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Experimental Study of the Performance of Floating Breakwaters with Heave Motion

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ABSTRACT: Nowadays, the application of floating breakwaters in small or recreational harbors has found more popularity. These types of breakwaters are more flexible in terms of design, configuration and especially installation compared with fixed breakwaters. In the current study, the performance of floating breakwater (FBs) under regular waves was studied using the physical modeling method. For the modeling practice, a wave flume with a flap-type wave generator and progressive wave absorber was designed, constructed and used in order to investigate the performance of FBs. In this regard, a number of geometrical and hydrodynamic parameters were chosen including the degree of freedom, width variation, FB shapes (pontoon, T and π types) and draft depth. In each scenario the water level variation was measured in three points along the flume. Based on the measured water levels transmission, reflection and energy dissipation coefficients were obtained. The effect of each parameter on the performance of FBs was investigated and the best configuration was proposed for further studies. According to the collected experimental data, the mathematical descriptions for calculating the transmission coefficient were also proposed.

Keywords: Energy Dissipation, Floating Breakwater, Hydrodynamics, Physical Modeling, Transmission.

INTRODUCTION

One important element in coastal engineering is the construction of necessary structures for marine commerce and recreational activities. In this regard, many types of breakwaters have been designed and constructed over the past few years. In recent years, researchers have focused on the design and construction of floating breakwaters. Preserving the natural hydrodynamic environment of coastal areas is one of the advantages of this type of structure. Moreover, bottom founded breakwaters in deep waters and soft beds are not cost-effective. The main function of an

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FB is to attenuate the wave energy which takes place by reflection and absorption from its floating body. It should be mentioned that such a structure cannot dissipate all the wave energy. The incident wave is partially reflected, transmitted and dissipated. Energy is normally dissipated due to damping, friction and the generation of eddies at the edges of a breakwater (Koutandos, 2005). Generally, studies which deal with interaction of wave and FBs can be divided into three separate categories including analytical, numerical modeling and experimental approaches.

Analytical approach, which describe the full hydrodynamic problem have been deployed by several researcher, each one of them make their own approximations and simplifications (Drimer et al., 1992; Lee, 1995; Tang, 1986; Williams and McDougel, 1991; Rahman and Bhatta, 1993; Isaacson and Bhat, 1998; Kreizi et al., 2001 and Wang, 2010). On the other hand, Numerical modeling approaches for fluid-structure interactions were used by Hsu and Wu (1997), Sannasirij et al. (1998), Lee and Cho (2003) and Gesraha (2006) to cite just a few. As the main purpose of this study is to investigate the FB behavior by means of physical modeling therefore details of analytical and numerical investigations are not included.

As the hydrodynamic interaction between a wave and FB is extremely complex and its study is difficult, hence the physical modeling of this process is a suitable approach for simulation of hydrodynamic conditions close to the structure. However, the experimental studies of such processes are limited compared with analytical and numerical studies due to the cost of supplying wave flume and its instrumentation. There are a number of studies carried out to explore the efficiency of FBs from different point of views. For instance, Koutandos et al. (2005) studied the performance of a FB under regular and irregular waves and different configurations of the FB. Pena et al. (2011) worked on the wave transmission coefficient, mooring lines and module connector forces with different designs of FBs. In addition, Wang and Sun (2010) studied the influence of geometrical configuration of a porous FB.

FBs with heave motion such as fixed FBs are those that can be used with pile-anchored systems. FBs with this anchoring system have been used since 1981 (Readshaw, 1981). Inducing smaller wave forces on the structure and having less fatigue problems are two main advantages of FBs with heave motion.

Abdolali et al. (2012) carried out a series of numerical studies and laboratory measurements on π type FBs allowed to heave in order to investigate the effect of width and draft of body. Their studies showed that the attached plate can improve the efficiency of breakwater by increasing the energy dissipation around edges and reflection in seaside. In addition, they compared the outcomes with empirical formula proposed by Roul et al. (2012).

In the current study, the performance of FBs under regular waves in shallow and intermediate waters was experimentally studied. This study aimed to i) investigate the effect of width, draft depth and geometry of FBs on its performance, ii) consider the influence of degrees of freedom (compared with FBs that are fixed or having heave motion) on the efficiency of FBs, and iii) examine the effect of incident wave heights on the hydrodynamic coefficients. These effects were then generalized and appropriate empirical relationships between different parameters were developed.

MATERIALS AND METHODS

Experiments considered for this study were conducted in the hydraulic laboratory of the

Department of Civil and Environmental Engineering (Amirkabir University of Technology), Tehran, Iran. A wave flume with a flap-type wave generator and a progressive wave absorber were designed, constructed and used to investigate the FBs performance. The dimensions of the flume were 11m length, 0.4 m depth and 0.3 m width. The water depth in the flume was set to 0.3 m. The FB used was made from Plexiglas sheets and the material used in the attached plates was the same.

Figure 1 shows a schematic layout of the wave flume and installed components. In the flume set up, the distance between wave gauges and distance between wave gauges and the floating body were chosen to be $L/4$, where L is the wavelength (Abdolali, 2011 and Abdolali et al. 2012). To undertake the experiments a beach from porous materials for the dissipation of wave energy was also designed. The experiments were conducted using both the fixed FB and FB with heave motion. These two types of FB motion represent zero and one degrees of freedom. To anchor the FB and prohibit the motion of FB in unwanted directions, four thin plates were installed in the flume walls. Three wave gauges were used to record the water level over time. The sampling frequency during the experiments was 7.14Hz.

Wave reflection and transmission coefficients were calculated for each scenario. The wave reflection analysis used was based on the method proposed by Mansard and Funke (1980). This method uses the signals received from the wave gauges so that a least squares method is applied to separate the incident and reflected spectra from the measured co-existing spectra. The wave recorded at a wave gauge location is generally composed of components of many frequencies σ_i and amplitudes a_i with different phases δ_i, Eq. (1). In this process the fast Fourier technique was used to change water elevations recorded in time domain ($\eta(t)$) to frequency domain. Then, by using the time series of water elevation in two points in the seaward part, incident and reflected waves are decomposed. More details regarding the decomposition of incident and reflected waves can be found in Mansard (1980).

$$\eta(t) = \sum_{i=1}^{\infty} a_i \cos(\sigma_i + \delta_i) \tag{1}$$

Energy dissipation in the region of the breakwater is also studied using Eq. (2) as follows:

$$C_r^2 + C_t^2 + C_e^2 = 1 \tag{2}$$

where C_r, C_t and C_e are reflection, transmission and energy dissipation coefficients, respectively, which are defined as follows:

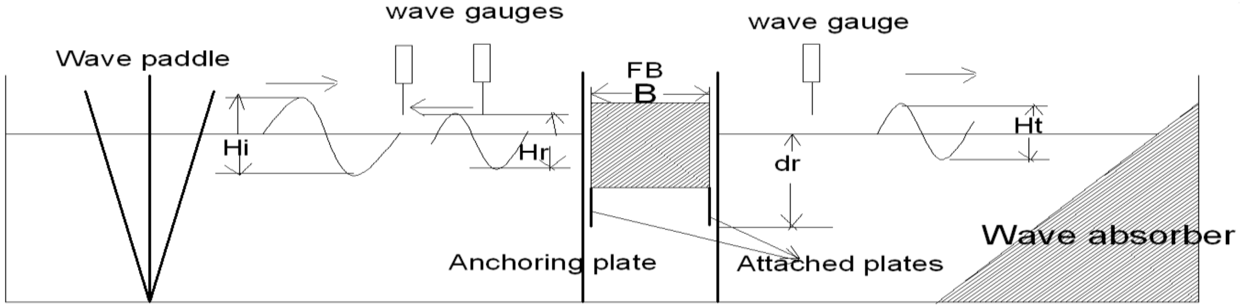

Fig. 1. Schematic layout of wave flume.

$$C_r = \frac{H_r}{H_i} \tag{3}$$

$$C_t = \frac{H_t}{H_i} \tag{4}$$

in which H_r = the height of reflected wave, H_t = the height of transmitted wave and H_i= the height of incident wave. Dimensional analysis and dynamic similitude were carried out for different type of FBs according to Abdolali (2011).

SENSITIVITY ANALYSIS

Reliability of data is one of the most important factors that should be considered in experimental studies. Hence, sensitivity analysis for distance between wave gauges and the location of wave gauges in the flume were carried out.

Distance between Wave Gauges

Distance between wave gauges affects the accuracy of results and is a function of wavelength. To estimate the sensitivity of distance between wave gauges, a wave with a period of 1.8 s and length of 2.84 m was generated in the laboratory flume. In these sets of experiments, different sets of gauge distances were applied and incident and reflected waves were separated. For the purpose of incident and reflected wave separation, two approaches were deployed including (i) the Mansard-Funke (frequency domain) method using three time series and (ii) the Goda-InvFFT (time domain) method using two time series.

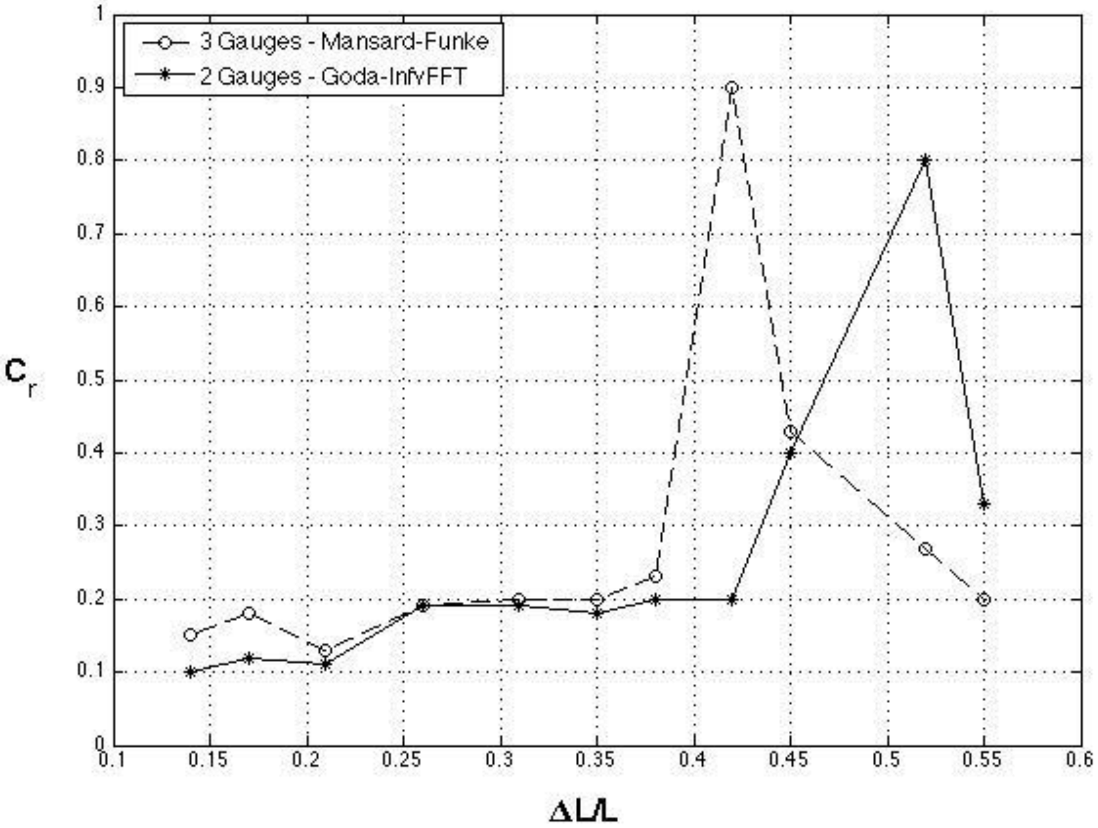

Fig. 2. Effect of gauge location on the reflection coefficient.

Figure 2 shows the effect of $\Delta L/L$ on the reflection coefficient where ΔL is the distance between gauges. From Figure 2 it can be concluded that the allowable reach for distance between wave gauges is $\Delta L/L \leq 0.35$ (Abdolali and Kolahdoozan, 2011).

Location of Wave Gauges

To analyze the sensitivity of results to the location of wave gauges, the same approaches were deployed. In all cases the distance between wave gauges were assumed to be constant and equal to $L/4$. Figure 3 represents the effect of the wave gauge location to flume length ratio on the magnitude of reflection coefficient. From Figure 3 it can be concluded that the location of wave gauges has no important effect on the reflection coefficient. In other words, the results are not sensitive to the location of wave gauges.

RESULTS AND DISCUSSIONS

The transmission coefficient is generally considered as a criterion for the performance of FBs. In this regard, the successful installation of FBs has been associated with a transmission coefficient less than 0.5. Also, among FBs with the same value of transmission coefficient, a FB with more dissipative behavior is preferred rather than a FB with more reflective manner. Another set of experiments were carried out to investigate the effect of degrees of freedom (FB width, FB configuration and incident wave height) on the performance of FBs. To do this, four main scenarios were considered. In this regard, results related to the reflection, transmission and energy dissipation coefficients were compared with $H_i/L, dr/d$ and W/L for different wave periods, where H_i represents the height of the incident wave, W indicates the FB width, dr is the FB draft, and d represents the water depth in the flume.

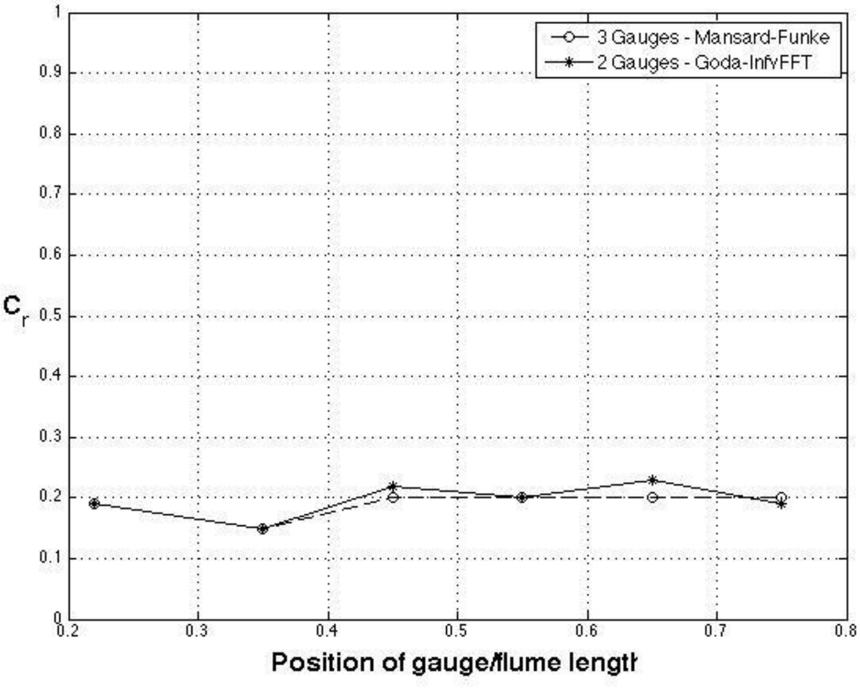

Fig. 3. Reflection coefficient versus dimensionless ratio of gauge position.

The Effect of FB Freedom

To study the effect of freedom in the hydrodynamic parameters, experiments were conducted for the T-type FB in both fixed and heave modes. The dimensions of FB considered was 0.15 m height, 0.3 m length and 0.25 m width (width was assumed in the direction of wave propagation). Also, a plate with 8 cm height was attached to the pontoon type FB with an initial draft of 10 cm. The obtained results of reflection, transmission and energy dissipation coefficients for different wave periods were compared with H_i/L are presented in Figure 4. From Figure 4 it can be concluded that for different wave periods, the fixed FB acts in a reflective manner compared with a FB with one degree of freedom (heave motion). However, the wave energy is more dissipated when the FB is free to move vertically (heave motion). The maximum value of reflection coefficient for the fixed FB was 0.7 while for the FB with heave motion it decreased to 0.5. The maximum value of energy dissipation coefficient for the fixed FB was less than 0.6 while it exceeded 0.7 for the FB with heave motion. The fluctuations of the FB play an important role in dissipating the wave energy and the fixed FB reflected a greater amount of wave energy because of acting in more rigid mode.

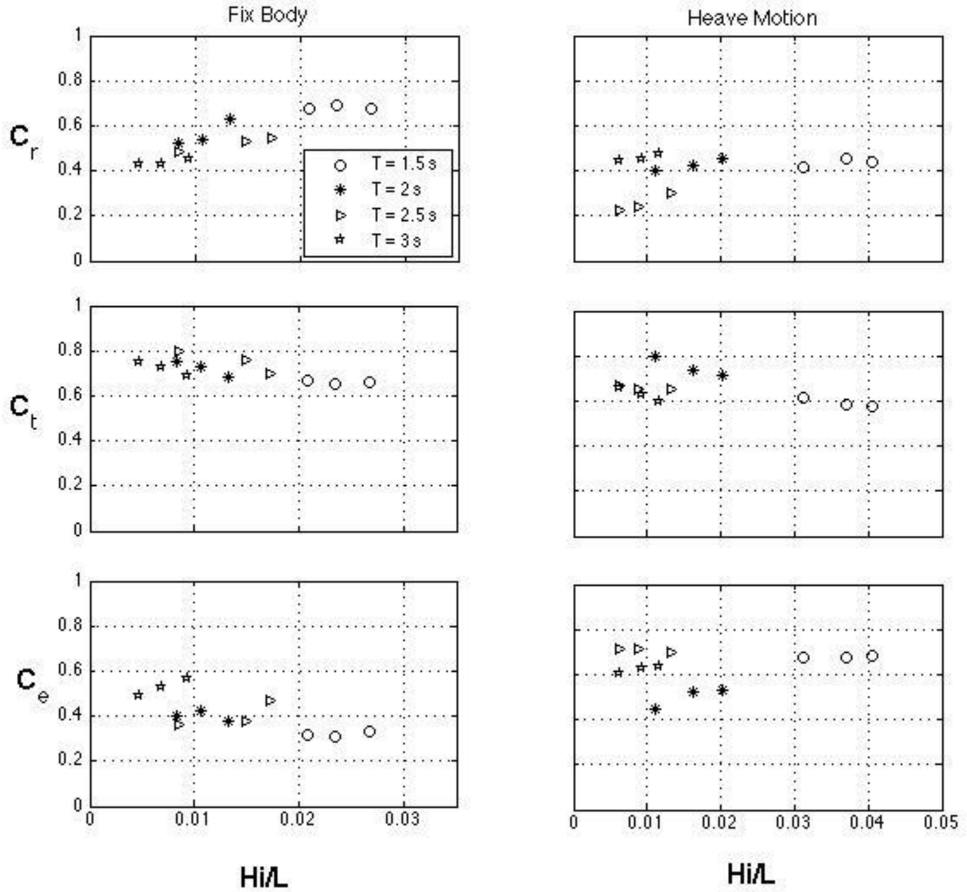

Fig. 4. Hydrodynamic coefficients for T type FB.

According to Figure 4, the reflection coefficient for a FB in fixed and heave modes increases when H_i/L goes up but the gradient of variation is greater in the heave mode. The transmission coefficient always decreases when the ratio of H_i/L, increases, implying that the FB is more effective in higher values of H_i/L. In terms of the energy dissipation coefficient, it can be concluded that during the heave mode it always increases with H_i/L. Results represented in Figure 4 show that the wave period variation has an effect on the performance of FBs. For instance, in the heave mode the higher value for wave period leads to more reflection while in the fixed mode it results in less reflection. In addition, the higher wave period results in a lower transmission coefficient in both fixed and heave modes. Again, regarding the energy dissipation coefficient the higher wave period causes that more energy to dissipate, while in the heave mode this trend does not occur.

The Influence of Width

The experimental results related to the effect of FB width are presented in Figure 5. In this set of experiments, tests were carried out for the T-type FB with the heave motion for two time periods of 2 and 3 seconds and two different wave heights in each time period. In this regard, six different widths of 0.2, 0.25, 0.3, 0.35, 0.5 and 0.7 m were considered.

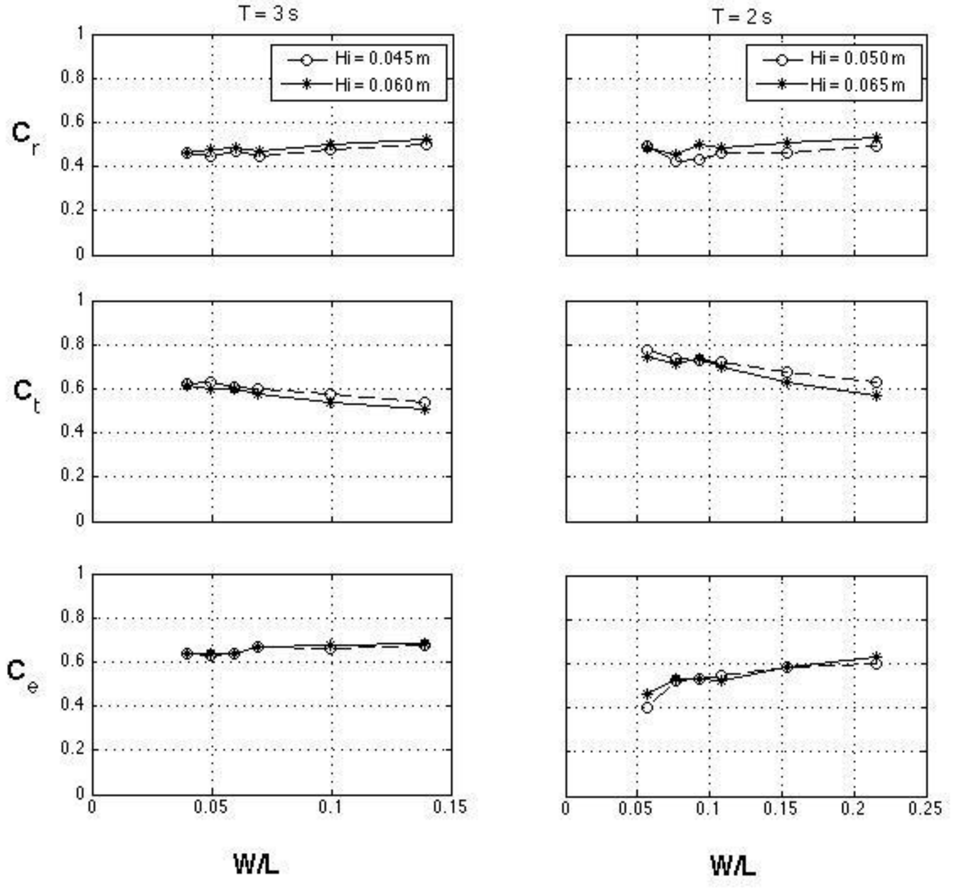

Fig. 5. Hydrodynamic coefficients for T type FBs with different width.

The comparison of reflection, transmission and energy dissipation coefficients under different values of FB width indicates that the increase of the FB width leads to an increase in reflection and energy dissipation coefficients and a decrease in the transmission coefficient. Therefore, For the T-type FB with heave motion, the satisfactory performance (C_t<0.5) can be obtained with increasing the FB width so that its maximum was experienced when the period is 3 seconds and $\frac{W}{L} > 0.15$. As seen in Figure 5 it can be said that this type of FB in the heave mode performs in a more efficient manner for longer period of waves.

The Effect of FB Configuration and Draft Depth

To investigate the effect of draft depth on the three different configurations of FB (pontoon, π and T types), experiments were carried out for a FB with dimensions of 0.3 m length, 0.3 m width ($\frac{W}{L} = 0.092$) and 0.15 m height. The best hydrodynamic performance of the FB can be achieved under scenarios defined with the FB configuration and draft depth. In this regard, the results related to C_r, C_t and C_e are depicted versus dr/d (i.e. relative draft depth). In these scenarios FBs are allowed to have heave motion (one degree of freedom). More details related to the physical model of these scenarios are presented in Table 1.

Figure 6 represent the hydrodynamic coefficients for the pontoon-type. A pontoon-type FB can be considered as a T or π types FB with one or two attached plates with a height of zero. From Figure 6 it can be concluded that the pontoon type FB is the least efficient shape. According to Figure 6 the minimum values of reflection and energy dissipation coefficients and the maximum value of transmission coefficient are associated with the pontoon type FB. As seen in Figure 6, the hydrodynamic coefficients significantly depend on the dr/d ratio, and the graph of C_r, C_t and $C_e$versus dr/d shows a steep slope. This implies that an increase in dr/d, the values of C_r and C_e are increased and the value of C_t is rapidly decreased in both shapes of FBs. Also, π type FBs is considerably more efficient than T-types FBs. Table 2 represents the rate of changes of C_r, C_t and C_e versus with dr/d and for both shapes of FBs.

Table 2 shows that the rate of changes of C_t and C_e versus dr/d for π type FB is greater than T-type FB, implying that an increase in dr/d, leads to a more decrease in C_t and more increase in C_e in π type FBs which is desirable for engineering and design purposes. In addition, both types of FBs presented better hydrodynamic performances for greater heights of incident wave so that the rate of changes of C_t and C_e are greater for bigger incident wave heights.

Table 1. Details of physical models.

Type of FB	dr/d	wave period (s)	H_i (cm)	Height of attached plate (cm)
pontoon	0.33	2	4.5, 5.5	0
T Type	0.46, 0.6, 0.73	2	4.5, 5.5	4, 8, 12
π Type	0.46, 0.6, 0.73	2	4.5, 5.5	4, 8, 12

Table 2. Rate of changes for C_r, C_t, and C_e versus dr/d.

Type of FB	C_r (rate of changes)	C_t (rate of changes)	C_e (rate of changes)
T $type$ ($H_i = 0.045m$)	0.473	-0.306	0.2
π type ($H_i = 0.045m$)	0.42	-1.04	0.954
T $type$ ($H_i = 0.055m$)	0.393	-0.331	0.265
π type ($H_i = 0.055m$)	0.43	-1.21	0.969

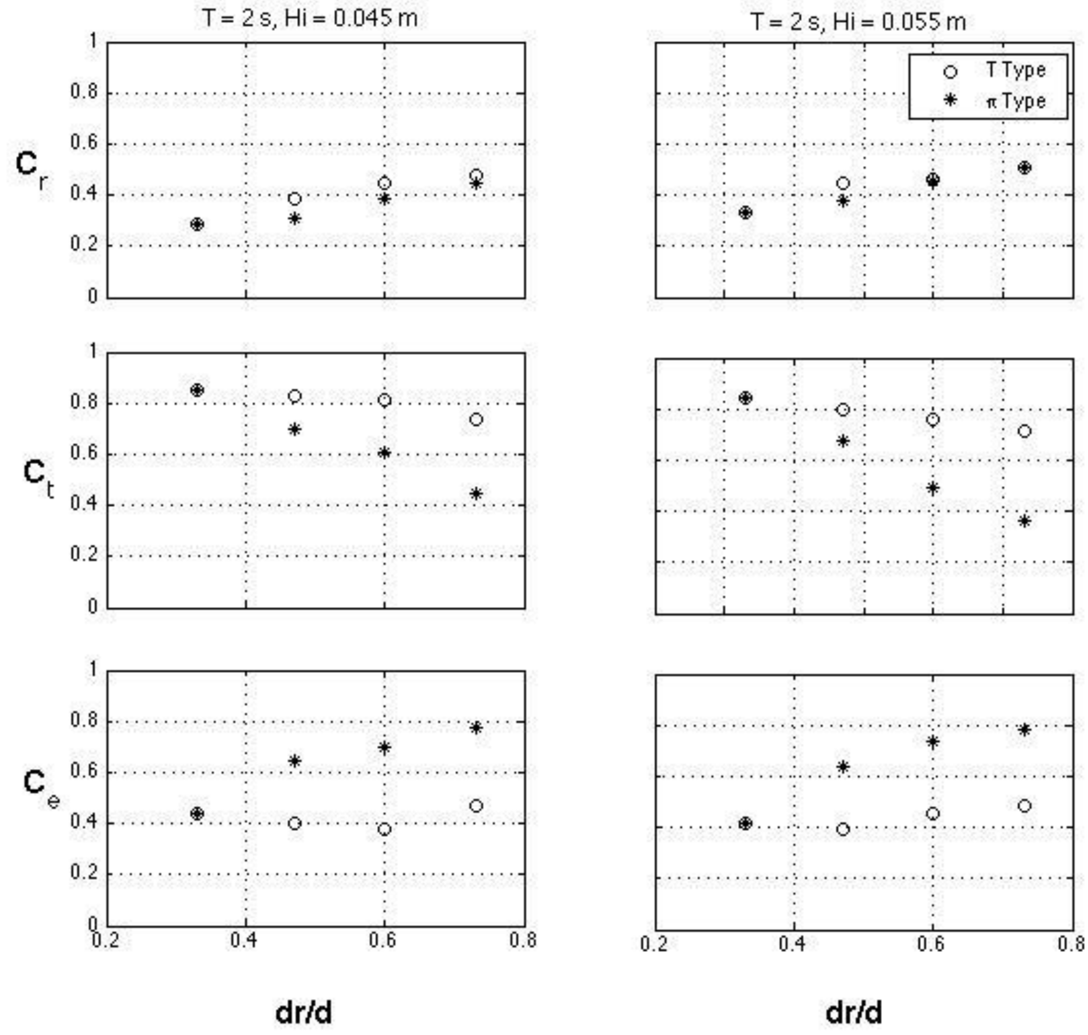

Fig. 6. Hydrodynamic coefficients versus *dr/d*.

The Influence of the Incident Wave Height

According to Figures 4-6, when the incident wave height increases, the reflection and energy dissipation coefficients also goes up and the transmission coefficient decreases for all shapes, periods and modes of FB. The reflection coefficient increases because the wave energy is dependent on the wave height. When it clashes to a solid body, the solid body reacts with the same magnitude and subsequently a wave with greater energy and height will be reflected. Energy dissipation is greater for greater wave height because it makes greater movements and fluctuations and leads to more turbulence and dissipation. The transmission coefficient will decrease due to the increase of other two coefficients. As seen in Table 2, FBs under a greater height of incident wave show better performances e.g. C_t changes from -1.04 to -1.21 and C_e changes from 0.954 to 0.969 (π type FB).

DEVELOPMENTOF MATHEMATICAL DESCRIPTION

In this section, the FB transmission coefficient is related to hydrodynamic parameters using the statistical modeling methods. As a result, equations are proposed to estimate the transmission coefficient according to dimensionless parameters of H_i/L, W/L, dr/d and dp/dr. In these equations, $dp$is the height of attached plate and dr represents the initial draft depth of pontoon FB which is added to dp for the calculation of total FB draft.

To achieve appropriate relationships, 200 experimental tests were carried out. Dependency of hydrodynamic and geometrical parameters to the transmission coefficient was then obtained through the mathematical modeling using the SPSS software. The experimental results associated to both pontoon- and T-type floating breakwaters and, hence, developed relationships can be applied to both geometries. Eqs. (5) and (6) represent the dependency of C_t to the geometrical and hydrodynamic parameters as follows:

$$C_t = 0.0256\left(\frac{H_i}{L}\right)^{-0.2}\left(\frac{W}{L}\right)^{-0.1283}\left(\frac{dr}{d}\right)^{-1.091} + 0.4637\left(\frac{dp}{dr}\right)^{0.0213} \qquad T = 3s \tag{5}$$

$$C_t = 0.00031\left(\frac{H_i}{L}\right)^{-0.199}\left(\frac{W}{L}\right)^{-1.119}\left(\frac{dr}{d}\right)^{-2.558} + 0.605\left(\frac{dp}{dr}\right)^{0.0175} \qquad T = 2.5s \tag{6}$$

It should be noted that for the pontoon-type FB where dp/dr is equal to 0.002, the least errors were achieved. Therefore, in the case of pontoon-type FBs, in Eqs. (5) and (6) dp/dr should be replaced by $dp/dr = 0$ in order to obtain the minimum error in the estimation of the C_t.

Results obtained using the above equations were compared with experimental measurements and a maximum error of 10% was observed. Table 3 represents a comparison between the experimental and computational transmission coefficient values under different sets of parameters.

The application Eqs. (5) and (6), showed that an increase in dp/dr, causes that the value of C_t increases too. The increase of dr/d, W/L and H_i/L can be leaded to smaller values of C_t; in other word, the better hydrodynamic performance of FB. Based on the results obtained from this research study, the most effective parameter on the FB performance is dr/d.

It is essential to point out that Eqs. (5) and (6) are applicable if the following conditions are satisfied: $W/L < 0.17$, $dr/d < 0.73$, $\frac{H_i}{L} < 0.03$ ($H_i < 0.12\,m$) and $dp/dr < 0.55$. For the wider range of parameters an extensive experimental program needs to be designed and carried out.

Table 3. Comparison of experimental and computational C_t.

T=3 s		T=2.5 s	
Transmission coefficient (C_t)			
Experimental	Computational	Experimental	Computational
0.633	0.667	0.646	0.647
0.705	0.684	0.68	0.659
0.58	0.607	0.9	0.954
0.866	0.858	0.841	0.816
0.77	0.772	0.752	0.785
0.671	0.693	0.587	0.645

CONCLUSIONS

In this study, the effect of hydrodynamic parameters on the performance of FBs with different shapes and aspect ratios are investigated. The results of this research showed that heave motion of a FB plays an important role in wave energy dissipation. Moreover, the results indicated that the transmission coefficient does not differ significantly for FBs in heave and fixed modes. Due to more reflective action in the fixed FB, stronger anchors should be designed and installed compared with a FB with heave motion. This phenomenon is more important in deep waters. Therefore, FBs that can vertically move (heave motion) are appropriate alternatives from both economic and design point of views.

The results of this study also showed in order to achieve a satisfactory performance of FB (C_t<0.5), the width aspect ratio (W/L) must be greater than 0.15 for both T- and pontoon-type FBs. In contrast, the maximum performance of a π type FB can be reached under smaller values. Also, the increase of dr/d can improve the performance of FB significantly so that its effect is significantly greater than the positive effect obtained from increasing W/L. The preference of the π type FB compared with pontoon- and T-type FBs has been qualitatively shown by different researchers (e.g. Koutandos et al., 2005). However, in this study the results of T and π type FBs were compared quantitatively. Using the results obtained through experimental program, a statistical mathematical description has been obtained for the performance of the FBs.

Using Eqs. (5) and (6), it was concluded that an increase in W/L and dr/d leads to improve the FB performance and dr/d has the greatest effect on C_t for both types of FBs (T and pontoon types). Also, the FB performs in more efficient manner under greater values of incident wave height. Increasing dp/dr causes that the performance of the FB decreases for the T type FB. Therefore, it can be concluded that increasing the draft depth of a FB by attaching plates is not as efficient as increasing the draft depth throughout the width of FB.

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