 3.5 meters and the results in Table 4, it becomes evident that the rubble mound breakwater incorporating a berm exhibits lower deformation characteristics (Figures 6 and 8) compared to the one without a berm. Figures 19, 20, 21 and 22, provide a graphical representation of the variations in acceleration, extreme total displacements, extreme horizontal displacements, and extreme vertical displacements for the two models during this 10-second dynamic analysis for an amplitude of 2mm and a frequency of 3Hz. Thus, it can be deduced that the model with a berm exhibits significient structural stability under seismic loads. The comparison of the curves in Figures 20, 21 and 22 reveals a significant disparity in displacements, underscoring the stabilizing effect of the berm. Figure 23 shows the extreme displacements corresponding to the rubble mound breakwater with berm and the rubble mound breakwater without berm for the seismic load with an amplitude of 2 mm and a frequency of 3 Hz. This effect has led to a notable reduction in the overall displacement, specifically, a decrease of 4.75 cm in extreme total displacements, 4.11 cm in extreme horizontal displacements, and 3.1cm in extreme vertical displacements.

The findings of this research contribute to the previous research on the design of rubble mound breakwaters, with a particular focus on their stability under seismic loading conditions, as investigated by Cihan and Yuksel (25). Their research demonstrates the impact of incorporating toes into the design of conventional rubble mound breakwaters, which enhances their seismic response by reducing deformations. This research presented the berm as an other element of the design of rubble mound breakwater that can significatively reinforce the seismic response of rubble mound breakwaters by reducing displacements in the structure. This paper highlights the berm as an additional design element for rubble mound breakwaters, significantly enhancing their seismic response by improving their stability under seismic loading.

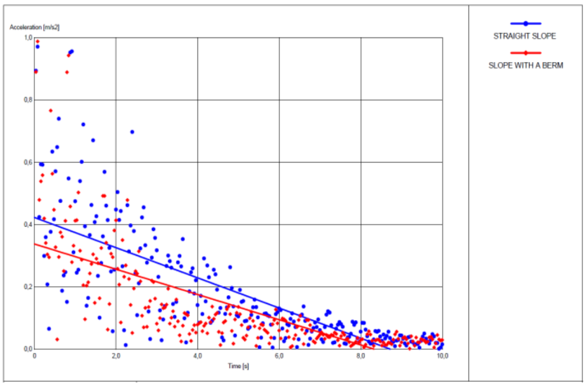

Figure 19. Slope-acceleration time history calculated for the two models with a berm and without a berm

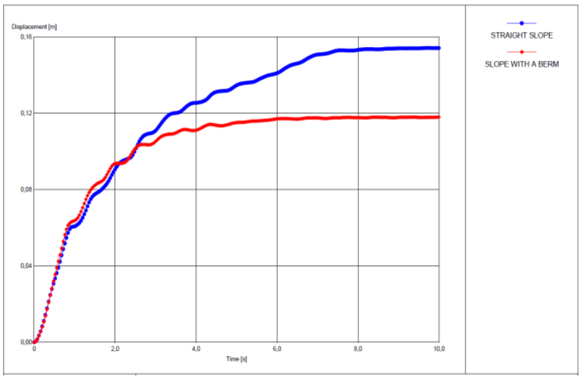

Figure 20. Slope- horizontal displacement time history calculated for the two models with a berm and without a berm

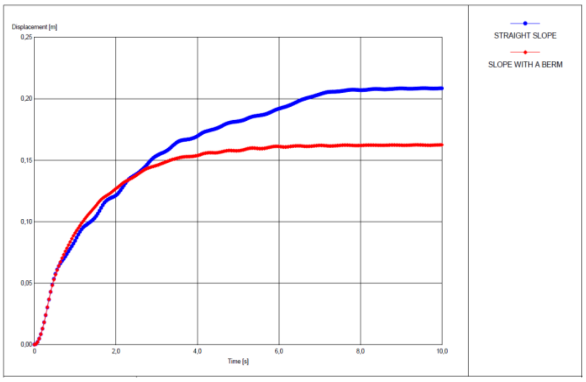

Figure 21. Slope- total displacement time history calculated for the two models with a berm and without a berm

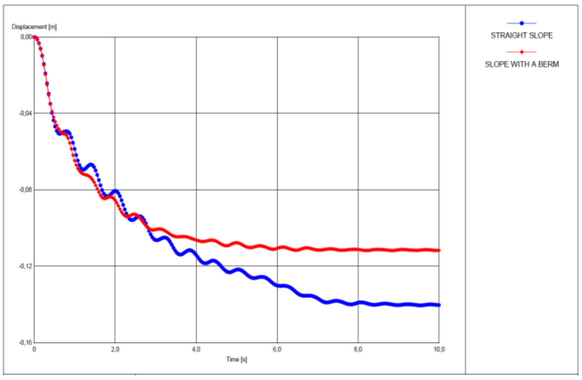

Figure 22. Slope- vertical displacement time history calculated for the two models with a berm and without a berm

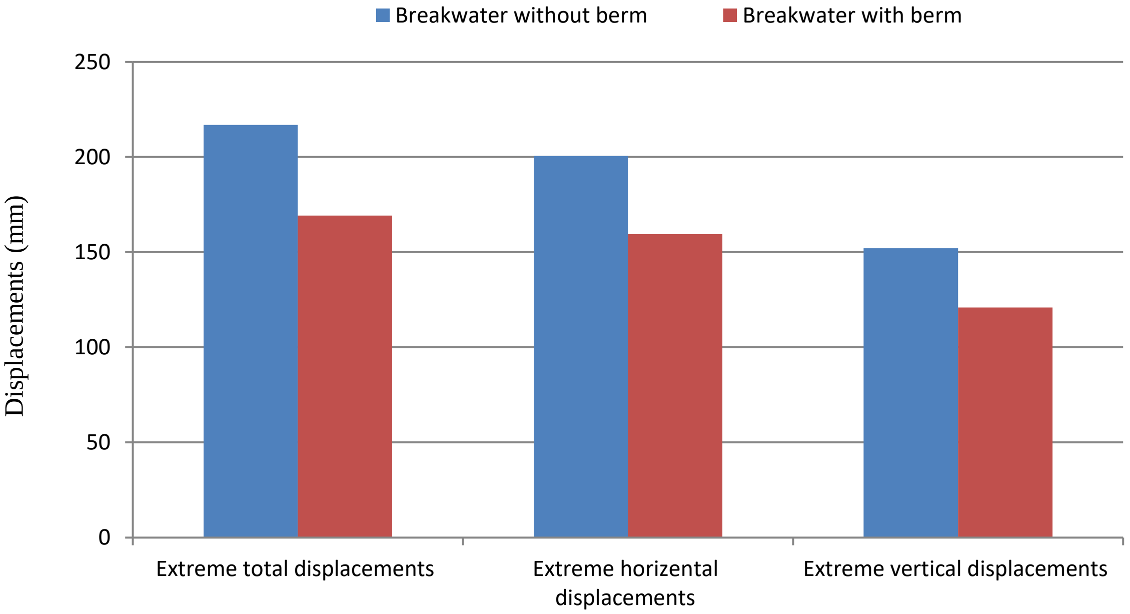

Figure 23. Comparison of the extreme displacements among the models of breakwaters, without a berm and with berm

Moreover, the results of this research further support previous research regarding the stabilizing effect of berms (16, 18, 22) by demonstrating the stabilizing effect of the berm under seismic loading conditions.

4. CONCLUSION

In this paper, numerical study on finit element method was performed to observe the response of conventional rubble mound breakwater with berm subjected to seismic loads with different frequencies and amplitudes. The numerical method results have revealed the following conclusions:

- The higher the value of the berm height level, the more extreme displacements at the rubble mound breakwater decrease under seismic loading.
- The higher the value of the berm length, the more extreme displacements at the rubble mound breakwater decrease under seismic loading.
- The inclusion of a berm in the design of breakwaters reduces total displacements, horizontal displacements, vertical displacements and accelerations in the rubble mound breakwater under seismic loading.

This research underscores the critical importance of considering berms in the planning and construction of rubble mound breakwater, particularly in regions prone to significant seismic activity. Adding a berm to a rubble mound breakwater proves to be an effective strategy for reinforcing its stability and reducing the risk of failure. This study provides valuable insights for engineers and designers involved in brekwaters construction and management, thereby contributing to the resilience of coastal infrastructure in the face of current and future environmental challenges. This article advances knowledge in the domain by providing empirical evidence of the effectiveness of berms in improving breakwater stability during seismic events, offering practical insights for coastal engineering practices. Despite its contributions, this study has limitations such as the focus on a specific range of berm dimensions and seismic conditions. Future research could explore a broader range of parameters and consider dynamic interaction effects between berms and other breakwater elements.

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Persian Abstract

چکیده

برای موج شکن های تپه قلوه سنگ، گنجاندن اسکله در شیب دریا می تواند در کاهش سرازیر شدن موج و کاهش بار موجی که بر روی عناصر زرهی موج شکن تأثیر می گذارد بسیار مؤثر باشد. هدف از این تحقیق بررسی اثر برم افقی بر پاسخ لرزه ای موج شکن های معمولی تپه قلوه سنگ با در نظر گرفتن دامنه ها و فرکانس های مختلف مشخص کننده بارهای لرزه ای است. مدل های المان محدود موج شکن های معمولی تپه قلوه سنگ، با و بدون برم، با استفاده از نرم افزار Plaxis 2D برای این منظور توسعه یافته اند. علاوه بر این، پایداری موج شکن های تپه قلوه سنگ با برم ها از طریق مدل های عددی مختلف با در نظر گرفتن طول ها و سطوح ارتفاعی مختلف برم مورد مطالعه قرار می گیرد. تجزیه و تحلیل مقایسه‌ای نتایج نشان می‌دهد که موج‌شکن‌های تپه قلوه سنگ که دارای برم‌ها هستند، ویژگی‌های تغییر شکل کمتری را در مقایسه با آن‌هایی که بدون برم دارند، نشان می‌دهند. نتایج مطالعه عددی نشان می دهد که برم ها می توانند به طور قابل توجهی پایداری را افزایش داده و جابجایی موج شکن های تپه قلوه سنگ تحت بارگذاری لرزه ای را در مقایسه با موج شکن های بدون برم کاهش دهند.