Performance Characteristics of a Submerged Semicircular Breakwater Exposed to Regular Waves: An Experimental Study

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Abstract. Many mangrove replanting programs fail due to the drifting of the mangrove sapling by waves and coastal currents soon after the replanting. Hence, adequate wave protection for the mangrove planting site is required to enhance the survivability rates of the newly planted saplings. A small scaled modular submerged semicircular breakwater (SBW) is perceived to be a viable option to provide the required level of wave protection to mangroves. The study is set to investigate wave transmission, reflection, and energy loss by a SBW subjected to different immersion depths under a regular wave environment via physical modelling. The SBW model was tested in a wave flume and was subjected to relative immersion depth, i.e., a ratio of water depth to the height of the SBW, of 1.00 and 1.33, and wave steepness ranging from 0.02 to 0.06. The alternatively submerged SBW was found to be an effective breakwater design to provide the required level of wave tranquility to various coastal applications.

1 Introduction

Breakwaters are structures that are typically constructed near the coast to prevent wave action from causing damage to beaches, bluffs, dunes, and harbor areas. A breakwater is typically constructed by a trapezoidal core overlaid with filter rocks and amour rocks as the external layer providing wave energy dissipation to the structure. When good quality rock is not available, concrete armor units, e.g., Dolos, Tetrapod, etc., are used to substitute the armor rocks. Both are gravity-type structures having a large footprint and may not be suitable to be constructed at sites with soft soil conditions [1-3].

Depletion of coastal mangroves has become a common problem in Malaysia [4-7]. Various attempts were made to regenerate the mangrove ecosystem through replanting programs by various agencies and NGOs; nevertheless, very few were successful [8-10]. This was partly due to the drifting of the mangrove saplings by the intrusive wave and current actions. Hence, these mangrove replanting sites require wave protection by an appropriate coastal engineering structure, e.g., geotextile tubes, which have a somewhat semicircular cross-section [10]. However, geotextile tubes are easy to be punctured by sharp objects and the life span is usually 3-5 years [11, 12].

Constructions of the large-scaled semicircular breakwater (SBW) consisting of a precast reinforced concrete structure composed of a semicircular caisson and a bottom slab, were previously undertaken at Miyazaki Port (Japan), Tianjin Port (China), Yangtze Estuary in (China), Nha Mat Bac lieu (Vietnam) and Ca Mau in (Vietnam) [13-15]. These gigantic breakwaters were built to provide safe channel entrances and wave protection to port basins. There are several advantages of the semicircular breakwaters [1]: (i) wave forces acting on the SBW pass through the center of the circle, (ii) high stability against wave action, and (iii) The vertical forces acting on the foundation are minimal and almost evenly distributed because the SBW is hollow.

In this study, emphasis is given to a small-scaled submerged semicircular breakwater primarily used for mangrove protection on muddy coasts. Complete wave attenuation in some coastal applications, e.g., mangrove protection and fish farms, is not necessary. Hence, a submerged semicircular breakwater is perceived to be able to provide the solution to such applications. The submerged breakwater intercepts part of the waves by reflection and wave breaking over it, and the remaining wave energy gets transmitted to the lee side of the breakwater with a reduced wave height. Another merit of this submerged structure is that it poses minimal visual disturbance, sustaining the natural beauty of the beach. In this research, an attempt was made to investigate wave transmission, reflection, and energy loss by a submerged semicircular breakwater subjected to regular waves, using physical modeling.

2 Methodology

Figure 1 provides the schematic diagram of a semicircular breakwater (SBW) model, which has an external radius (R), thickness, and length of 0.6, 0.1, and 0.8 m, respectively. The breakwater width (B) is 1.2 m, and the height (h_c) is equivalent to R. A Froude scaling of 1:2.5 was adopted so that the test model could appropriately fit the geometrical requirement of the test facility. The test model was made of concrete that has a density of 2400 kg/m3.

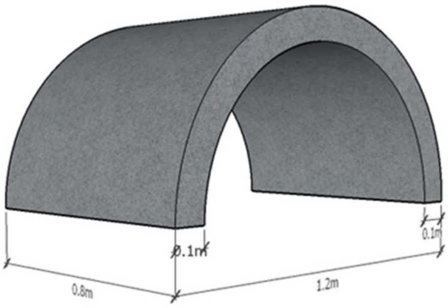
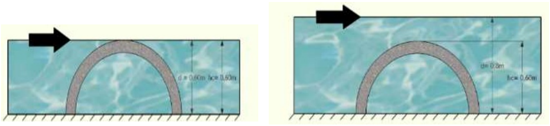


Fig. 1. Semicircular breakwater model

A series of experiments were conducted in a 20-m wave flume at the Offshore Laboratory of Universiti Teknologi PETRONAS to assess the hydraulic properties of the semicircular breakwater. The width of the flume was 0.8 m. The test model was placed at a distance of 10 m from the piston-type wave generator located at one end of the flume, as shown in Figure 2. Six units of wave probes were placed along the wave flume to measure the water profiles. Utilizing Mansard and Funke's (1980) [16] least-squares method, the offshore probes WP1, WP2, and WP3 were used to distinguish between incident and reflected waves. Similar wave probes setting (WP4, WP5, and WP6) were arranged at the shoreward of the test model to obtain the transmitted wave height and the reflected waves if there were any. Prior to the experiment, all wave probes used in this study were meticulously calibrated. The wave absorber placed at the end of the placed at the end of the dlume was to eliminate the incoming waves. Hence, the reflected waves at the shoreward of the test model were consistently small. Under the regular wave environment, the semicircular breakwater model was tested with a range of wave steepness from 0.02 to 0.06 and relative depth parameters (i.e., a ratio of water depth to the radius of the semicircular breakwater) of 1.00 *alternatively submerged) and 1.33 (submerged). The two test scenarios of d/h_c are schematically illustrated in Figure 3. The details of the test parameter are summarized in Table 1. A total of 108 experiments were conducted for this study.



(a) $d/h_c = 1.00$ (b) $d/h_c = 1.33$

Fig. 2. Laboratory Set-up

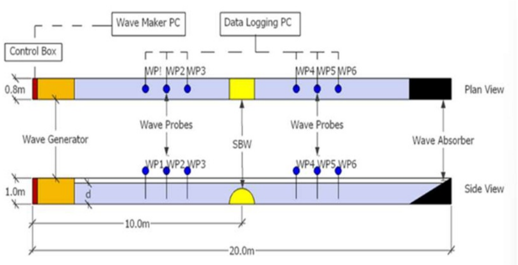


Fig. 3. SBW with different immersion depths

Table 1. Test parameters

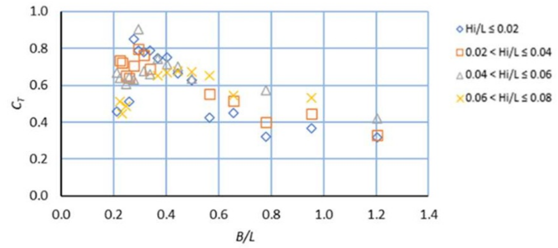
Parameter	Value Range
Incident wave height, Hi (m)	0.02 - 0.33
Water depth, d (m)	0.6, 0.8
Wave period, T (s)	0.8 - 2.5 ($\Delta T = 0.1$s)
Wave steepness, Hi/L	0.02, 0.04, 0.06
Relative depth, d/h_C	1.00 (Alternatively submerged) 1.33 (Submerged)
Relative wave period, B/L	0.2 – 1.2

3 Results and Discussions

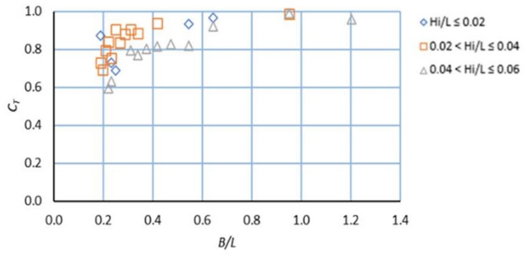
The data collected from experiments were analyzed and plotted in the form of wave transmission, wave reflection and energy loss graphs. These graphs relate wave transmission/reflection/energy loss with some dimensionless parameters, i.e., relative width, B/L (where B is the width of the structure, and L is the wavelength), wave steepness, H_i/L (where H_i is the incident wave height) and relative water depth, d/h_c (where d and h_c are the water depth and breakwater crest height, respectively). The mentioned graphs will be explicitly discussed in the following section.

3.1 Wave Transmission

The ability of the SBW in transmitting the wave energy is measured by wave transmission coefficient (C_T), which is the ratio of transmitted wave height (H_T) to incident wave height (H_i) [17-20]. The lower the C_T value, the higher the wave attenuation performance of the breakwater [17]. Figure 4 shows wave transmission coefficients for $d/h_c = 1.00$ and 1.33. In Figure 4(a), the C_T of the alternatively submerged breakwater ($d/h_c = 1.00$) decreases with the increase of B/L regardless of H_i/L. The maximum and minimum C_T values recorded are about 0.9 and 0.3, respectively. This implies that the alternatively submerged SBW was more capable of intercepting the waves of shorter periods or lengths when subjected to regular wave actions. This is sensible because the short waves that carry less energy flux (less developed) become unstable when approaching the alternatively submerged breakwater. Some waves might successfully pass over the breakwater and be transmitted to the lee of the structure with reduced wave height. Parts of the wave will get reflected and dissipated, which the details will be elaborated on in Sections 3.2 and 3.3. For the submerged SBW (d/h_c = 1.33), the C_T values are relatively high (ranging from 0.6 to 1.0) compared to that of the breakwater with d/h_c = 1.00 (Figure 4b). This means that the wave attenuation of the submerged breakwater is less superior than the alternatively submerged breakwater. The presence of the submerged breakwater seems to be able to intercept the longer period waves when B/L < 0.6. For shorter period waves, the more circular water particle orbits reduce in size as water column extends in z direction [21]. The effect of the water particle orbits on the semicircular structure is almost negligible; hence, the incident waves passed the submerged structure at ease without much flow interference. From Figure 4, the influence of wave steepness on C_T is significant for both d/h_c = 1.00 and 1.33.



(a) Alternatively submerged SBW (d/h_c = 1.00)



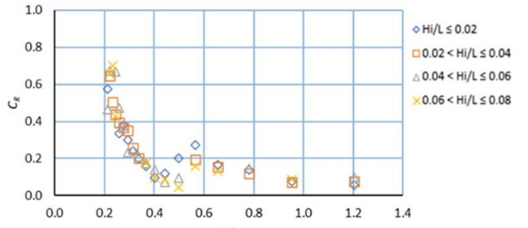
(b) Submrged SBW (d/h_c = 1.33)

Fig. 4. Wave transmission: (a) d/h_c = 1.00, and (b) d/h_c = 1.33

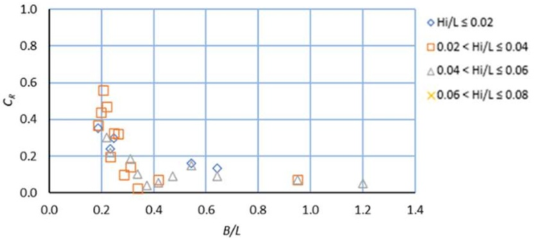
The C_T values reduce with the increase of H_i/L for d/h_c = 1.33. Opposite relation is seen when B/L > 0.5 for d/h_c = 1.00. At this stage, waves of higher steepness were partly intercepted by the SBW, and the remaining waves overtopped the crest of the structure and formed transmitted waves of appreciable sizes. Therefore, the C_T of the higher steepness waves exhibits larger values.

3.2 Wave Reflection

The ability of the SBW in reflecting the wave energy is measured by the wave reflection coefficient, C_R which is defined as the height of the reflected wave (H_R) divided by the height of the incident wave (H_i)) [20-22]. Wave reflection characteristics of the SBW models are investigated with respect to the influence of wave period, immersion depths and wave steepness in Figure 5. It is obvious that the C_R variation corresponding to wave steepness is almost invisible, suggesting that wave steepness is an insignificant parameter affecting wave reflection of the submerged and alternatively submerged semicircular breakwater in which d/h_c = 1.00 – 1.33. However, the influence of wave period, B/L on C_R is substantial, particularly at B/L < 0.4. A sharp drop of the C_R is observed for both immersion depths and hit a minimum value at 0.4 < B/L < 0.5. The C_R subsequently achieves a small peak at B/L = 0.55 before the gradual dipping for the larger range of B/L. The bragging effect of C_R was also identified and reported in the large scale semicircular breakwaters [23, 24]. In short, the proposed SBW is highly reflective (0.2 < C_R < 0.7) when exposed to longer waves (B/L < 0.3). For shorter waves, the wave reflection is fairly small with anticipated C_R values of less than 0.2. A comparison between the C_R graphs of Figure 5a and Figure 5b shows that the wave reflection by the alternatively submerged SBW is more dominant. This can be explained by the fact that the alternatively submerged SBW (d/h_c = 1.00) poses more disturbance to the advance of the incident waves. It is also worthwhile to note that the high wave reflection characteristics of the SBW at lower range of B/L in Figure 5 contribute to the low wave transmission as shown in Figure 4. In summary, the proposed SBW is a strong reflector only at B/L < 0.3 for d/h_c = 1.00 – 1.33. The reflective performance of the alternatively submerged breakwater surpasses the submerged breakwater by about 10%.



(a) Alternatively submerged SBW (d/h_c = 1.00)



(b) Submerged SBW (d/h_c = 1.33)

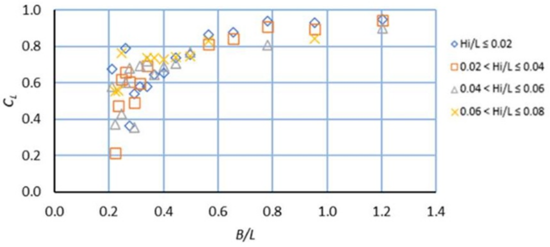
Fig. 5. Wave reflection: (a) d/h_c = 1.00, and (b) d/h_c = 1.33

3.3 Wave Energy Loss

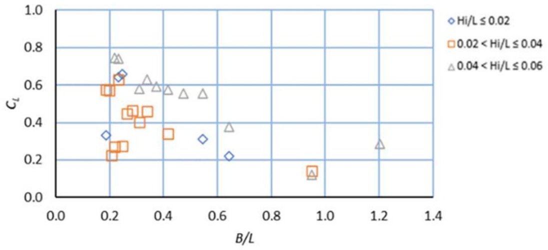
It is known that the most efficient breakwater has low wave reflection, low wave transmission, and high energy dissipation [25]. Wave dissipation coefficient, C_L, is an index to reveal the hydraulic efficiency of breakwaters [25]. It is derived based on the energy conservation law ($C_T^2 + C_R^2 + C_L^2 = 1$) [19, 21, 24, 26-28]. The wave energy dissipation is mainly caused by either wave breaking or flow percolation [29]. In the case of the semicircular breakwaters, the energy dissipation is higher compared to other conventional types of breakwaters due to their curvature shapes [30].

Figure 6 shows the variation of energy dissipation coefficients, C_L for the SBW model, corresponding to relative width, B/L and wave steepness, H_i/L, for $d/h_c = 1.00$ and $d/h_c = 1.33$ due to regular waves. Overall, the submerged SBW attenuates lesser wave energy compared to the alternatively submerged SBW because more transmission occurs for a higher relative depth of submergence. Due to the small relative depth of submergence, the alternatively submerged breakwater poses larger interception to the incoming waves, resulting in wave breaking as the waves pass over the crest of the breakwater. It is seen from Figure 6(a) that the C_L increases drastically with the increase of B/L, regardless of the wave steepness ratios. The maximum C_L value of 0.95 was recorded at $B/L = 1.2$. Waves of smaller wavelengths tend to release the energy better upon reaching the structure. For instance, the waves of $B/L > 0.6$ are capable of yielding C_L's of more than 0.8 when approaching the breakwater of $d/h_c = 1.00$. For $d/h_c = 1.33$, an opposite trend is observed, whereby the C_L decreases with the increase of B/L, as shown in Figure 6(b). When being appeached by the longer waves, the submerged SBW displays some energy dissipative mechanisms to increase the C_L values appreciably ($0.2 < C_L < 0.7$). In short, the alternatively submerged SBW acts as an efficient energy dissipator when subjected to smaller wave period waves, and the submerged SBW is a better energy dissipator when subjected to longer period waves.

From Figure 6, it is noticed that the effect of wave steepness on C_L varies with the range of B/L and d/h_c. For $d/h_c = 1.00$, the variations of C_L values are small, suggesting that C_L is less governed by wave steepness when $B/L > 0.5$. On the contrary, the influence of wave steepness is considerable at $B/L < 0.5$; however, there is no definite relationship between C_L and wave steepness. The long period waves having larger displacements in the direction of wave propagation and the obstruction extending over the entire water depth would result in a substantial dissipation of orbital motions, leading to a lesser C_T and higher C_L for a larger B/L [31]. The SBW behaves very differently with the state of immersion $d/h_c = 1.33$ in Figure 6 (b). For $d/h_c = 1.33$, it is noticed that the C_L decreases with the decrease in incident wave steepness H_i/L. C_L values become maximum at $0.04 < H_i/L < 0.06$. This was due to wave breaking occurrence as the incident waves propagate over the submerged structure. In short, it can be deduced that the wave dissipation performance of the alternatively submerged SBW ($d/h_c = 1.00$) is superior than that of the submerged SBW ($d/h_c = 1.33$).



(a) Alternatively submerged SBW ($d/h_c = 1.00$)



(b) Submerged SBW ($d/h_c = 1.33$)

Fig. 6. Energy loss: (a) $d/h_c = 1.00$, and (b) $d/h_c = 1.33$

4 Conclusion

The modular semicircular breakwater (SBW) suitable for various coastal protection applications i.e., mangrove sapling protection, was developed in this study. The hydraulic characteristics of the proposed SBW were ascertained using physical modelling. From the experimental results, the wave attenuation performance of the alternatively submerged SBW of $d/h_c = 1.00$ is superior than the submerged SBW of $d/h_c = 1.33$. The alternatively submerged SBW is capable of limiting the incident wave height as high as 70% when subjected to regular waves of shorter periods. The alternatively submerged SBW exhibited a higher wave reflection characteristic than the submerged SBW by about 10% when exposed to longer period waves. Evident wave reflection happens at $B/L < 0.3$ for $d/h_c = 1.00 – 1.33$. When alternatively submerged and attacked by shorter waves, the SBW showed a higher energy dissipation performance due to wave breaking and other energy losses. The breakwater can dissipate up to 90% of the wave energy. Nevertheless, the wave energy dissipation performance deteriorates when the immersion depth increases.

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