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Performance Comparison of Hybrid Protection Methods in Weakening coast Waves

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ABSTRACT

Considering the strategic importance of coastal areas from various aspects, their protection against waves is a coast management necessity. Since long ago, strong coastal structures have protected coasts, but since they disturb the coastal ecosystem balance, effort has been made to use them less or make them more compatible with the coast. This research is specifically aimed to estimate the efficiency of environment-based methods such as the combined tree planting-structural methods compared with merely structural methods, in damping the coastal waves and, hence, protecting the coasts. In this research, coastal dikes with 3 different height situated in 3 different locations in combination with 3 rows of tree under the influence of 5 wave heights are investigated. Experimental results showed that the highest wave damping (80%) occurs by positioning the structure in the beginning of the protected area, covered by trees at its tail. To check the force reduction rate, the most effective protection plan is when the structure is in the middle of the protected area and the tree cover lies in front as well as in the back of the structure. In this case, the wave force damping is 10.7 times the case when the coast has no obstacles; when there are no trees and the structure is alone, the wave force damping is more than 50%. This mode, compared to the best performance mode - the structure lies alone at the beginning of the protected area, has increased the wave force damping efficiency by about 14%.

1. Introduction

As sea waves cause the coast appearance to change continuously, considering their effects in the design of coastal structures is quite important. Methods to protect coasts against the waves' destructive effects are either structural or non-structural.

Tides and storms erode coasts, and since coasts have to be protected against erosion, coastal protection methods such as breakwaters, groynes and artificial reefs have been subjects of research and investigation [1]. Since sea waves change the coast's geometrical shape, constructing offshore groynes, breakwaters and coastal walls is a vital issue because they change the natural conditions of the regional waves/currents. Therefore, before constructing these costly structures, it is necessary to carefully check their efficiency in effective protection of the coast [2].

Rigid coastal structures (coastal walls, breakwaters, etc.) not only affect the coastal ecosystem highly negatively, but are also quite expensive economically; however, since they are highly resistant against sea waves, their use to prevent the coast erosion/destruction is unavoidable [3].

Over the years, coast protection methods changed from constructing coastal structures to strengthening coasts against strong waves through preventing them to enter the coast by sending them back to the sea and damping their energy by passing them through porous environments. But, using the nature itself in various ways is an economical method that improves the biological and aesthetic conditions of the coast. One natural solution, which has become quite popular with the engineers, is to fight tsunami waves and reduce their destructive effects by different-density tree covers (green belts) because their function is like creating a turbulent flow in the body of a porous structure [4]. Aid of the nature in coastal protection from natural disasters has attracted the attention of researchers because of economical, biological, and esthetical reasons [5].

Experimentally studying rigid coastal vegetation covers 1.5 and 2 cm in diameter under non-submerged conditions, with 5 x 5 and 10 x 10 cm interval tree arrangements, 10, 30 and 40 cm cover widths, 0, 3, 5, 7 and 10% slopes and 1.5, 3, 4, 6 and 8 cm wave heights, and using an electronic dynamometer for direct force measurements, Ghanbari Adivi and Fathi Moghadam [5] concluded that: 1) coastal green belts reduced the destructive effects of sea storm-/tsunami-induced waves significantly by absorbing their destructive force in the form of the tensile force of trees, 2) for a specific wave height, a denser arrangement absorbed and damped more force and 3) the highest force variation rate per density change was found to be 26% under 10x10 cm arrangement, 3% slope and 8 cm wave height. Jalil Masir et al. [6] conducted a series of experiments to study the efficacy of coastal mangrove trees in reducing the energy of tsunami waves under different length-width arrangements. They concluded that tree covers reduced the destructive force by 71.28% and increased the wave damping by 91.52%. Comparing different tree arrangements, they [7] reported the triangular arrangement was superior in all cases in terms of damping the wave force and, hence, reducing the sediment transport on the coast. Marcel et al. [8] studied the effects of inclined wave attacks on the breakwater structure under smooth and rough conditions for both even and uneven slopes towards the sea. The tests performed on the physical model under oblique wave conditions revealed that: 1) the wave dominance reduction was very large for highly oblique waves, 2) existing methods for estimating the attack of vertical waves agreed well with measured discharges and 3) large reduction of the flow rates measured for Mal waves conformed to test results for other structures.

Examining various solid coastal tree cover arrangements and different wave heights in the presence of sediment, Mirzakhani et al. [9] showed that increasing the vegetation density from 32 to 66% reduced the post-cover wave height by 20%, and estimated the effect of tree cover on the wave force absorption as 62.38% in the densest case compared to the no-cover state. Agh Tooman et al. [10] used physical modeling to study the effects of coastal structures, slopes of their walls and heights of passing waves on reducing the heights of incoming waves, and showed that reducing the structure slope reduced the overflowing waves.

Valipour et al. [11] simulated the impact of waves on a coastal dike with OpenFoam software. Modeling was done in two general conditions with structure and without structure and the results showed that the consumption of forces has increased up to 10 times compared to the state without structure

Igrashi et al. [12] used a hybrid embankment-pile system to study the energy damping of high waves and showed that it depended on the pile arrangement and diameter and on the embankment height; The higher the height of the embankment and the higher the height and diameter of the piles, the more energy is consumed from the wave.

Reviewing the literature revealed that the past trends were mostly towards using rigid structures alone, with their specific merits and demerits, to reduce the waves' destructive effects. On the other hand, using only natural tree covers can involve the risk of insufficient wave damping on coasts. Past studies have paid less attention to the simultaneous combination of structural methods with those compatible with the coastal ecosystem such as tree planting, and the few ones that have addressed the issue have used rigid tree covers and ignored the more flexible parts of trees. Therefore, effort has been made in this research to quantify the effects of the simultaneous use of structural designs combined with protection plans conforming to the nature (planting coastal trees) considering the full structure of a tree, and measure, directly and more accurately, the force induced by hitting waves to coastal barriers, with a mechanism based on wave momentum, and specific to this research, and use it as a criterion for the efficiency of the mentioned plans.

2. Materials and methods

2.1. Dimensional analysis

Here, many effective independent and dependent parameters (Table 1) are involved in the wave hydraulics, coast conditions and types of the applied protection plans. Since this section is aimed to investigate the efficiency of the latter in reducing the wave force and the height of the passing waves, concentrating on extracting these parameters as a function of other independent parameters effective in the phenomenon.

Effective force and height parameters in wave damping due to the presence of coastal structures and trees can be listed as follows (Eq.1):

Table 1. Parameters used in this research

Parameter	Symbol	Unit	Study zone
Coast slope	%S		Constant &no slope
Wave-induced tensile force	F	N	-
Fluid density	ρ_w	kg/m^3	998
Dynamic viscosity	μ_w	N.s/m^2	0.001
Gravity acceleration	g	m/s^2	9.8
Pre-coast wave height	H_0	cm	6, 7.5, 9, 10.5, 12
Post-coast wave height	H	cm	-
Pre-coast wave velocity	V	m/s	1.1-1.53
Height of coastal structure	H_s	cm	7.5, 10, 15
Length of vegetation cover	*BG*	cm	60
No. of trees	Nt	-	12
Height of trees	hv	cm	25
Tree diameter	D	cm	2
Sill height	Y	cm	8

$$f_1(S, Y, \rho_w, \mu_w, g, D, BG, Nt, h_v, F, V, H_0, H, H_s) = 0 \quad (1)$$

Here, since the wave type is solitary in nature, its height, for modeling, is preferable to its length (Sorenson [13]; Dean and Dalrymple [14]); hence, the latter has been ignored.

Next, dimensionless parameters were extracted according to Eq. (2) using the Buckingham π method in dimensional analyses and selecting V, ρ_w and H, as repeating variables.

$$f_2(Re = \frac{\rho_w HV}{\mu_w}, Fr = \frac{V}{\sqrt{Hg}}, \frac{H}{H_s}, \frac{H}{H0}, \frac{H}{Y}, \frac{H}{BG}, \frac{H}{h_v}, \frac{H}{D}, \frac{\rho_w H^2 V^2}{F}, Nt, S) = 0 \quad (2)$$

Famous dimensionless numbers were extracted by examining the dimensionless parameters obtained based on the cases shown in relation 2-3. Froude's number (Fr), due to the flow's unsteady nature (single wave), and Reynolds number (Re), due to its fully turbulent nature, were omitted from the ratios to ignore the viscosity effects. The $\frac{H}{H_s}, \frac{H}{BG}, \frac{H}{h_v}, \frac{H}{D}, Nt\ and\ S$ were removed because here the studied parameters were constant. Finally, the desired dimensionless ratios are found from Eq. (3).

$$f_2\left(\frac{F}{\rho_w H^2 V^2}, \frac{H}{H0}, \frac{H}{Y}\right) = 0 \quad (3)$$

Here, the first dimensionless ratio refers to the force absorbed by the structure from the wave in the form of drag force, which if divided into: 1) with structure (F) and 2) without structure (F_0), their comparison ($\frac{F}{F_0}$) enables evaluating the efficiency of the "structure with tree cover" in absorbing the wave force compared to the case "without the structure and tree cover". To evaluate the performance of the desired protection plan in reducing the wave height, use was made of the second dimensionless ratio, and to obtain the direct value of the wave height reduction, this ratio was changed to $(1 - \frac{H}{H0})$; $\frac{H}{Y}$ is the ratio of the submergence of the incoming wave at the foot of the coast to the sill depth at the same place.

2.2. Laboratory equipment

Tests were done in the Shahrekord University hydraulic laboratory rectangular flume 20 m in length, 0.6 m in width and 0.6 m in height with a metal floor and plexiglass walls; to create a reservoir to supply the wave height, 2 m of the channel was blocked by two walls, one of which was a valve that could open suddenly. Figure (1) shows a general view of the flume along with the coastal wall structure and trees in the laboratory.

Effort is made here to study the damping rate of the coast-entering wave when it collides with the coastal structure and the tree cover using the wave force and height. The wave force was measured with an electronic dynamometer (load cell) installed on the supporting frame of the coast plate and recorded the force when the wave hit the frame and showed, in each test run, its maximum value on a screen connected to it (Fig. 2).

1 m length of the flume was allotted to the coast plate and its edge knife supports with a novel mechanism capable of keeping the contact friction close to zero quite freely under movement threshold conditions. The movable plate, placed on knife blades in the movement threshold state, fell down with a small force causing the load cell to create a balance allowing the applied force

to be recorded on its connected screen at any moment the wave passed through this 1 m length.
Here the wave height was measured using 0.1 mbar pressure transducers that record and store the liquid height data at each point with the help of a data logger (Fig. 3).
To perform the tests, use was made of three coastal structures 7.5, 10 and 15 cm in height, each of which were placed separately at the beginning, middle and end of the coast plate in combination with three rows of tree covers in each test (Fig. 4). The desired waves were then passed over them and the wave height was measured before and after the structure by the transducers and the absorbed force was measured by the electronic dynamometer and then the wave damping indices were calculated.

Figure 1- Tree-structure arrangement in the laboratory flume

Figure 2- Electronic dynamometer

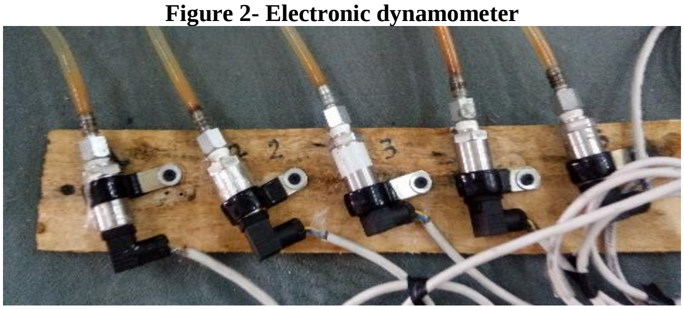
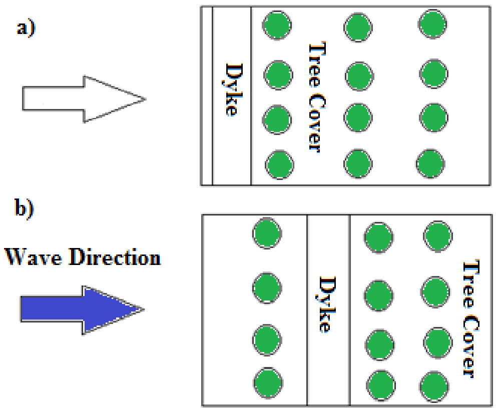


Figure 3- Data logger, transducers and their installation on the coast



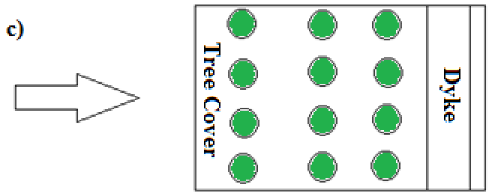


Figure 4- Different tree-cover positions with respect to the coastal structure

Table 2 shows the scenarios studied in this research and, hereinafter, each test will be called with a combination of codes provided in Tables 2 to 4, respectively, from left to right; for instance, Code 2-1-3 means a coastal structure with tree cover (Structure, Code 2) with a structure 7.5 cm in height (Height, Code 1) standing at the end of the coast (Position, Code 3).
It is worth mentioning that, here, Code 2, which the structure is alone, has been omitted because it is not addressed in this research.

Table 2. Test scenarios

Test scenario	Specifying code
With no protection plan	1
Coastal structure with tree cover	3

Table 3. Different types of coastal structures studied in this research

Characteristics of the coastal structure	Specifying code
Height 7.5 cm	1
Height 10 cm	2
Height 15 cm	3

Table 4. Structure location

Location of coastal structure	Specifying code
Beginning of coast plate	1
Middle of coast plate	2
End of coast plate	3

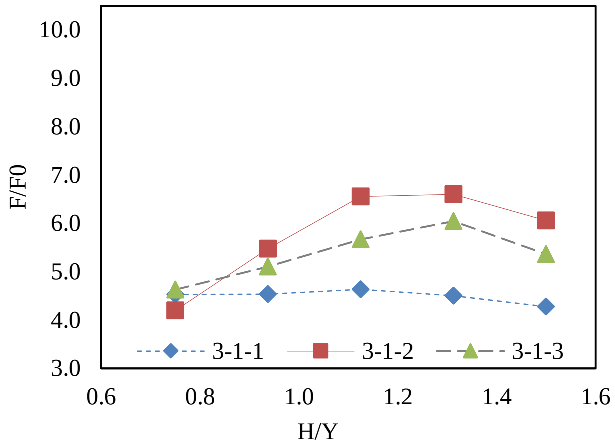
3. Results and discussion

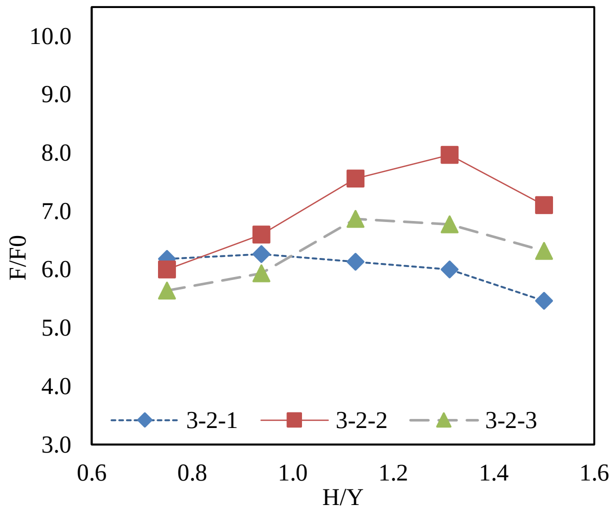
3.1. Force reduction in coastal structure-tree cover combinations

This research has investigated the force reduction of sea-waves when they hit coastal structures 7.5, 10 and 15 cm in height located at the beginning, middle and end of the coast plate in combination with tree covers, where there are no obstacles on the coast. Fig. 5 shows the force reduction of sea waves when they hit the coastal structure wall and tree cover under different situations. In these investigations, *H/Y* is the ratio of the height of the desired wave to the sill height (here, 8 cm) according to Table 5.

Table 5- H/Y for different wave heights

wave relative height	6cm	7.5cm	9cm	10.5cm	12cm
H/Y	0.75	0.95	1.13	1.31	1.5





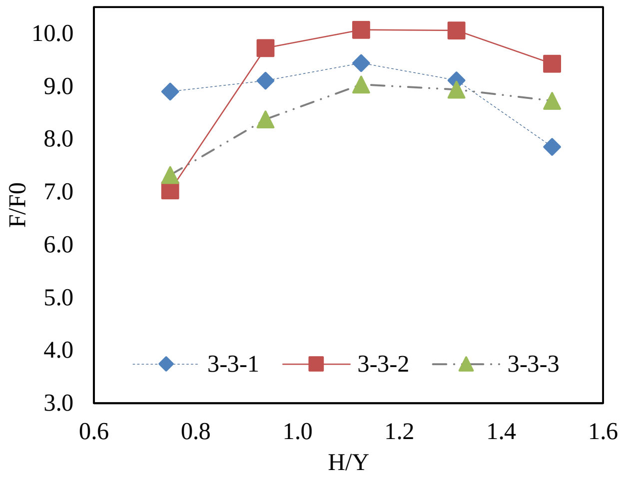


Figure 5- Relative wave-force variations when hitting the coastal structure-tree cover combination in different modes (based on test Codes)

As shown, when sea waves hit the coastal structure and tree cover, their force reduces significantly.

When the 7.5 cm height coastal structure is in States 1 (beginning), 2 (middle) and 3 (end), the highest wave force reductions relate, respectively, to the 9, 10.5 and 10.5 cm waves, which are, respectively, 4.63, 6.60 and 6.05 times the case with no obstacles on the coastal plain.

When the 10 cm height coastal structure is in States 1 (beginning), 2 (middle) and 3 (end), the highest wave force reductions relate, respectively, to the 7.5, 10.5 and 9 cm waves, which are, respectively, 6.26, 7.97 and 6.87 times the case with no obstacles on the coastal plain.

When the 15 cm height coastal structure is in States 1 (beginning), 2 (middle) and 3 (end), the highest wave force reductions are, respectively, 9.44, 10.07 and 9.03 times the case with no obstacles on the coastal plain.

Reviewing graphs A, B and C in Fig. 5 concludes, generally, that when the coastal structure with tree cover stands against sea waves, if the structure is in State 2 (middle), its height is 15 cm and the wave height is 10.5 cm, the highest wave force reduction is 10.07 times the case with no obstacles on the coastal plain.

In comparison, the best and most effective protection method is when the structure is alone, its height is 15 cm and is located at the beginning of the coastal area; in this case, the highest wave force reduction is 8.83 times the case with no obstacles on the coastal plain [12]. According to the results, at initial wave heights, the structure efficiency shows a different rate due to the wave's very low height compared to that of the structure, and the passing wave flows more on the body of the structure tangentially than impacting on it; hence, the structure acts more as a wave transmitter rather than a wave absorber.

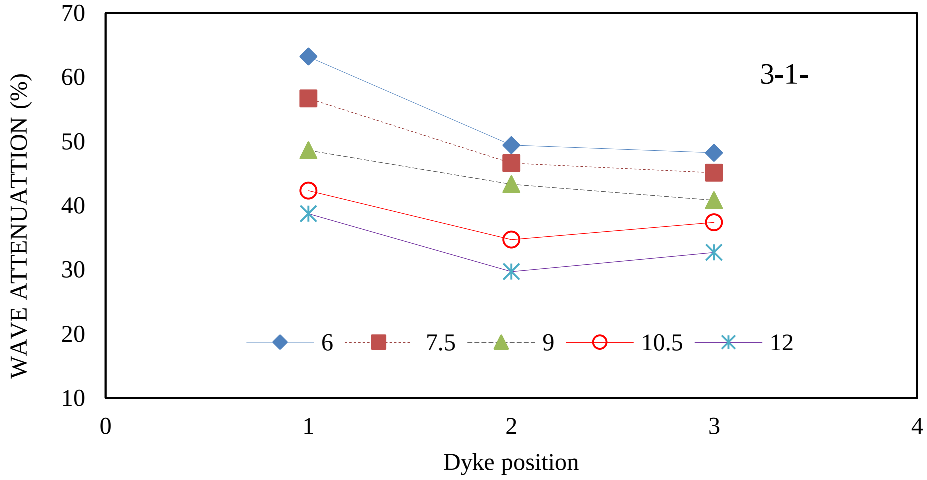
3.2. Damping of coast-entering waves in coastal structure-tree cover combinations

Damping means height reduction of coast-entering waves, which was discussed in the current research after hitting the obstacles (structure with tree cover) compared to the case with no obstacles on the coastal plain.

3-2-1- Height reduction of coast-entering waves as a function of the structure location and height

When waves hit the coastal structure with tree cover, their heights reduce greatly because they hit the structure and pass through the tree cover.

This research has studied the wave height damping/reduction when the coastal structure with tree cover is on the coastal plain according to graphs A, B and C in Figure 6, which shows damping after different-height/-characteristic waves hit the structure when it is alone (all different cases) compared with the combined cases [15].



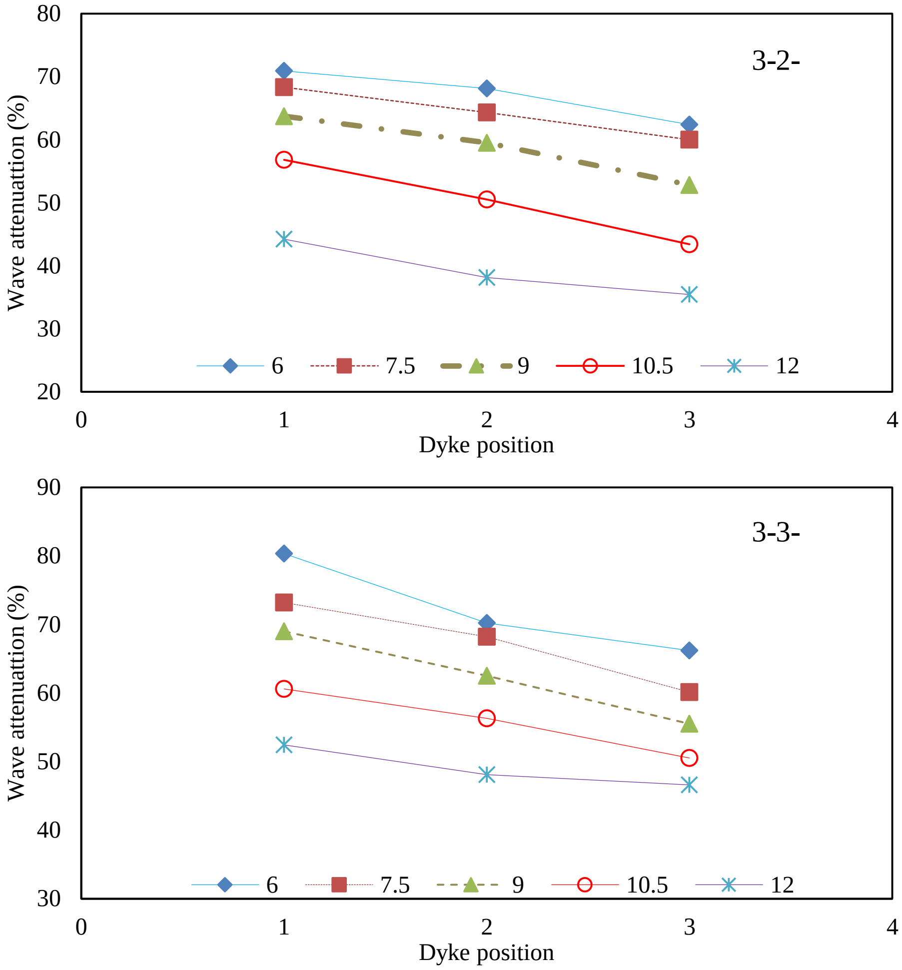


Figure 6- Height reduction (%) of coast-entering waves in various combined structure-tree cover cases

In Fig. 6A, when 6, 7.5, 9, 10.5, and 12 cm-height waves hit the 7.5 cm-height structure, if it is at the beginning of the coastal plain (State 1) and the tree cover is after it, the highest wave height damping/reduction is 63.2% related to the 6 cm wave, but if the structure is in the middle (State 2) and the tree cover is on its both sides, the highest reduction rate is 49.4% and if it is in the end (State 3) and tree cover is on its both sides, the highest damping rate is 48.2%.

In Fig. 6B, when the above mentioned waves hit the 10 cm-height structure, if it is in State 1 and the tree cover is after it, the highest reduction rate is 70.9% related to the 6 cm wave, if it is in State 2 and the tree cover is on its both sides, the highest reduction rate is 68.1% and if it is in State 3 and the tree cover is before it, the highest reduction rate is 64.2% related to the 6 cm wave.

In Fig. 6C, when the above mentioned waves hit the 15 cm-height structure, if it is in State 1 and the tree cover is after it, the highest reduction rate is 80.3% related to the 6 cm wave, if it is in State 2 and the tree cover is on its both sides, the highest reduction rate is 70.2% related to the 6 cm wave and if it is in State 3 and the tree cover is before it, the highest reduction rate is 66.2% related to the 6 cm wave.

A review of graphs A, B and C in Fig. 6 concludes that the highest wave height reduction/damping rate is 80.3% related to when the coastal structure is in State 1, its height is 15 cm, the tree cover is after it and the wave height is 6 cm.

Results in Table 6 conclude that the highest wave damping rate is 73.3% occurring when the structure is at the end of the coastal plain, its height is 15 cm (tallest) and the relative wave height is 0.75 cm.

Comparing the results of the structure-tree combination scenario with the one where the structure is alone reveals that the former has increased the wave-height reducing efficiency by 16% compared with the latter.

Comparing all the desired cases, for the highest efficacy, the combined scenario has increased the damping by 64% at a structure height = 10 cm and a wave height = 9 cm.

In general, using trees, as a roughness factor that creates resistance against wave movement, has had positive effects, in all cases, on reducing the wave height as an important hydrodynamic parameter.

Table 6. Wave damping after hitting the structure standing alone in the coastal plain [13], (all studied states) for different characteristic/height waves

Dyke position	Dyke height (cm)	Wave height (cm)				
		6	7.5	9	10.5	12
		Wave damping rate (%)				
1	7.5	48.7	46.6	43.3	34.7	29.7
	10	45.0	48.0	32.4	30.3	23.7
	15	70.3	68.9	54.5	51.4	49.3
2	7.5	54.1	51.3	41.8	38.9	34.2
	10	66.5	56.1	32.1	30.4	24.5
	15	72.2	67.8	55.8	45.7	41.9
3	7.5	49.9	45.1	40.8	37.4	32.7
	10	56.4	55.3	42.3	39.3	34.5
	15	73.3	68.8	59.1	54.4	47.1

3.2.2. Damping rate as a function of the wave height when entering the coast

Next, the wave damping rate is investigated and compared for different-height structures as a function of the entering wave height variations under three different cases.

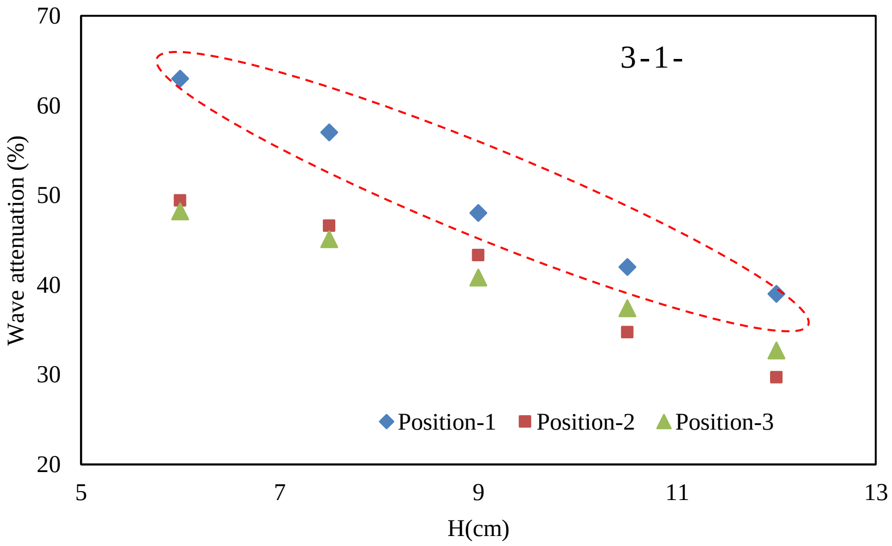


Figure 7- Wave height reduction (%) for a 7.5 cm-height structure with tree cover (Code 3-1) (different states)

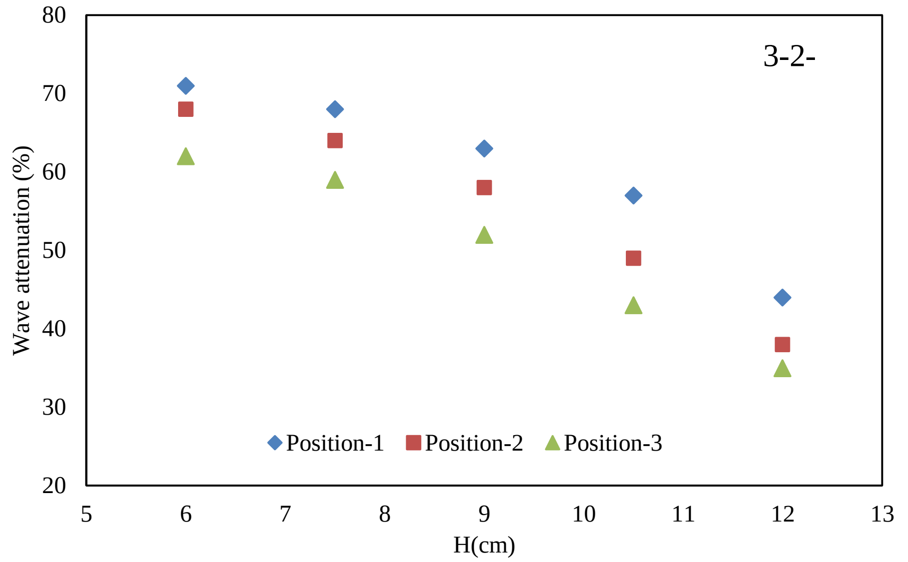


Figure 8- Wave height reduction (%) for a 10 cm-height structure with tree cover (Code 3-1) (different states)

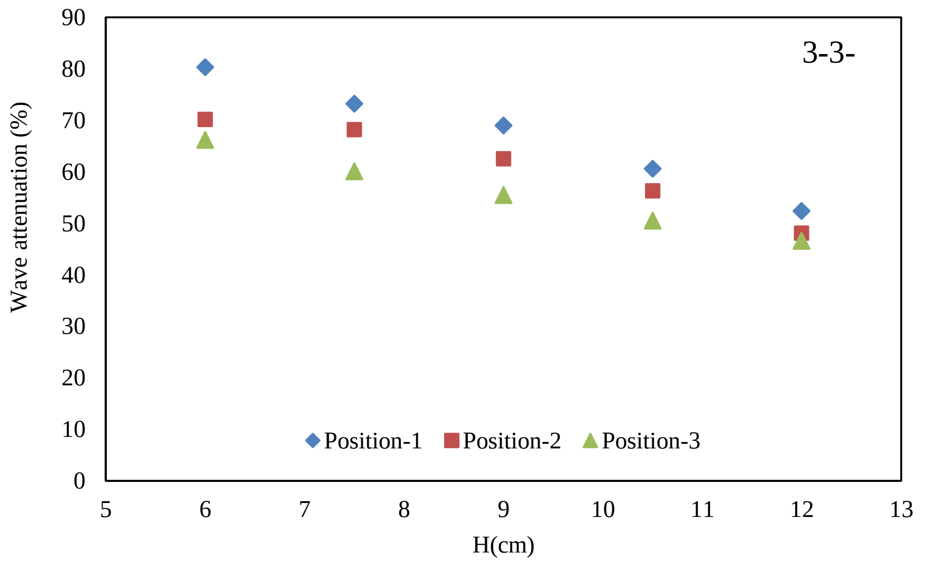


Figure 9- Wave height reduction (%) for a 15 cm-height structure with tree cover (Code 3-1) (different states)

If a 10 cm-height structure is on the coastal plain with tree cover, the highest wave reduction rate occurs if the structure is at the beginning of the coastal plain (State 1) and the tree cover is after it, because when a known-height wave hits it, some of it is reflected and causes the incoming wave height to increase, but when it returns, it hits the tree cover, which acts as a porous structure and its height decreases significantly up to the end of the coastal plain. When the structure and the tree cover are together, the reflection occurs again when the wave hits the structure, but the tree cover acts as a porous medium and reduces the passing wave height significantly because it is after the structure.

In Figs. 7-9, the highest wave height reduction occurs when the structure is at the beginning of the coastal plain and the tree cover is after it because when the wave hits the structure, it gains more height, due to reflection, and loses height again after passing the structure. In this case, since the tree cover is after the structure, it acts as a porous medium and reduces the wave height considerably because of touching the trees and the wave height reflection trend increases.

3.3. Comparison of the results of this research with those of the others

Jalil Masir [6] found out that the wave height reduction rate with respect to its initial height was averagely 52.94 and 70.75% at, respectively, the lowest and highest densities when hitting the cover. The increased efficiency of the coastal forest in reducing the wave height obtained in their research confirms the trend of these variations in the present research

Igrashi and Tanaka [16] studied the efficiency of coastal embankments with tree cover against strong tsunami waves and showed that their combination highly reduced tsunami waves' destructive effects especially when the tree cover was after the coastal embankment facing the dry coast (i.e., first was the coastal embankment and then the tree cover was behind it); here, the embankment volume was reduced by only 10%. They also showed that if the tree cover thickness was high (40 rows), the volume of water passing over the embankment was reduced by 57-97%, but if it was low (2 rows), the reduction rate was 10-20%. According to their final results, even if the tree cover was thin and trees overturned or bent under the wave, the tsunami wave height would still be lower than that of the embankment. Results of these researches confirm the findings of the present study, but the difference, as regards the efficacy of the proposed combined design, can be due to the type of the covering Igrash et al. (2018) have used, which consists of rigid cylindrical rods for the modeling of trees; whereas, the present research has tried, through using flexible plastic trees and simulating their real behavior in terms of initial flexibility against waves, to do a closer-to-reality study of the desired scenario.

Salehi et al. [17] studied the wave force/height reduction rate under only vegetation cover with different arrangements, and conditions similar to those of this research, and observed that the highest and the lowest wave height reduction rates were 63.1 and 24.3% for tree cover densities of 80 and 25% and wave heights of 6 and 12 cm, respectively. They also showed that the coastal green belt could absorb and damp the sea waves' destructive force by about 0.43 to 3.18 times more compared to the no-tree cover case. They finally concluded, in general, that coasts could be protected against destructive sea waves by tree cover alone, without any coastal structures, depending on the coastal conditions.

In the current research, the highest wave force reduction is related to when the coastal structure and the tree cover are together and the structure lies in the mid coastal zone; in this case, the wave force reduction rate is 10.07 times the case where no obstacle are on the area, which compared to reference [16] there is a significant increase in the efficiency of this combined structure-tree protection plan due to the altered obstacle arrangement. Here, compared to the same reference [16], in one of the scenarios, the tree cover was placed both behind and in front of the structure and trees were arranged alternately and, hence, increased the plan efficiency. Regarding the damping of passing waves, the highest value relates to when the structure and tree cover are together, where the former is at the beginning of the coastal plain. In such a case, the damping is 80.3%, which compared to references [17] and [18], shows a significant increase because they reported a damping rate of about 60% under relatively similar conditions, but using only vegetation cover without combining with coastal structures.

Considering the discussed issues, performance of the coastal structure and tree cover together in reducing the force and height of the destructive waves is quite acceptable compared to other coast protection plans, concluding that this combined plan is justified and suggestible for coast management measures. However, implementing such systems requires not only more comprehensive studies, but also some pilot projects for a more accurate study of the natural behavior of the structure-tree cover interaction against waves.

4. Conclusions

Protecting coasts against destructive waves is a necessity of the today's world and determining the best protection method that is both economical and least damaging to the nature is quite important. Nowadays, combined coastal structure-tree cover methods are more welcomed due to their more effective protection against sea waves.

This research addressed both wave force and wave height reduction issues (wave damping), in each of which, a comparison was made between situations where: 1) the structure was on the coast along with 3 rows of trees and 2) the structure was alone or no protection plan was implemented on the coast.

Regarding the reduction of the force of passing waves, results found from relevant tests revealed that when the structure and tree cover were together, the highest force reduction was related to case where the 15 cm-height coastal structure was in the middle of the protected area, the passing wave height was 1.35 cm and the tree cover was distributed on both sides of the structure; in this case the efficiency was about 10 times that when there were no obstacles on the coast.

Regarding the damping/reducing the wave height, results found from the tests showed that if the structure and tree cover were together, the coastal structure height was 15 cm, the relative height of the passing wave was 6 cm (equivalent to 0.75) and the structure was at the beginning of the protected area the highest damping rate was 80.3%.

Comparing the results of these experiments conclude that the combination of the structure with tree cover can be more effective in reducing the waves' destructive effects than when the structure is alone, but this efficacy is affected by how trees are arranged with respect to the structure. Here, considering the highest recorded efficacy, the most efficient method in this research is when the structure is in the middle of the protected coastal area and trees are both before and after it.

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