Performance Efficiency of a Membrane-Type Floating Breakwater for Protection of Coastal and Offshore Facilities

E J Pereira\textsuperscript{1*}, H M Teh\textsuperscript{1,2}, W L Chan\textsuperscript{3} and T Silavaraj\textsuperscript{4}

\textsuperscript{1}Civil and Environmental Engineering Department, Universiti Teknologi PETRONAS 32610 Bandar Seri Iskandar, Perak, Malaysia.
\textsuperscript{2}Centre for Urban Resource Sustainability, Institute of Self-Sustainable Building, Universiti Teknologi PETRONAS
\textsuperscript{3}Department of Bridge and Marine, Sepakat Setia Perunding, Wisma SSP, No 1, Jalan Serdang Raya, 8/3, Serdang Raya, 43300 Seri Kembangan, Selangor.
\textsuperscript{3}Cast Laboratories Pte Ltd, 17 Tuas Ave 8, 639232, Singapore.
\*Corresponding authors: ericjpereira@gmail.com; heemin.teh@utp.edu.my

Abstract. A flexible box-type floating breakwater composed of a number of membrane ballasts filled with air, water and sand has been developed for wave protection of various coastal and offshore applications. The combination of ballasts of different materials would eventually result in the same draft for all the tested models, and the performance efficiency of each breakwater model was ascertained by the means of physical modelling. A total of four rectangular breakwater models of different dynamic properties have been developed and tested in regular wave environment in a wave flume. The performance efficiency of the breakwater is determined by the wave transmission and energy dissipation characteristics. For comparison purposes, a control test model with similar dimensions is also tested in the similar test conditions. The proposed model with sand ballast at the bottom has been proven to have a higher wave attenuation capability than the other test models and the performance efficiency is comparable to that of the rigid box-type floating breakwater in some cases.

1. Introduction

Coastal protection becomes relevant to the sea-bordered countries that are subjected to the extreme wave climates during storms. The bottom mounted breakwaters are employed to withstand the rough waves as they are perceived to provide higher level of wave protection to the coastal properties. Nonetheless, the adverse implications they posed to the neighbouring environment are very often overlooked. These include interruptions to the nearshore sediment transport, interference to the migrating marine life, the downcoast erosion and water contamination during the construction stage. To reduce the level of environmental impacts, the use of floating breakwaters for the sensitive sites may be a more viable option. These lightweight marine structures are adaptable to the tidal changes and pose less interruption to the morphological cycle of the adjacent beaches. The construction cost of such facilities becomes more economical if installed in a water depth of more than 6.1 m \cite{1}.

Both bottom mounted breakwaters and floating breakwaters offer wave protection at different levels. Even though the wave attenuation efficiency of floating breakwaters is not as good as the bottom mounted breakwaters, they remain pertinent in some of the recreational and marine related industry in which complete wave attenuation is not anticipated. Floating breakwaters mainly function to reduce surface waves by intercepting the wave orbitals and attenuating the energy flux by the means of energy
loss through destruction of water particle orbital motions, viscous damping, friction, turbulence and nonlinear wave breaking [2-3].

Teh (2013) classified free-surface breakwaters into four types, i.e. solid-type, plate-type, caisson-type and multipart-type [4]. Other breakwaters with complex features are semi-circular breakwater with truncated wave screen [5-6] and H-type breakwater [7]. Among all free-surface floating breakwater configurations, the most basic design is the box-type rectangular breakwater, in which the performance efficiency is principally governed by the height, width and length of the floating barrier. The weight of the box-type floating breakwater determines its draught level, i.e. the height of the submerged part. The draught of the structure governs wave attenuation of the short-period waves. Additional local turbulence and energy dissipation would be anticipated when the draught increases. Suppression of long period waves, on the other hand, is dependent upon the structural width for effective dissipation [8]. Researches on box-type breakwater have innovated by methods of addition of vertical plates [9] and slotted barriers [10] to increase the draught, allowing for increased interactions with the wave orbitals below the breakwater.

Besides variation of the breakwater draft, increasing the width of the structure is another method to increase wave attenuation. Researches were undertaken to increase the wave attenuation by the addition of pneumatic chambers [11] and mesh cage within the structure [12]. These supplementary features of the breakwater would increase dissipation of wave orbitals over a single wavelength as compared to the standard box-type breakwater. The pneumatic chamber and mesh cage induce energy damping through pressure variations and viscous dissipation, respectively. In short, floating breakwaters of larger width (in line with the wave direction) and draught would effectively suppress wave particle orbits in vertical direction due to wave breaking and wave fission induced by collision between the accelerated incoming waves and the vertical barrier that create a strong reverse flow [13].

Floating breakwaters have a wide range of applications. Besides providing coastal protection, floating breakwaters with rapidly installation mechanisms are also used to support the off-loading and on-loading operations of the military ship in open seas [14]. The typical examples of such breakwaters are the Rapidly Installed Breakwater System (RIBS) [14], Deployable Floating Breakwater [15] and the Floating Modular Breakwater [16]. They can be easily and rapidly deployed when needed and are commonly used for offering temporal wave protection in the open seas. These temporary breakwater systems are light and relatively cost effective; however, their lifespan is somewhat short. These structures are made of solid materials and has various configurations. The rigidity of the breakwaters has resulted in high wave reflection at the seaward of the structures, which in turn leads to confusing sea state that may endanger the small floating vessels. In this study, a rapidly installed rectangular floating breakwater made of a flexible or membrane-type material is devised. The advantages of this membrane-type breakwater include reduction of mooring loads and elimination of resonance effects which causes peaks in wave loadings [17]. The objective of this study is to assess the wave transmission and energy dissipation ability of the membrane-type rectangular floating breakwater in regular waves using physical modelling approach.

2. Methodology

2.1. Test Models
A total of four rectangular test models of 0.15m high, 0.25m wide and 0.30m long with different ballasting properties were constructed, namely FLEX-1W, FLEX-1S, FLEX-2W and FLEX-2S. The geometrical properties and the ballasting configurations of these test models are demonstrated in Table 1. These models were made of a clear plastic sheet for the ease of visibility during the experiment. The ballasting materials, i.e. water and sand, were confined in modules and were placed within the body of the membrane-type floating pontoon in a unique way as shown in Table 1. These ballasting modules were cushioned by airbags placed vertically for FLEX 1 models and laterally for FLEX 2 models as shown in the table. Consequently, the position of the ballasting modules within the floating pontoon yielded a variety of buoyancy properties to the test models. The draught, centre of gravity and metacentric height of the respective test model are given in Table 1. Apart from the membrane-type models, a control model
A rectangular pontoon that was made of a rigid material was also developed for performance comparison purposes. Each of the test model was fixated by four mooring lines of 0.25 m long.

| Modal ID | FLEX-1 W | FLEX-1 S | FLEX-2 W | FLEX-2 S | RIGID |
|----------|----------|----------|----------|----------|-------|
| Model Configuration | Water ballast at the base | Sand ballast at the base | Water ballast at the centre | Sand ballast at the centre | Rigid shell with sand ballast |
| Width | 0.3 m | 0.3 m | 0.15 m | 0.15 m | 0.30 m |
| Height | 0.075 m | 0.047 m | 0.15 m | 0.094 m | 0.047 m |
| Mass | 6.75 kg | 6.75 kg | 6.75 kg | 6.75 kg | 6.75 kg |
| Centre of gravity | 0.038 m | 0.023 m | 0.075 m | 0.047 m | 0.025 m |
| Draft | 0.075 m | 0.075 m | 0.075 m | 0.075 m | 0.075 m |
| Metacentric height | 0.083 m | 0.096 m | 0.046 m | 0.072 m | 0.094 m |

2.2. Experimental Setup
A series of experimental testing were conducted in a wave flume at Hydraulic Laboratory of Universiti Teknologi PETRONAS, Malaysia. The five models were tested in a 10 m long, 0.32 m width and 0.48 m deep wave flume furnished with a wave generator at one end and a wave absorber at the other end of the facility. A total of four membrane-type floating breakwater and a rigid floating breakwater were tested in regular wave environments to investigate their wave transmission, reflection and energy loss characteristics with respect to wave period $T$ ranging from 0.8 s to 2.0 s with a sampling interval of 0.1 s, at three water depths, $d = 15, 20$ and $25$ cm. For each wave period, each test model was subjected to three different wave heights, giving a range of wave steepness, $H_i/L$ varying from 0.005 to 0.080, where $H_i$ and $L$ are height and wavelength of the incident waves, respectively. During the experiment, three wave probes were placed at seaward side of the test models for measurement of incident waves and reflected waves from the test model. On the lee-side of the model, another three wave probes were used to determine the transmitted waves. These wave probes were connected to a data logger which recorded the water level elevation outputs. The measured data were transmitted to the HR Wallingford data acquisition system to obtain water surface elevations of the six wave probes for further analysis of the wave properties using WaveLab software developed by Aalborg University. It is worth to note that all wave probes were carefully calibrated against systematic errors prior to the experiments. In total, 108 tests were conducted for this experimental study. The complete set up of the experiment is presented in Figure 1.
3. Results and Discussion

3.1. Hydrodynamic Performance
In this study, the wave transmission, wave reflection and energy loss of the breakwaters are respectively characterised by the coefficients of wave transmission ($C_t$), reflection ($C_r$) and energy loss ($C_l$). The wave transmission coefficient ($C_t$) is a ratio of the transmitted wave height ($H_t$)-to-the incident wave height ($H_i$):

$$C_t = \frac{H_t}{H_i}$$

(1)

The wave reflection coefficient ($C_r$) compares the reflected wave height ($H_r$) and the incident wave height ($H_i$) in the following:

$$C_r = \frac{H_r}{H_i}$$

(2)

To determine the amount of energy dissipated by the breakwater, the loss coefficient ($C_l$) of the structure is derived based on the principle of conservation of energy:

$$C_l = \sqrt{1 - C_r^2 - C_t^2}$$

(3)

Note that this paper will only report the wave transmission and energy loss characteristics of the test models. For this study, the wave transmission and energy loss coefficients are plotted against the relative the width of the breakwater ($B/L$) to understand the relative performance of the breakwaters with respect to the width ($B$) of the structure when subjected to regular waves of various wavelengths ($L$).

3.2. Results and Discussion
The transmission coefficient ($C_t$) is the key indicator to show the overall performance of a floating breakwater. The higher the $C_t$, the better will be the wave attenuation efficiency of the breakwater. As for $C_l$, the higher values indicate good energy dissipation by the breakwater. Figure 2 shows the variations of $C_t$ and $C_l$ of the five test models, i.e. FLEX-1W, FLEX-1S, FLEX-2W, FLEX-2S and the rigid box-type models, at a depth of 25 cm. It is seen from the Figure 2a that the $C_t$ decreases drastically with the increase of $B/L$. This indicates that all test models suppress wave energy of the shorter waves more effectively. Both FLEX-1 models filled with water and sand at their bases have higher wave attenuation ability compared with those FLEX-2 models filled with water at their centres. The metacentric heights yielded by FLEX-1 models are higher than those of FLEX-2 models; hence, the FLEX-1 models are hydraulically more stable than the FLEX-2 models. The $C_l$ discrepancies between
FLEX-1 and FLEX-2 models become more distinct when $B/L > 0.15$. It is also found that the models filled with sand perform slightly better than those filled with water due to the lower centroid and rigidity of the ballasting material. In comparison with the control model – rigid box-type model, the recorded $C_t$ values are the lowest throughout the $B/L$ test range. The findings are anticipated as the rigid body structure tends to reflect and dissipate the energy more than the membrane-type structures do. However, as wave period increases the $C_t$ variations between the membrane-type and solid-type breakwaters become less apparent, with an average discrepancy of 0.05. Hence, it can be deduced that the wave attenuation ability of the membrane-type breakwater is almost comparable with that of the solid-type breakwater at $B/L < 0.15$.

The energy dissipation abilities of the membrane-type and solid-type floating breakwaters are demonstrated in Figure 2b. It is evident that the $C_l$ values of both models increase with the increase of $B/L$, revealing that the test models have the capability of dissipating more energy when exposed to shorter period waves. The maximum $C_l$ attained by FLEX-1 and FLEX-2 models at $B/L = 0.22$ are 0.64 and 0.86, respectively. This explains the rapid drop of $C_t$ at $B/L = 0.22$ for both FLEX-1 and FLEX-2 models in Figure 2a. It is also noticed that the $C_l$ of the FLEX-2 models are consistently lower than those of the FLEX-1 models throughout the range of $B/L$. This implies that the FLEX-1 models with the ballasting modules at the bottom help not just to stabilize the floating body but also to prolong the wave-structure interaction time for enhancement of frictional losses by the structure. Surprisingly, it is noticed that the energy dissipating performance of the FLEX-1S model is as good as that of the solid-type model for the test range of $B/L$. In summary, the FLEX-1S model has been selected as the most effective membrane-type energy dissipator. It becomes particularly effective in promoting energy losses using its features when confronted by shorter period waves.

![Figure 2. Variations of $C_t$ and $C_l$ at $d = 0.25$ m: (a) Wave transmission (b) Energy loss](image-url)

As water depth reduces from 25 cm to 20 cm, the $C_t$ and $C_l$ trends with respect to $B/L$, as seen in Figure 3, resemble those of $d = 25$ cm (Figure 2). At intermediate depth ($d = 20$ cm), the overall $C_t$ plot reduces as $B/L$ increases, and $C_l$ has a reversed relationship with $B/L$, regardless of the types of model. It is seen from the figure that the $C_l$ values of $d = 20$ cm are lower than those of $d = 25$ cm, and the $C_t$ values of $d = 20$ cm are higher than those of $d = 25$ cm. This reveals that the tested floating breakwater models exhibit enhanced wave suppression and energy dissipation abilities in intermediate water. As water depth is limited, the water particle orbits are more effectively hindered by the floating breakwaters.
As expected, the FLEX 1-S model outperforms the other membrane-type models for the entire B/L range. It is surprising to notice that the FLEX 1-S model also outperforms the rigid box-type model in wave dampening at B/L < 0.25. In another word, the non-rigid membrane of the FLEX 1-S model does help to enhance the energy dissipation capabilities and reduce peak impacts during wave impingement which in turn leading to extensive wave attenuation when exposed to longer period wave environment. This observation agrees with the finding of Hales [17].

Figure 4 shows the variations of C_t and C_l of the test models with B/L at a depth of 15 cm. It is found that both C_t and C_l variations are relatively small compared to those of d = 20 cm and 25 cm, and the C_t and C_l trends are less defined with respect to B/L. This means that the wave transmission and energy loss characteristics of the test models are less affected by the wave period or the wavelength. However, it is evident from the figure that further improvement of wave attenuation and energy dissipation are seen for the membrane-type models as well as for the solid-type model. For the FLEX-1S model, the lowest C_t and maximum C_l attained are 0.30 and 0.88, respectively. Even though the C_l of the FLEX-1S model is comparable to that of solid-type model at B/L > 0.25, the overall performance of the FLEX-1S model falls short of that of the rigid-type model at d = 15 cm. This is attributed to high reflectivity of the solid-type model throughout the test range of B/L at d = 15 cm. The solid-type model becomes an excellent wave attenuator and a great energy dissipator at shallow waters. Relatively, it is 20% better than the FLEX-1S model in terms of wave attenuation due to its highly reflective surfaces. It is worthwhile to note that extreme wave reflection in front of the structure is undesirable as it may result in navigation hazards to the small floating vessels.
To summarize, the flexible membrane floating breakwater has been proven to be effective in attenuating wave energy in water depths ranging from 0.15m to 0.25m with a draft of 0.075m to address both offshore and nearshore application. The floating breakwater performance is governed according to priority by the relative water depth, configuration of internal ballasting (eg: FLEX-1, FLEX-2) and lastly ballasting material or external rigidity. The rigid model outperformed the flexible models as the water depth decreased due to increased wave reflection and energy dissipation of orbitals by the hard surface. The FLEX-1 S model with lower and wider distributed configuration of ballasting performed comparable to that of the rigid with a maximum difference of 20% in wave energy dissipation.

4. Conclusion
In conclusion, the membrane-type model proposed with the FLEX-1 configuration was able to function effectively as a wave attenuator achieving a $C_t$ value as low as 0.3 which was comparable to that of the rigid type floating breakwater. In offshore conditions with deeper water depth, it is recommended that the FLEX-1 model to be ballasted with the surrounding sea water; however, for shallower sites within the coastal regions, the use of sand as ballasts is the most suitable. This would save deployment time, resources and allow for the breakwater to be deployed more easily on site in deeper regions where logistics of heavy mass is a concern. In order to yield effective wave dissipation, the membrane-type floating breakwater needs to have properties of a high and positive metacentric height to achieve greater stability of the breakwater when acted upon by waves. The design of this membrane-type floating breakwater is proven to be effective with the FLEX-1 configuration and further research needs to be carried out to study the methods of deployment of the proposed design.

5. References
[1] McCartney B L 1985 Floating Breakwater Design. J. of Waterway, Port, Coastal, and Ocean Eng. 111 304-318
[2] Wang H Y and Sun Z C 2010 Experimental study of a porous floating breakwater Ocean Eng. 37 520-527
[3] Ozeren Y, Wren D G, Altinakar M and Work P A 2011 Experimental Investigation of Cylindrical Floating Breakwater Performance with Various Mooring Configurations J. of Waterway, Port, Coastal, and Ocean Eng. 137 300-309
[4] Teh H M 2013 Hydraulic performance of free surface breakwaters: A review. *J. Sains Malaysian* 42 1301-1310

[5] Teh H M and Venugopal V 2013 Performance evaluation of a semicircular breakwater with truncated wave screens *Ocean Eng.* 70 160-176

[6] Teh H M and Venugopal V 2015 Optimization of Hydraulic Efficiency of a free surface semicircular breakwater using wave screens’ *The 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015)* (St. John’s, Canada)

[7] Teh H M, Kurian V J and Hashim A M 2014 Hydraulic investigation of the H-type floating breakwater *Proceedings of the IEEE/MTS OCEANS’14* (Taipei, Taiwan)

[8] Koutandos E V, Prinos P E and Gironella X 2005 Floating breakwaters under regular and irregular wave forcing: reflection and transmission characteristics *J. Hydraul. Res.* 43 174-188

[9] Koutandos E V and Prinos P E 2011 Hydrodynamic characteristics of semi-immersed breakwater with an attached porous plate *Ocean Eng* 38 34-48

[10] Huang Z, He F and Zhang W 2014 A floating box-type breakwater with slotted barriers. *J. Hydraul. Res.* 52 720-727

[11] He F, Huang Z, and Wing-Keung Law A 2012 Hydrodynamic performance of a rectangular floating breakwater with and without pneumatic chambers: An experimental study. *Ocean Eng.* 51 16-27.

[12] Ji C-Y, Chen X, Cui J, Gaidai O and Incecik A 2016 Experimental study on configuration optimization of floating breakwaters *Ocean Eng.* 117 302-310

[13] Dai J, Wang C M, Utsunomiya T, and Duan W 2018 Review of recent research and developments on floating breakwaters *Ocean Eng.* 158 132-151

[14] Briggs M, Demirbilek Z, Pratt T, Resio D and Zhang J 2000 Performance Characteristics of a Rapidly Installed Floating Breakwater *27th International Conference on Coastal Engineering (ICCE)/Sydney* pp 2254-2267

[15] Meyers F and Brown J A Kepner Plastics Fabricators Inc 2004 *System and apparatus for rapidly installed breakwater* U.S. Patent 6,767,162

[16] Steinberg D 2005 *Floating modular breakwater* U.S. Patent Application 10/661,781.

[17] Hales L Z 1981 *Floating Breakwaters: State-of-the-art Literature Review* (No. CERC-TR-81-1). (Fort Belvoir Va : Coastal Engineering Research Center)