Sains Malaysiana 42(9)(2013): 1301–1310

Hydraulic Performance of Free Surface Breakwaters: A Review

(Prestasi Hidraulik Pemecah Ombak Permukaan Bebas: Suatu Tinjauan)

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ABSTRACT

This paper introduces the concept of free surface breakwaters for coastal protection. The advantages, limitations and applications of these breakwaters are discussed. Based on their configurations, free surface breakwaters have been classified into four types, namely solid-type, plate-type, caisson-type and multipart-type. Typical designs of the respective breakwater types are presented and the hydraulic characteristics are reviewed. In addition, comparisons of hydraulic efficiency of some of the free surface breakwaters are also addressed in this paper.

Keywords: Energy dissipation; free surface breakwater; wave attenuation; wave reflection

ABSTRAK

Kertas penyelidikan ini memperkenalkan konsep pemecah ombak permukaan bebas untuk perlindungan pantai. Kelebihan, batasan dan aplikasi bagi pemecah ombak dibincangkan. Pemecah ombak permukan bebas ini telah dikelaskan berdasarkan kepada empat jenis, iaitu jenis konfigurasi jasad, jenis plat, jenis caisson dan jenis berbilang-bahagian. Reka bentuk pemecah ombak yang tipikal masing-masing dibentangkan dan ciri-ciri hidraulik dikaji. Di samping itu, perbandingan kecekapan hidraulik bagi beberapa jenis pemecah ombak permukan bebas juga disertakan dalam kertas ini.

Kata kunci: Pantulan ombak; pelesapan tenaga; pemecah ombak permukaan bebas; pengecilan ombak

INTRODUCTION

The enormous power of sea waves has been one of the most challenging tasks for coastal and offshore engineers to combat for many reasons; one of which is to protect the coastal infrastructures, amenities and communities from destructive waves. A reasonably good tranquility condition is expected in ports, harbours and marinas for the safety of navigation and berthing within the perimeter of the basin. Another purpose is to bring restoration to the eroded beaches by 'realigning' the profile and shape of the beach. Coastal protection by breakwaters is particularly relevant for beaches of high commercial and recreational values as the defence structures may save lives, valuable resources and properties, as well as commercial activities in coastal areas.

In this study, an emphasis has been given to the sea defence breakwaters that are mainly used to provide protection against wave attack. In general, the size of such breakwaters depends on their applications and the level of wave protection required. For instance, port and harbour breakwaters are usually larger than marina and recreational breakwaters. These breakwaters can be classified as gravity-type and free-surface-type.

GRAVITY-TYPE

Gravity-type breakwaters are the most conventional structure in the history of breakwaters. They rest on the sea bottom and the crests of these structures can be either emerged or submerged. They are generally massive in size and have enormous weight so as to provide structural strength and stability against waves. Although the gravity-type breakwaters offer advantages in the form of excellent storm protection, they pose several drawbacks associated with their use which may be detrimental to the environment, i.e. the change of aqua-ecosystem and beach profiles in the adjacent of the structures. Some other major concerns of the construction of such breakwaters are high construction cost, navigation hazard due to their large footprints, settlement problem due to their weight and the standing waves present in front of the structures which may, in turn, lead to scour problem.

FREE-SURFACE-TYPE

In an environmentally sensitive site where complete wave tranquility is not needed, free surface breakwaters may be a viable alternative to the gravity-type breakwaters. Free surface breakwaters, also known as open breakwaters, have generated a great deal of interest in coastal and ocean engineering industry in recent years. They are essentially barriers located near free surface where the energy flux is dominant. They are built to distort orbital motion of the water particles near sea surface, where the particle amplitudes and velocities are maximal. The total height of such caissons is smaller than the water depth; thus permitting water circulation beneath the structures. The breakwater barriers could be installed on a group of piles or jacket structures, or even held floating by mooring cables. These structures, which control the height of the incident waves mainly by reflection and energy loss, are most effective when used at locations that are exposed to waves with period up to 5 s (Isaacson et al. 1995).

FREE SURFACE BREAKWATERS

Advantages Free surface breakwaters offer a number of desirable characteristics that allow them to be potentially used as sea defence structures in both harbours and marinas:

1. *Low construction cost*: Free surface breakwater barriers require less concrete per unit run as compared with the conventional breakwaters especially when constructed at sites with relatively large water depths (Neelamani & Reddy 1992);
2. *Ease of construction*: Free surface breakwater barriers can be mass fabricated and assembled on land and then towed to the site by floating barges for installation;
3. *Applicability in poor soil foundation and complex bathymetry*: The construction of free surface breakwaters is less subjected to the bottom soil condition, particularly for the floating ones. The pile-supported breakwaters can be constructed at steep slope foreshore where the nature of the bathymetry makes the construction of the conventional breakwater to be less feasible;
4. *Less interference to the ecosystem*: The methods used for breakwater installation reduce environmental impacts, e.g. noise and dust pollutions on site, at the quarry and in transport to the site. The breakwaters permit adequate flow exchange between the partially enclosed water body and the open sea, enabling fish migration, preservation of water quality and sediment transport activity;
5. *Relocation and recyclability*: The free surface breakwater barrier can be dismantled and relocated with minimum effort and without leaving permanent damage to the environment and
6. *Reduced visual impact*: The breakwaters have low profile and are particularly favourable to the beach users. They can sustain and preserve natural beauty of the beach.

Limitations The use of free surface breakwaters as sea defence structures is only restricted to semi-sheltered sites that are exposed to short period waves such as bays, estuaries, reservoirs, marinas, lakes and rivers. During extreme wave conditions, an under-designed breakwater may be unable to provide adequate protection to the sheltered regions or suffers from functional failures despite surviving structurally. The excessive wave loadings and overtopping may also pose a threat to both stability and integrity of the structures. Therefore, it has been proposed that the free surface breakwaters be built together with the main structures such as seawalls, jetties or even fixed breakwaters, so as to reduce the pressures and forces exerted on the main structures and to maximise their overall hydraulic efficiency (Hsu & Wu 1999; Hu et al. 2002).

Applications Despite their limitations, the free surface breakwaters are still being widely studied by a number of researchers worldwide due to their application potentials in various sectors. Currently, the interest in free surface breakwaters mainly comes from the pleasure boat market, from the expansion of commercial harbours, from the creation of safe recreational zones and from the military for constructing deployable ports. Most of these sites will need some forms of perimeter protection from wind waves as well as waves generated by boat traffic. Even a sheltered site will likely require some separation between the berthing area and the river or outlet in order to reduce the impact of short period waves and to keep out floating debris. They can be useful even in the most unusual applications such as installation in sewage ponds by simply helping to moderate the wave or providing access from one place to another. Most of these facilities do not require a high level of wave attenuation. For recreational harbours, coastal swimmers and surfers prefer to have acceptable wave conditions to suit their sporting activities and for fishing harbours, creation of still water conditions is not a necessity. Therefore, the free surface breakwaters may be a viable and economical solution for such applications.

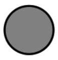
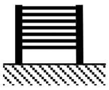
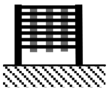
TYPES OF FREE SURFACE BREAKWATERS

In this study, the emphasis has been given to the fixed free surface breakwaters. Numerous ingenious designs of fixed free surface breakwaters have been proposed, tested, reported and even constructed with mixed success in the past. Based on their configurations, Teh et al. (2010) has classified the fixed free surface breakwater designs into four categories, namely solid-type, plate-type, caisson-type and multipart-type. The cross sectional view of each type of the breakwater is given Table 1.

Solid-type The solid-type barriers are generally simple in design and have high effective mass for stability. The typical designs for solid-type barriers include box, cylinder, quadrant front face and trapezoidal structures. The majority of the solid-type barriers suppress wave energy mainly by reflection.

Box-type breakwater is the most classic and simplest form of design in the development of free surface breakwaters. It has a rectangular section typically made of reinforced concrete. Koutandos and Prinos (2005) conducted large-scale physical tests to study the hydraulic characteristics of a fixed box-type wave barrier in shallow and intermediate waters for both regular and irregular waves. They found that the breakwater of deeper immersion induced greater wave reflection and the effect intensified as the barrier was exposed to shorter-period waves. With wave steepness, H_i/L ranging from 0.0015 – 0.0480, the wave reflection coefficient, C_R, which is a ratio of the reflected wave height-to-the incident wave

TABLE 1. Types of fixed free surface breakwater

Breakwater Types	Geometry & Cross Sectional View	References
Solid-type	Box 	Koutandos & Prinos (2005), Koutandos (2007), Koutandos & Prinos (2011)
	Cylinder 	Li et al. (2005)
	Quadrant front face 	Sundar & Subba Rao (2002, 2003)
	Trapezoid 	Koftis & Prinos (2005a)
Plate-type	Horizontal plate 	Hsu & Wu (1999), Hu et al. (2002)
	Inclined plate 	Rao et al. (2009)
	Twin-plate 	Neelamani & Gayathri (2006), Liu et al. (2008)
	T- type 	Neelamani & Rajendran (2002a)
	⊥- type 	Neelamani & Rajendran (2002b)
	H - type 	Neelamani & Vedagiri (2002)
Caisson-type	U - type 	Gűnaydın & Kebdaşlı (2004)
	Π - type 	Gűnaydın & Kebdaşlı (2007)
	Ш - type 	Brossard et al. (2003)
	Semicircular - type 	Teh et al. (2010, 2011, 2012)
Multipart-type	Multiple-layer 	Wang et al. (2006)
	Porous-piles 	Hsiao et al. (2008)

height, increased from 0.4 – 0.9 as the relative breakwater width, B/L increased from 0.045 – 0.312. (Note that H_i = incident wave height, L = wavelength and B = breakwater width). The corresponding wave transmission coefficient, C_T, which is a ratio of the transmitted wave height-to-the incident wave height, decreased from 0.90 – 0.25. The effect of double box barriers parted by a distance was further explored by Koutandos (2007). Apart from wave reflection, the box barrier also induces some amount of energy dissipation when interacting with waves. In the numerical simulation of vorticity around the fixed box-type barrier using Reynolds Average Navier-Stokes equations (RANSE) solver, Duclos et al. (2004) noticed a pair of eddies formed around the two sharp bottom edges of the body, at which the upstream vortices were more developed than the downstream ones. The formation of eddies around the barrier is believed to be the key mechanism that governs the energy dissipation. However, the amount of energy dissipated by the barrier is relatively small even with an addition of a solid or porous front plate to the bottom of the barrier (Koutandos & Prinos 2011).

The use of a circular section as a breakwater has the advantage of preventing significant torsional moments and corner stress concentrations that are induced by the wave action on the box-type breakwaters. Significant cost savings may be attainable by using circular concrete pipe due to the low manufacturing cost (Isaacson et al. 1995). Isaacson et al. (1995) experimentally studied wave transmission of a circular cross-section floating breakwater with moorings in regular waves. They reported that the B/L had more influence on the C_T of the cylindrical barrier compared to H_i/L. The C_T decreased noticeably from 1.15 – 0.3 as B/L increased from 0.08 – 0.52. They also compared the experimental results with the corresponding results for a rectangular-section breakwater. Both sections were reported to perform similarly, exhibiting a decrease in C_T as B/L was increased and both geometries became ineffective for $B/L < 0.2$. At larger range of B/L, the rectangular cross section performed slightly better than the circular one. Li et al. (2005) modeled the characteristics of wave transmission past an infinitely long cylinder in fixed position in shallow, transitional and deep waters using the modified Tsay and Liu's approximation (Tsay & Liu 1983). The numerical results showed a decrement in C_T with the increase of the relative breakwater width and relative breakwater immersion depth.

A quadrant front face barrier comprises a rectangular section and a quadrant of a circular section in which the radius is equivalent to the width of the rectangular section. Sundar and Subba Rao (2002, 2003) investigated a quadrant front face barrier that was supported by a group of closely spaced piles. The structure was designed to reduce the excessive wave energy by reflection from the quadrant front face during high tides and to dissipate the wave energy with its closely spaced piles when water level stayed below the barrier. The test results in regular waves obtained by Sundar and Subba Rao (2002) showed a rapid improvement in wave attenuation as the relative breakwater width was increased. The wave suppression of the barrier was mainly prompted by energy dissipation at the structure and some amount of reflection. The reflection was found to be stronger ($C_R > 0.5$) when the breakwater was subjected to shorter period waves. The model was also tested in irregular seas (Sundar & Subba Rao 2003). The C_R and C_T due to irregular waves were found to be greater than those due to regular waves by 10% – 15% and about 5%, respectively. Whereas, the energy dissipated by irregular waves was reported to be about 5% – 10% less than that by regular waves.

A trapezoidal-section barrier has a pair of upper and lower surfaces of unequal length and the front and rear surfaces can be inclined or curved. The trapezoidal barriers offer advantages by providing increased surface areas for wave interaction and energy dissipation. Duclos et al. (2004) numerically simulated vorticity around a trapezoidal barrier with a concave front face. The geometry of the barrier generated multiple higher harmonic components in the reflected waves resulting in energy dispersion over a large range of angular frequency. In comparison with the box-type barrier, the vortices generated in front of the trapezoidal barrier are more developed than those generated in front of the box-type barrier under identical test conditions. This subsequently leads to the conclusion that the trapezoidal barrier is a better energy dissipater than the box-type barrier. This finding agrees with the numerical results obtained by Koftis and Prinos (2005) who compared the hydraulic efficiency between the trapezoidal barrier with inclined faces of 45° and the rectangular barrier.

Plate-type A plate-type barrier consists of a single or a combination of multiple plates with different alignments located at various submergence depths in the water domain. The typical plate-type breakwaters include a single horizontal plate, twin horizontal plates, inclined plate, T-type barrier, ⊥-type barrier and H-type barrier.

Pile supported horizontal submerged plates have been proposed as offshore breakwaters for coastal protection since the 1970s. They are generally more economical in the use of construction materials. The presence of a horizontal plate near the free surface tends to steepen the waves over the plate due to shoaling and part of the incident wave energy gets dissipated by wave breaking, turbulence and friction on the plate surface. The hydraulic efficiency of the breakwater often relates to its submergence from the still water level D'. In an early study, Hattori (1975) investigated wave transmission and reflection of a single horizontal plate fixed at different relative submergence, $D'/d = 0$, 0.25 and 0.50, in regular waves. They found that both the wave attenuation and reflection were high at smaller value of D'/d, signifying that the surface plate was a better wave attenuator and a stronger reflector than the submerged plate. These findings somehow contradicted with the results obtained by Dattatri et al. (1977) whereby the maximum reflection was found to occur at $D'/d = 0.07$. Dattatri et al. (1977) suggested that for maximum wave reflection, the optimum plate width B should be about 0.3 – 0.4 times the incident wavelength, L, *i.e.* $0.3 < B/L < 0.4$.

Patarapanich (1984) provided numerical solutions of wave reflection and transmission for a horizontal plate subjected to a large range of water conditions covering from shallow to deep water limits using the finite element method. It was found that the C_R generally increased as D'/d and d/L decreased and the minimum C_T occurred at $B/L \approx 0.7$. The drawback of this model is that it does not account for energy loss at the structure. This aspect was later addressed by Patarapanich and Cheong (1989) through experimental studies of a horizontal plate. They recommended that for a plate of $0.05 < D'/d < 0.15$ in regular waves the optimum width should be about 0.5 – 0.7 times the wavelength above the plate.

To enhance the hydraulic performance of the breakwater, an additional plate is introduced at a distance below the surface plate, forming a double-plate system. The wave interactions with double-plate breakwaters were studied by Usha and Gayathri (2005), Neelamani and Gayathri (2006) and Liu et al. (2008). Alternatively, it was also suggested that the single horizontal plate be used as a secondary structure placed in front of a primary wave defence structure so as to boost the overall hydraulic performance. The optimisation of performance by the horizontal plate was investigated by Hsu and Wu (1999) and Hu et al. (2002).

Rao et al. (2009) experimentally explored the wave transmission of a plate at varying inclinations and submergence in regular waves. They found that wave transmission of the breakwater was not affected by the forward and reverse inclinations of any plate configuration. The plate inclined at 60° performed efficiently ($C_T < 0.6$) at $H_i > D'$, where D' is the submergence depth between still water level and the upper hinge of the plate. Although the upright plate outperformed ($C_T < 0.4$) the other incline plates, it induced excessive reflection in front of the breakwater. On the other hand, Neelamani and Rajendran (2002a, 2002b) experimentally investigated the T-type and ⊥-type breakwaters at varying submergence under regular and irregular seas. The experimental results showed an improvement of wave attenuation with an increase in wave steepness, H_i/L and relative water depth, d/L. They reported that the T-type breakwater was superior to the ⊥-type breakwater by about 20-30% in wave attenuation under identical testing conditions. The H-shape barrier, which consists of a pair of vertical plates of varying length, is another unique plate-type breakwater. Neelamani and Vedagiri (2002) experimentally explored the geometrical effect of the partially immersed twin vertical barrier under different wave conditions. The breakwater with longer rear plate was recommended as it suppressed waves more effectively particularly under deeper immersion. The twin plate breakwater was also found to be highly dissipative to the energy of the larger waves.

Caisson-type The key feature in distinguishing a caisson-type barrier from a solid-type barrier is that the caisson-type barrier is usually equipped with an open interference chamber that permits wave interaction taking place from within. The chamber is also used to 'tune' waves to be out of phase so as to minimise the wave activity in the vicinity of the breakwater; thus, it is often termed as 'absorbing caisson'. In some cases, multiple-chamber caissons are used to optimise the overall performance of the breakwater. Gűnaydın and Kebdaşlı (2004, 2007) experimentally studied the hydraulic performance of the U-type and Π-type barriers under regular and irregular waves. These caissons were perforated to enhance the energy dissipation performance. They discovered that the Π-type barrier was a better wave attenuator compared with the U-type barrier and both impervious barriers were shown to be slightly more effective when compared with the perforated ones. The Π-type barrier was further investigated by Koftis and Prinos (2005) using the unsteady Reynolds Averaged Navier-Stokes equations. These rather limited results derived led to the conclusion that the maximum wave reflection for this structure occurs at $B/L = n/2$ (where $n = 1, 2, 3\ldots$) due to resonant excitation. They also found that the turbulent kinetic energy field near the front wall was consistently higher than that of the rear wall and the wave activity in the chamber was relatively small at higher immersion depth.

Brossard et al. (2003) developed a Ш-type barrier comprising two chambers – a solid chamber and an absorbing caisson with perforation at the seaside wall. The effectiveness of the absorbing caisson was experimentally compared with a non-absorbing caisson. The C_R of the non-absorbing caisson was about 0.9 over a broad range of wave period; whereas the C_R of the absorbing caisson ranged from 0.05 – 0.60. This implies that the absorbing caisson is indeed a good anti-reflection structure. They further mentioned that wave energy was suppressed much effectively by increasing the immersion depth of the caisson than by increasing the width.

Teh et al. (2010) initiated research on hydraulic performance of a free surface semicircular breakwater. The effect of the front screen porosity was subsequently discussed in Teh et al. (2011, 2012). The experimental results revealed that the solid semicircular caisson was a better wave attenuator than the perforated ones; whereas, the perforated caissons exhibited a lower reflectivity and a higher energy dissipation.

Multipart-type A multipart-type barrier is formed by an assembly of multiple structural elements, e.g. planks, rods and pipes. These barriers are highly porous to the incoming waves, thus limiting the wave reflection and the horizontal wave forces acting on the breakwaters. Wang et al. (2006) proposed a barrier that was made of a large number of closely-spaced horizontal plates to retard the fluid particle motions in the vertical direction. The experimental results revealed that the breakwater exhibited a maximum C_R of about 0.6 and C_T values of less than 0.5 at $B/L > 0.25$. The influence of the relative gap interval of the plates on C_T and C_R was found to be marginal. Besides, Hsiao et al. (2008) developed a multipart-type breakwater that was an assembly of a number of closely-spaced bars placed in lateral and transverse manners interchangeably. The double barriers were arranged in pair with a gap spacing, s. The experimental results showed increased wave transmission as well as reduced reflection and dissipation performance with an increase in the porosity of the structure with a fixed gap distance. The C_R displayed a series of peak values when the $s/L = 0.5$ and 1.0.

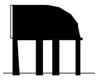
COMPARISONS OF BREAKWATER EFFICIENCY

Efficiency of the respective free surface breakwater models is assessed by comparing their hydraulic characteristics.

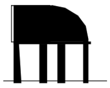
For this exercise, seven breakwater designs are adopted for comparison. These include the box-type barrier (Koftis & Prinos 2005; Koutandos & Prinos 2005); the cylindrical-type barrier (Li et al. 2005); the quadrant front face-type barrier (Sundar & Subba Rao 2002, 2003); the trapezoidal-type barrier (QUAD) (Koftis & Prinos 2005); the catamaran-type barrier (Koftis & Prinos 2005); the solid semicircular barrier (SCB0) (Teh et al. 2011, 2012) and the perforated semicircular barrier with a front wall of 9% porosity (SCB9) (Teh et al. 2011, 2012).

These breakwaters were predominantly studied by using physical models at selected test ranges. Table 2 summarizes the details and test conditions of these breakwaters in both regular and irregular wave fields. These physical models were tested in wave flumes equipped with wave paddles at one end of the flume. At the other end, wave absorbers or sloping beaches were used to reduce the reflected waves in the flume. Note that these models were tested on fixed barriers, with the exception of the quadrant front face breakwater (QUAD) which was seated on a group of piles arranged in a way that the pile gap was five times greater than the pile diameter. The relative immersion depths for these breakwaters mostly vary at $0.20 < D/d < 0.33$. For the semicircular caisson models, the test data for $D/d = 0.214$ were selected for comparison. A direct evaluation of the efficiency of the respective breakwaters is difficult to carry out due to the fact that each breakwater is unique in design (with different dimensions) as well as

TABLE 2. Details of the breakwaters selected for comparison
(a) Regular waves

Breakwater type	Cross section	Modelling type	D/d	H/L	Reference
Cylinder		Numerical (*Modified Tsay & Liu's approximation*)	0.250 0.500 0.750	n.a.	Li et al. 2005
SCB0		Experimental	0.214	0.015 – 0.044	Teh et al. 2011, 2012
SCB9		Experimental	0.214	0.015 – 0.044	Teh et al. 2011, 2012
Quadrant front face with supporting piles		Experimental	0.313	n.a.	Sundar & Subba Rao 2002
Box		Numerical (*COBRAS model*)	0.325	0.021 – 0.042	Koftis & Prinos 2005
Trapezoid		Numerical (*COBRAS model*)	0.325	0.021 – 0.042	Koftis & Prinos 2005
Catamaran		Numerial (*COBRAS model*)	0.325	0.021 – 0.042	Koftis & Prinos 2005

(b) Irregular waves

Breakwater type	Cross section	Modelling type	D/d	H/L	Reference
SCB0		Experimental (JONSWAP)	0.214	0.020 – 0.042	Teh et al. 2011, 2012
SCB9		Experimental (JONSWAP)	0.214	0.020 – 0.042	Teh et al. 2011, 2012
Quadrant front face with supporting piles		Experimental (PM)	0.313	n.a.	Sundar & Subba Rao 2002
Box		Experimental	0.325	0.021 – 0.042	Koutandos & Prinos 2005

variations in the test procedures. It is worth mentioning that the following comparisons are made on the basis of $0.20 < D/d < 0.33$ and $0.015 < H_i/L < 0.044$. The results are discussed broadly based on the type of sea states, i.e. regular waves and irregular waves.

By superimposing the wave transmission coefficients, C_T data for the selected breakwaters in regular waves, as presented in Figure 1(a), it is found that the C_T values of the present test models are in good agreement with other breakwater models. The SCB0 model of $D/d = 0.214$ is found to outperform the quadrant front face breakwater of $D/d = 0.313$ at $B/L > 0.3$. The wave attenuation ability of the SCB0 model is even comparable to the cylindrical structure immersed at $D/d = 0.50$. On the other hand, the wave attenuation performance of the SCB9 model is somewhat weak especially when compared with breakwaters of larger D/d. The trapezoidal breakwater of $D/d = 0.325$ is shown to offer the highest wave dampening efficiency among the breakwaters.

Figure 1(b) shows the reflection capability of the aforementioned breakwaters with the exception of the cylindrical structure. The solid breakwaters, i.e. the box-type and the trapezoidal-type, appear to be highly reflective structures. The reflectivity of the quadrant front face breakwater is surprisingly low; which might be attributed to the influence of breakwater geometry as well as the influence of the closely-spaced piles that facilitate a large amount of energy dissipation. It is apparent from the figure that the SCB9 model is the best anti-reflection structure as it produces the lowest C_R among the breakwaters in comparison. Both SCB9 and the quadrant-front-face breakwaters exhibited a Bragg effect in their C_R, with the resonance occurring at $B/L \approx 0.25$.

The percentage of dissipation of the incident wave energy by the breakwaters is represented by the energy loss coefficient, C_L. The C_L values range from 0 to 1. $C_L = 1$ indicates the wave energy is completely dissipated by the breakwater; whereas $C_L = 0$ implies loss of wave energy does not exist. Figure 1(c) shows no definite trend of the C_L among the test models. The C_L values of the box-type, catamaran-type, trapezoidal-type and the SCB0 are relatively low ($C_L < 0.5$) compared with those of the SCB9 and quadrant front face breakwater. It is, therefore, safe to say that the models with quadrant front faces are better energy dissipaters than the remaining test models.

Figure 2 demonstrates another form of comparison of the energy coefficients in regular waves, for which the coefficients are plotted against D/d. In this study, the experimental results of the semicircular caisson models (i.e. SCB0 and SCB9) developed by Teh et al. (2011, 2012) were compared with the numerical results of the box-type, trapezoidal-type and catamaran-type breakwaters developed by Koftis and Prinos (2005), with both results taken at $B/L = 0.32$. Again, a direct comparison of results may be difficult because different ranges of D/d were used for the respective test models. Nevertheless, it can be postulated from the projected trend of the plots that the SCB0 model is an effective wave attenuator with high reflection ability; whereas the SCB9 model is a good anti-reflection structure with high energy dissipation potentials. For the case of irregular waves, comparison of the energy coefficients as shown in Figure 3 is restricted to the quadrant front face breakwater (Sundar & Subba Rao 2003), the box-type breakwater (Koutandos & Prinos

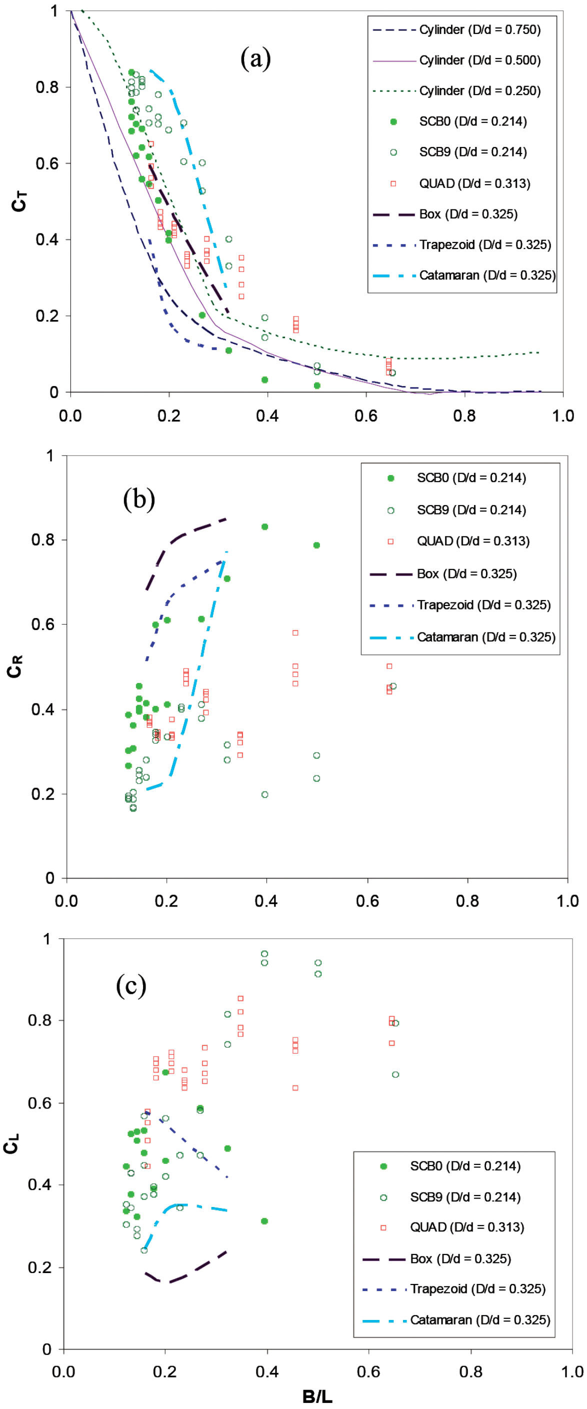


FIGURE 1. Hydraulic performance of various free surface breakwaters with respect to the relative breakwater width, B/L in regular waves at wave steepness $0.015 < H_i/L < 0.044$: (a) wave transmission, (b) wave reflection and (c) energy dissipation

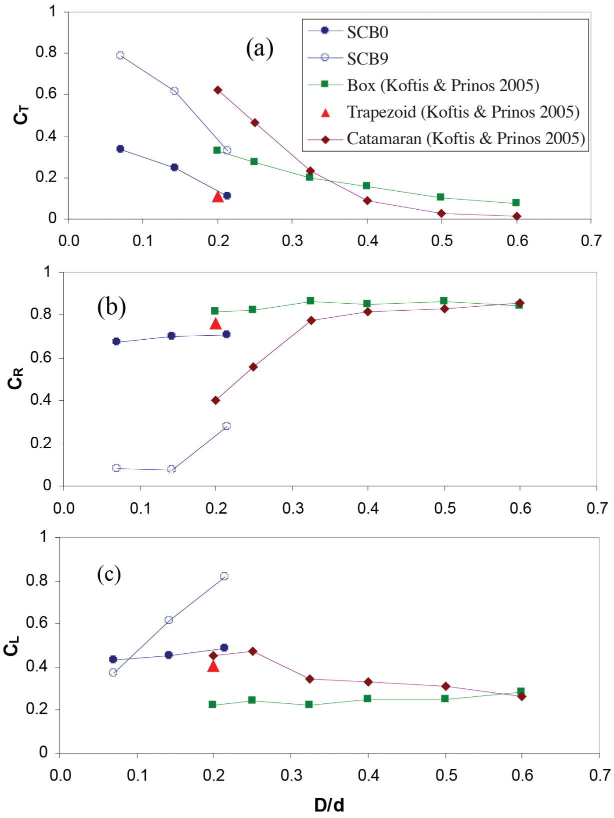


FIGURE 2. Hydraulic performance for various free surface breakwaters with respect to the relative breakwater immersion depth, D/d in regular waves at relative breakwater width $B/L = 0.32$ and wave steepness $0.02 < H_i/L < 0.04$: (a) wave transmission, (b) wave reflection and (c) energy dissipation

2005) and the semicircular caisson models, i.e. SCB0 and SCB9 (Teh et al. 2011, 2012). The overall outcomes of the comparisons are in good consensus with those of the regular waves.

CONCLUSION

The hydrodynamics exhibited by the free surface breakwaters are closely corresponded to the physical configuration of the breakwaters. The summary of the overall characteristics of the breakwaters is presented in Table 3. Overall, the solid-type barriers are strong wave reflector and may lead to considerable standing waves in front of the structures. The submerged plate-type breakwaters may be difficult to construct in sea environment and may pose navigation risk to the marine vessels that are insensitive to the presence of the structures. The caisson-type barriers may be highly reflective to the incident waves if wave energy absorbing features are not inherited in the structures. The perforation of the multi-part-type barriers is created to enhance the energy dissipation ability of the breakwater; nonetheless, the installation of multiple parts of the structure in the sea domain could be laborious and time consuming. The limitations of the free surface breakwaters require more extensive research efforts made to improve the existing breakwater designs so as to meet both the functional and economical requirements.

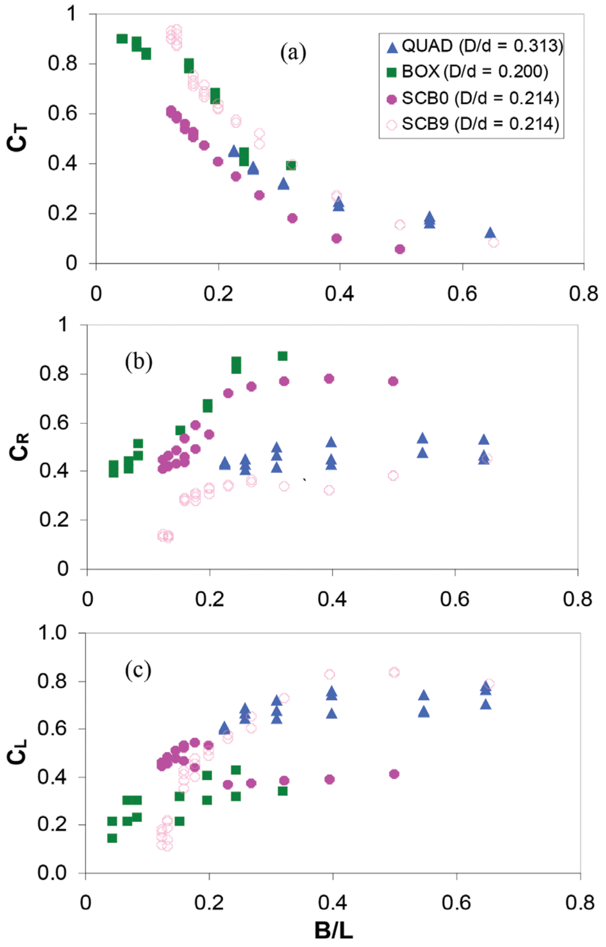


FIGURE 3. Hydraulic performance of various free surface breakwaters with respect to the relative breakwater width, B/L_p in irregular waves at wave steepness $0.020 < H_{m0,i}/L_p < 0.042$: (a) wave transmission, (b) wave reflection and (c) energy dissipation

ACKNOWLEDGEMENTS

The author acknowledges the financial support of the Institute for Energy Systems of School of Engineering, the University of Edinburgh, UK. The author would also like to thank Universiti Teknologi PETRONAS (Malaysia) for providing the scholarship for this study.

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TABLE 3. Characteristics of the free surface breakwaters

	Solid-type	Plate-type	Caisson-type	Multipart-type
Wave attenuation	High	Moderate	Moderate/High	Moderate
Wave reflection	High	Low/Moderate	Moderate/High	Low
Energy loss	Low	Moderate	Moderate/High	High
Effective mass	High	Low	Low/Moderate	Moderate
Installation cost	High	Low	Low/Moderate	High

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Received: 13 August 2012
Accepted: 25 January 2013