CLIMATE CHANGES IMPACT ON SUBMERGED BREAKWATERS EFFICIENCY AND PROPOSED SUSTAINABLE ALTERNATIVES

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ABSTRACT

Sea level rise (SLR) is one of the main consequences of global climate change, which threatens coastal areas, harbours and most protection structures. In the case of submerged breakwaters (S.B.W.), SLR increases submergence depth, reducing wave attenuation and breakwater efficiency. So, wave screens can be used as a sustainable solution to enhance submerged breakwater performance and increase wave attenuation. The study aims to investigate the impact of climate change and sea level rise on submerged breakwater performance, and wave screens' influence in restoring submerged breakwater efficiency. The experimental results showed that SLR significantly impacted submerged breakwater efficiency, which decreased by 10 % and 37.5 % in the case of relative SLR of 11 % and 25 % respectively. However, using a single wave screen behind submerged breakwater restored 59 % of S.B.W.`s efficiency which was increased by 22.22% on average. Moreover, the relative distance of the wave screen has a minor impact, so it is recommended to use the minimum relative distance of the wave screen. Also, double wave screens restored the breakwater performance by about 50 % to 70 %. Furthermore, placing wave screens on the leeward side of S.B.W. is the best alternative with higher efficiency and less construction cost.

Keywords*:* Sea level rise, climate change, submerged breakwaters, wave screen, performance.

1 INTRODUCTION

Climate change is one of the worldwide main crucial issues as it is considered the most serious environmental, and economic long-term challenges. Also, climate change is defined as a critical threat along the coastal zones of the Mediterranean, and it is very clear in the increased coastal erosion patterns in the last decades (Fatorić & Chelleri, 2012). Coastal areas are considered valuable spots in any country as they are reasonable sites for urbanization, recreational, industrial and commercial activities. So, they are densely populated in usual and accommodate more than 50 % of the world`s population. Moreover, the shoreline is the interface between land and sea and represents one of the main natural boundaries for many countries (Ezzeldin et al., 2020). Climate change impacts involve sea level rise (SLR), storm surges, and high waves which significantly influence shoreline erosion and coastal areas (Sharaan et al., 2022).

Submerged breakwaters (S.B.W.) are commonly used for shore protection as are relatively inexpensive and permit wave overtopping which improves the water quality at the leeward side. So, they are the best solution for areas prone to bacterial reproduction as it threatens beach users` health(Izzat Na'im et al., 2018). Moreover, they have aesthetic value as they do not obstruct the ocean view, so they are considered one of the main environmental solutions for shore protection (Saad, 2014). Furthermore, submerged breakwaters have a minor impact on the adjacent shorelines and minimum reflected waves, so they have an insignificant impact on ship navigation (Cheng et al., 2003). Also, they can afford significant efficiency and shore protection against tsunamis (Irtem et al., 2011). So, the submerged breakwater is one of the best environmental alternatives and has become more popular worldwide.

For instance, submerged breakwaters were the best solution to protect the shoreline and create a sloping beach at El- Alamein, Egypt (Iskander et al., 2008). Also, they offered significant protection for the Al-Ahlam resort on the Northwest coast of Egypt (Zahra, 2018). Moreover, submerged breakwaters at Miami, east of Alexandria, Egypt had an excellent performance during the December 2010 storm as the generating wave height reached 7.50 meters (El-Sharnouby & Soliman, 2011).

SLR is one of the main impacts of climate change and it is a significant threat to submerged breakwater performance, as SLR increases the submergence depth of submerged breakwater. Increasing the submergence depth of the breakwater allows more passage of waves and reduces the breakwater efficiency.

For instance, the constructed submerged breakwaters at Vero beach, Florida, USA, had low efficiency as the submergence depth increased by 1.02 m due to the excessive settlement (Ranasinghe & Turner, 2006). In addition, the proposed breakwater at the Gold Coast, Australia was rehabilitated by another construction phase to restore the crest level consequently as the submergence depth was increased due to the seabed erosion (Ranasinghe & Turner, 2006).

Many alternatives were proposed to restore the breakwater efficiency by using additional structures which were placed on the seaward or leeward side. For instance, a fixed horizontal plate was suggested to increase the efficiency of the submerged breakwater. It was placed on the seaward side with different relative distances and different submergence depths. The experimental study showed that the breakwater efficiency increased as the relative distance between the breakwater and the plate increased (Hsu & Wu, 1998). Moreover, floating breakwaters were suggested to restore the submerged breakwater performance. The results showed that using the floating breakwater above the submerged breakwater improved its efficiency and provided better performance than placing it on the seaward or leeward side (Cho et al., 2003).

Wave screens can be one of the reasonable and sustainable solutions as they are categorized as environmental friend breakwater. They are defined as vertical permeable walls with horizontal or vertical slots, and they have many advantages such as easy construction, inexpensive, allow water exchange. The construction of the wave screen is very easy, as it consists of horizontal slats which are fixed on supported piles, figure 1.

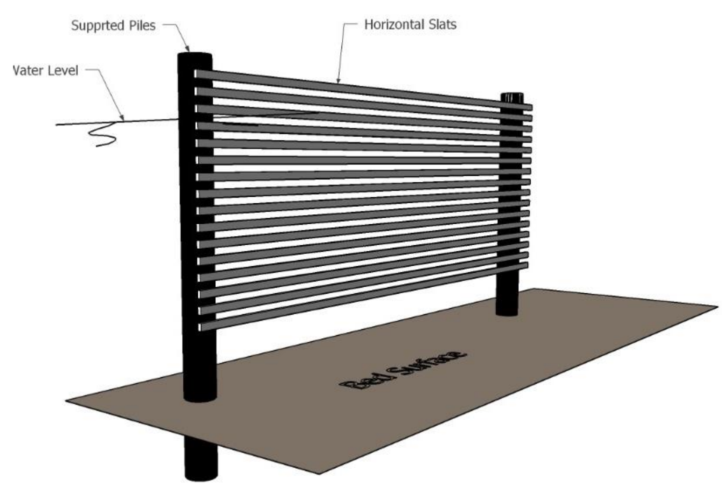

Figure 1. Schematic diagram of a horizontal slats wave screen

Single and double wave screens with horizontal slats were suggested to improve the submerged breakwater efficiency. The suggested alternatives were placed on the seaward side and they improved the efficiency by about 22 % on average (Rageh et al., 2013). This paper aims to investigate the impact of SLR on submerged breakwater efficiency and study the impact of placing wave screens on the leeward side of the submerged breakwater and their influence on restoring S.B.W. efficiency.

2 EXPERIMENTAL WORK

Experimental approach is commonly used to investigate the influence of different coastal phenomena and the performance of the various shore protection structures. Moreover, physical modelling is considered a significant tool for optimum coastal structure design (Romya et al., 2021). So, an experimental study was performed to investigate the impact of SLR and the increase of submergence depth of S.B.W. on its performance and efficiency. Also, the study aims to determine the impact of using wave screens at the leeward side to restore S.B.W. efficiency.

1.1 Wave basin

The experimental study was carried out in the Irrigation and Hydraulics lab, faculty of engineering, Mansoura University. The used wave basin was 15.10 m long, 1.00 m wide, and 1.00 m deep. The wave basin had a flap-type wave generator and an artificial beach with a slope of 1:3 at the end of the flume acted as a wave absorber, figure 2. The experiments were carried out in fixed water depth (d) of 0.50 m and variable speed motor to generate seven different wave conditions.

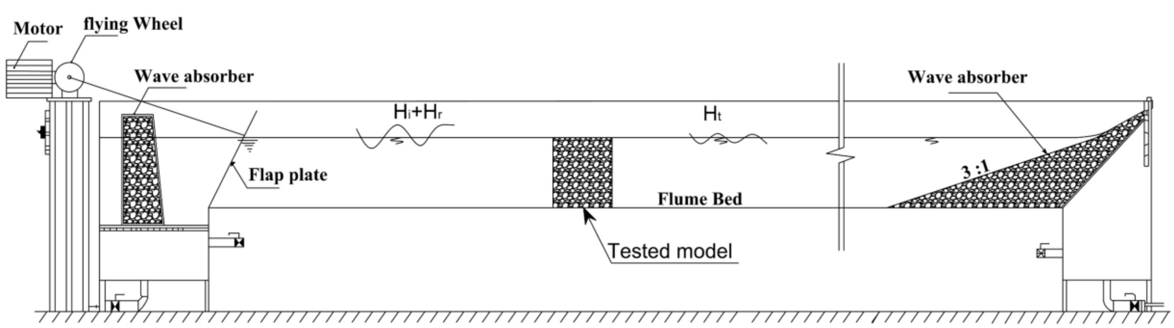

Figure 2. Schematic diagram of the wave flume

1.2 Submerged breakwater models

The used submerged breakwater models were steel screens filled with gravel, and they were 0.40 m wide, figure 3a. The tested models had three heights (h) of 0.50, 0.45, and 0.40 m to simulate the change in submergence depth and SLR impact, Figure 3.

Firstly, the S.B.W. model was used with the same height of water depth to simulate the original case without SLR impact, figure 3b. Then, the S.B.W. model was changed to simulate the SLR impact, figure 3c. The change in wave heights due to SLR was neglected in this study, so the used water depth was fixed and the S.B.W. model was used with different heights. The submerged breakwater models were placed in the middle of the wave basin.

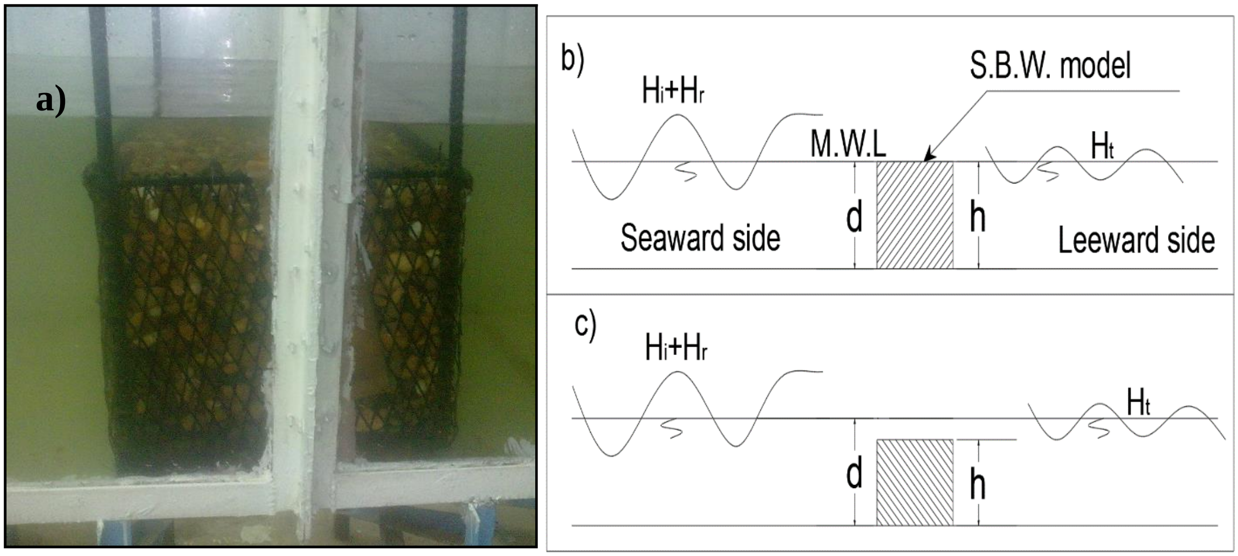

Figure 3, a) The S.B.W. model, b) The original case with no impact of SLR, c) The tested model in case of SLR.

1.3 Wave Screens models

The used wave screens were made from varnished wood and consisted of horizontal slats with equal spacing between them. The porosity of the screen is defined as the spacing between two slats (e) divided by the distance between the center lines of two slats (s). The horizontal wave screens were used with three porosities of 0.33, 0.4 and 0.50. Table 1 shows the porosity, slat size, slat spacing and distance between the center lines of two slats for the used wave screen model. The investigated parameters in the case of double wave screen were the relative distance (W/d) between the seaward wave screen and S.B.W. model, and the relative gap width (G/d) between seaward and leeward wave screens, figure 4.

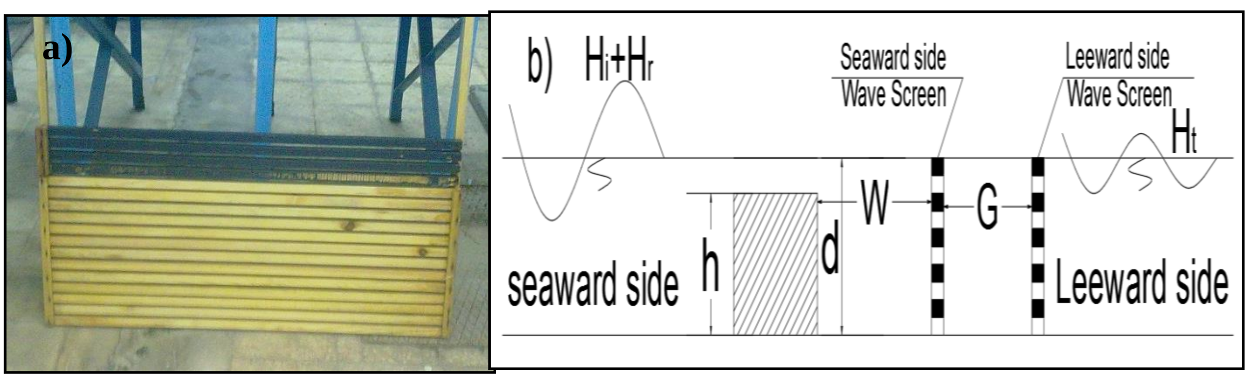

Figure 4: a) Horizontal slats wave screen model, b) The used wave screens in the leeward side of the S.B.W. model.

Table 1. Wave Screens Dimensions and Porosities

Porosity (P)	Slat size (cm)	Slat spacing (e) (cm)	Distance between C.L. of slats (s) (cm)
0.33	4.0 x 2.0	2.0	6.0
0.40	3.6 x 2.0	2.4	6.0
0.50	2.0 x 2.0	2.0	4.0

1.4 Study Procedures

The experimental study started with the wave calibration to determine incident wave heights and wave periods for seven conditions without any model. Table 2 shows the tested wave conditions used in the experimental study.

Table 1. Tested wave conditions

Motor frequency	Water height, d (m)	Wave characteristics		
		Wave period, T (sec.)	Incident Wave Height, H_i (m)	Wave length, L (m)
2.50		2.003	0.064	2.003
2.70		1.810	0.068	1.810
3.00		1.368	0.074	1.368
3.50	0.50	1.180	0.088	1.180
4.00		1.110	0.101	1.110
4.50		1.064	0.104	1.064
5.00		1.013	0.112	1.013

Then the experimental work had the following procedures:

1. S.B.W. model with 0.50 m height was placed, and the transmitted wave heights (H_t) were determined for each wave condition.
2. Then, the transmission coefficient (K_t) and breakwater efficiency (η) can be estimated according to the following equations:
3.

$$K_t = H_t / H_i \quad (1)$$

$$\eta = 1 - K_t \quad (2)$$

4. S.B.W. models with 0.45 m and 0.40 m heights were placed and both K_t and η were determined to illustrate the impact of SLR by 11% and 25 % respectively.
5. Singe wave screen with a porosity of 0.33 were placed at the leeward side of S.B.W. at three different relative distances (W/d) of 1.0, 2.0 and 3.0
6. Then, singe wave screens with three porosities of 0.33, 0.40, and 0.50 were placed at a fixed relative distance (W/d) of 2.0.
7. Double wave screens were placed at the leeward side at a fixed relative distance W/d = 1.0 and with three relative gap spacings (G/d) of 1.0, 2.0 and 3.0. The porosity of the seaward wave screen was 0.33 and the leeward wave had three different porosities of 0.33, 0.40 and 0.50.

3 RESULTES AND ANALYSIS

3.1 SLR impact on S.B.W. efficiency

As the experimental work is based on investigating the impact of SLR on the performance of S.B.W. and wave attenuation, without considering the increase in wave heights due to SLR. So, the water height was fixed and the S.B.W. model was used with the same height to simulate the original case without SLR, then the S.B.W. model height was reduced to 0.45 m and 0.40 m to simulate SLR by 11% and 25 % respectively.

Results showed that the transmission coefficient increased due to SLR which allows more wave overtopping, figure 5. Consequently, the efficiency of S.B.W. decreased by 10.0 % and 37.6% on average due to SLR by 11% and 25 % respectively, which illustrates the significant influence of SLR on wave attenuation and S.B.W. efficiency.

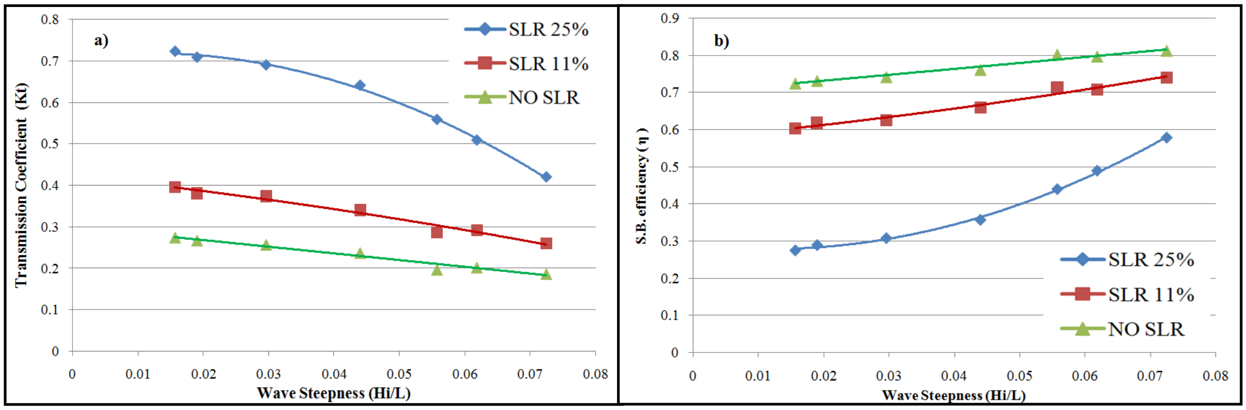

Figure 5. a) SLR impact on the transmission coefficient (Kt), b) SLR impact on S.B.W. efficiency (η).

So, it is clear that climate change and SLR threaten the stability of coastal areas protected by S.B.W., which proves the necessity of sustainable solutions to restore the breakwater`s performance. Single and double wave screens were used with different configurations in the leeward side of the S.B.W. model to improve the breakwater efficiency and increase the wave attenuation.

3.2 Single wave screen impact on S.B.W. efficiency

Single wave screens were placed at the leeward side of the S.B.W. model at a fixed relative distance (W/d) of 2.0 and three different porosities of 0.33, 0.40 and 0.50. Decreasing the screen porosity tends to afford better results but increases screen construction's initial costs.

As expected, decreasing the screen porosity reduces the transmission coefficient (K_t) and increases the S.B.W. efficiency (η). The S.B.W. efficiency increased by 20.40%, 16.30 %, and 13.30% on average in the case of single wave screen with porosities 0.33, 0.40 and 0.50 respectively. So, results show that a single wave screen with a porosity of 0.33 can average restore about 59 % of breakwater efficiency.

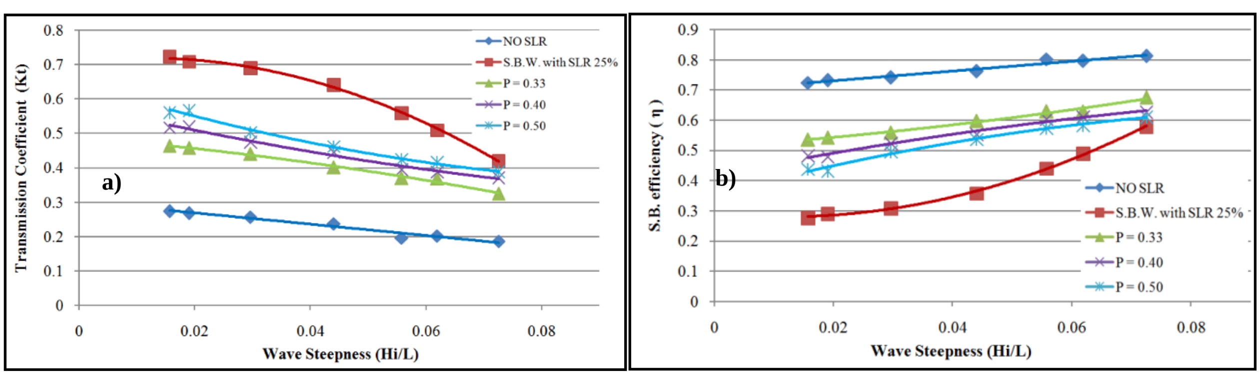

Figure 6. a) Single wave screen influence on the transmission coefficient (Kt), b) Single wave screen influence on S.B.W. efficiency (η).

To enhance screen influence and reach the optimum design parameters, a single wave screen with fixed porosity of 0.33 was placed at three relative distances (W/d) of 1.0, 2.0 and 3.0. However, results show that increasing the relative distance (W/d) from 1.0 to 3.0 increased the breakwater efficiency by about 5.0 % on average. So, the relative distance of the wave screen has a minor impact on wave attenuation, figure7.

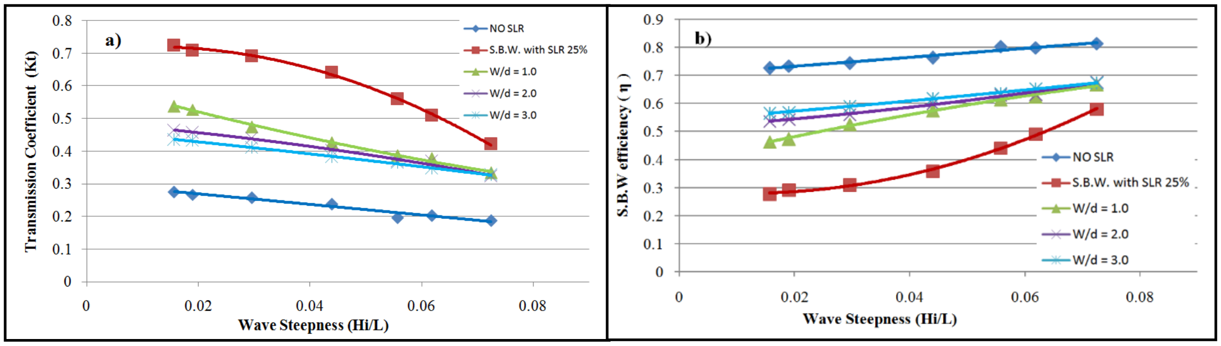

Figure 7. a) The influence of relative distance of screen on the transmission coefficient (Kt), b) The influence of relative distance of screen on S.B.W. efficiency (η).

The previous result was predicted as the permeability of the wave screen mitigates wave attenuation by water turbulence between S.B.W. and the screen. So, increasing the relative distance has a minor impact on the breakwater efficiency. Also, the leeward area of the breakwater is usually used by swimmers and recreational activities, so it is recommended to use the minimum relative distance of the wave screen.

3.3 Double wave screens impact on S.B.W. efficiency

Using a double wave screen is predicted to increase the breakwater efficiency and restore the performance of S.B.W.. Firstly, the impact of the relative distance (W/d) was investigated and the double wave screens with a fixed relative gap width (G/d) were placed at three relative distances (W/d) of 1.0, 2.0 and 3.0. The used seaward screen porosity was 0.33 and the leeward screen porosity was 0.50. As expected, the relative distance (W/d) has a minor impact on the wave attenuation and S.B.W. efficiency, Figure 8.

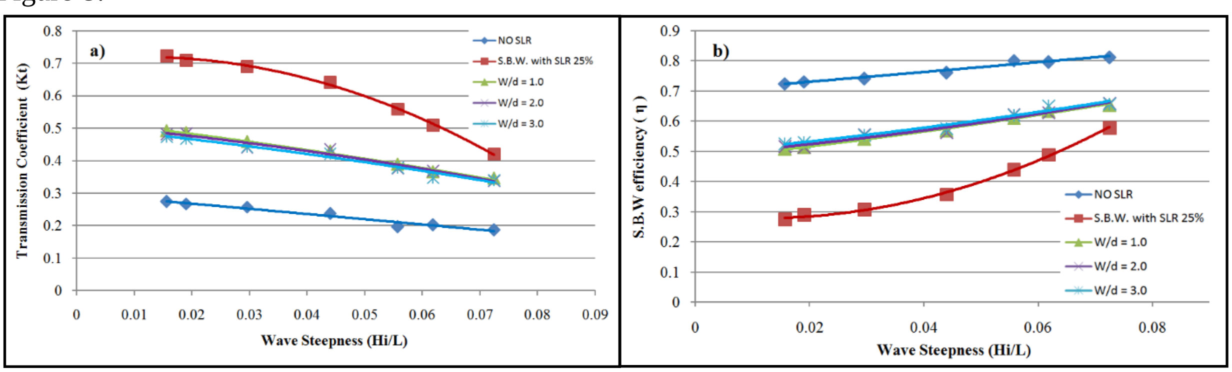

Figure 8. a) The influence of relative distance of double wave screens on Transmission coefficient (K_t), b) The influence of relative distance of double wave screens on S.B.W.. efficiency (η).

Moreover, the relative gap width (G/d) of the double wave screens was studied as the double wave screens were placed at a fixed relative distance (W/d =1.0) and relative gap width (G/d) of 1.0, 2.0 and 3.0. As predicted, increasing the relative gap width of double wave screens increases the S.B.W.

efficiency (η) and decreased the transmission coefficient (K_t). However, figure 9 shows that the relative gap has a minor impact on the breakwater efficiency. Also, using double wave screens with the minimum relative gap is predicted to be more stable, so it is recommended to use the minimum relative gap width in the case of double wave screens.

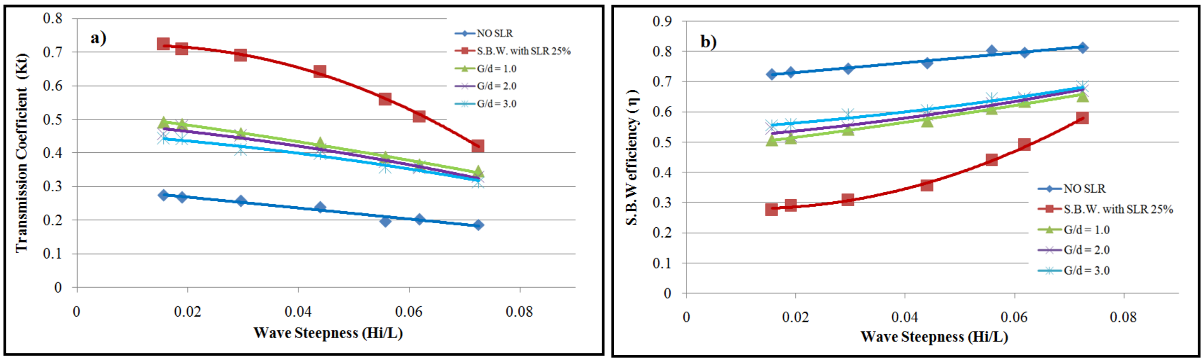

Figure 9. a) The influence of the relative gap of double wave screens on the transmission coefficient (K_t), b) The influence of the relative gap of double wave screens on S.B.W. efficiency (η).

As the screen porosity significantly impacts wave attenuation, the porosity of the leeward wave screen was investigated. Double wave screens with a fixed relative gap width (G/d =1.0) and a relative distance (W/d =2.0) were used with a seaward screen porosity of 0.33 and leeward screen porosities of 0.50, 0.4, and 0.33. As predicted the leeward screen porosity significantly impacts the wave attenuation, as the transmission coefficient decreased by 18.95 %, 22.10 % and 26.30 % in the case of screen porosities of 0.5, 0.4 and 0.33 respectively, figure 10. Moreover, the results show that using double wave screens restored the breakwater efficiency by about 50% to 70 % of the S.B.W. efficiency.

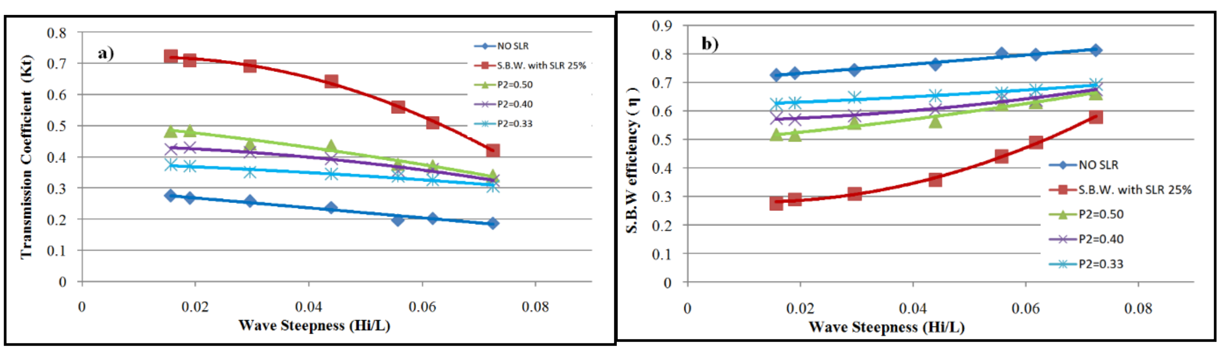

Figure 10. a) The porosity influence of leeward screen on the transmission coefficient (K_t), b) The porosity influence of leeward screen on S.B.W. efficiency (η).

4 DISCUSSION

The experimental work results show that SLR significantly impacts S.B.W.`s performance, as it permits more wave overtopping and reduces wave attenuation and breakwater efficiency. However, wave screens can be used as a sustainable solution to restore a significant part of the breakwater efficiency. For single and double wave screens, the porosity of the screen is the main design parameter that influences the breakwater performance and wave attenuation. As the porosity decreased, the transmitted waves through the screen are reduced and the wave attenuation increased. Also, the water turbulence in the confined area between S.B.W. and the wave screen increases which attenuates a part of wave energy. However, decreasing the screen porosity increases the required construction material and the resultant force due to dynamic wave pressure increases consequently, which increases the construction cost.

Moreover, although using double wave screens afford a better performance, it requires more construction costs and materials. On the other hand, figure 11 shows that single wave screen improved S.B.W. efficiency by 22.2 % and double wave screens improved S.B.W. efficiency by 26.3 % on average. So, it is clear that the difference between using single and double wave screens ranges from 2 % to 6% which is considered a minor difference. So, it is recommended to use a single wave screen to save construction costs, materials, and space.

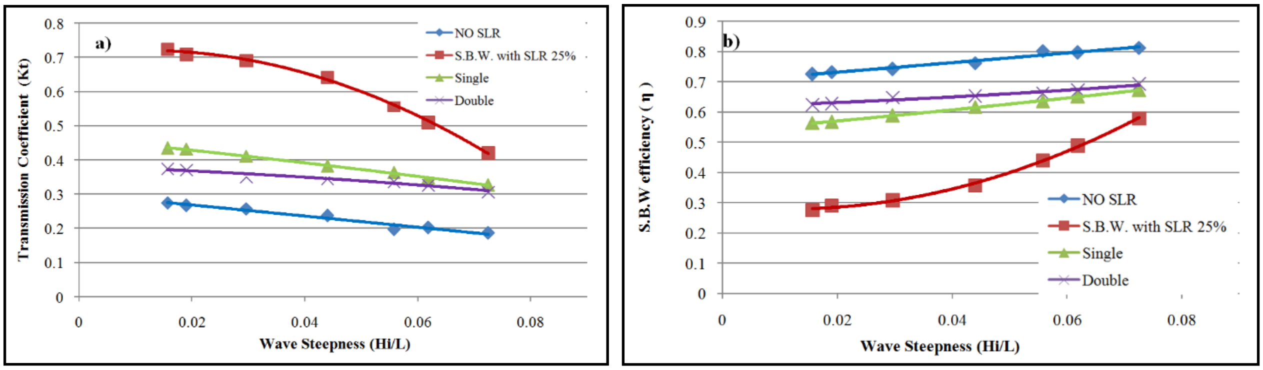

Figure 11. a) The influence of single and double wave screens on the transmission coefficient (K_t), b) The influence of single and double wave screens on S.B.W. efficiency (η).

Furthermore, **Rageh et. al 2013** suggested the use of single and double wave screens on the seaward side of the S.B.W. to improve its performance. The proposed solution improved the S.B.W. efficiency by about 14.0 : 22.0 % (Rageh et al., 2013). The previous solution provides less efficiency and requires more construction cost as placing the wave screens on the seaward side means higher screen height, and high wave pressure on the wave screens which requires larger cross sections. Also, **Saad et. al 2022** proposed using the wave screen above the S.B.W. crest which improved the efficiency by 19.3% (Saad et. al, 2022). Although the using wave screen above the S.B.W. crest saves the constriction cost, the screen fixation and the connection between the S.B.W. and the wave screen remains a technical issue. So, it is clear that placing wave screens on the leeward side of S.B.W. is the best alternative with higher efficiency and less construction cost.

CONCLUSION

Submerged breakwaters are commonly used around the world as they are considered one of the main environmental alternatives for shore protection. Sea level rise is one of the main impacts of climate change and it is a significant threat to submerged breakwater performance. So, single and double wave screens with horizontal slats were suggested to restore the submerged breakwater efficiency.

The experimental study concluded that:

1. SLR has a significant impact on wave attenuation and S.B.W. efficiency.
2. The efficiency of S.B.W. decreased by 10.0 % and 37.6% on average due to relative SLR of 11% and 25 % respectively.
3. A single wave screen with a porosity of 0.33 improved S.B.W. efficiency by 22.22 % and restore about 59 % of the breakwater efficiency.
4. The relative distance of the wave screen has a minor impact on wave attenuation, so it is recommended to use the minimum relative distance of the wave screen.

5. Double wave screens restored the breakwater efficiency by about 50 % to 70 % of the S.B.W. efficiency.
6. The minor difference between using single and double wave screens ranged from 2 % to 6%, so it is recommended to use a single wave screen to save construction costs, materials, and space.
7. Placing wave screens on the leeward side of S.B.W. is the best alternative with higher efficiency and less construction cost.

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