A machine learning method for the evaluation of hydrodynamic performance of floating breakwaters in waves

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ABSTRACT

This paper presents a two-dimensional simulation model for the idealisation of moored rectangular and trapezoidal floating breakwaters (FBs) in regular and irregular waves. Fast-Fictitious Domain and Volume of Fluid methods are coupled to track-free surface effects and predict FB motions. Hydrodynamic performance is assessed by a machine learning method based on Cuckoo Search–Least Square Support Vector Machine model (CS–LSSVM). Results confirm that a suitable combination of the aspect ratio of an FB and her sidewall mooring angle could help attenuate incoming waves to a minimum height. It is concluded that moored trapezoidal FBs are more efficient than traditional rectangular designs and subject to further validation CS–LSSVM can be useful in terms of optimising the values of predicted wave transmission coefficients.

Abbreviations: CS, Cuckoo search; FB, floating breakwater; FFD, fast-fictitious domain method; FSI, fluid–structure interaction; LSSVM, least square support vector machine; NWT, numerical wave tank; RFB, rectangular floating breakwater; SVM, support vector machine; TFB, trapezoidal floating breakwater; VOF, volume of fluid method

Nomenclature Symbols

AMPnf Amplitude of random wave corresponding to the target spectrum of irregular wave
AR \( b_0/l_0 \) Aspect ratio between the width (b0) and height (h0) of the breakwater (see Figure 1)
\( A_b \) Floating breakwater area
\( F_{ij} \) Volume fraction in cell (i,j)
FREf Frequency response function of irregular wave
\( F_{xm} \) Mooring force in direction acted on the floating breakwater
\( F_{ym} \) Mooring force in y direction acted on the floating breakwater
\( H_I \) Incident wave height (see Figure 1)
\( H_{I,i} \) Incident wave height of the component i of an irregular wave
\( H_s \) The height of the domain (see Figure 1)
\( H_w \) Water depth in NWT (see Figure 1)
\( H_{trans} \) Transmitted wave height (see Figure 1)
\( H_{trans,i} \) Transmitted wave height of the component i of an irregular wave
K Kernel function in LSSVM-CS model
\( K_h \) Horizontal transmission coefficient
\( K_h \) Horizontal transmission coefficient obtained from the numerical model
\( K_h \) Horizontal transmission coefficient obtained from the LSSVM-CS model
Ii Moment of inertia (see Figure 1)
\( I_l \) i = 1, 2, 3, input vector in LSSVM model (see Figure 4)
\( L_m \) The total length of the mooring line
\( l_T \) The length of the domain (see Figure 1)
\( M_l \) Mass of floating breakwater
PWH Per wave height
PWL Per wavelength
S The horizontal length of the mooring lines (see Figure 1)
\( S_I(w) \) Spectrum of incident irregular wave
\( S_T(w) \) Spectrum of transmitted irregular wave
T Transpose operator
\( T_l \) Calculation time
\( T_i \) Incident wave period
\( V_{open boundary} \) Velocity condition at the open boundary
\( U_{wavemaker} \) Velocity condition at the wavemaker location
\( V \) Velocity vector
\( V_{solid} \) Average translational velocity in the solid object zones
W Weight vector in LSSVM, W = [w1, w2, w3]
\( b_0 \) Floating breakwater width (see Figure 1)
\( d_I \) Cell volume
\( g \) Gravity acceleration
\( h_0 \) Floating breakwater height (see Figure 1)
k Kinetic energy in \( k - \varepsilon \) turbulence model
\( 2n \) Wave number of incident wave
\( k_{nf} \) Wave number of the regular component waves of an irregular wave
\( l_{b0} \) Low width of the trapezoidal breakwater (see Figure 1(b))
\( l_m \) Free hanging length of the mooring line
n Number of data in LSSVM model
\( u, v \) Velocity components in the x and y directions, respectively
p Pressure
r The selected point position vector of FB from the rotation centre
\( s_{b0} \) The up width of the trapezoidal breakwater (see Figure 1(b))
t Time
x Direction x
y Direction y
\( y' \) The predicted output parameter in LSSVM
\( a_i \) Airy wave amplitude
\( a_m \) A parameter to estimate the horizontal mooring force acted on the floating breakwater
\( e \) Dissipation rate in \( k - \varepsilon \) turbulence model
\( e_{nf} \) Random wave phase of irregular wave distributed between 0 and 1
\( s_{b0} \) Free surface elevation
\( \theta \) Sidewall angle of trapezoidal breakwater (see Figure 1(b))
\( \lambda_i \) Wavelength of nth component of the energy spectrum of an irregular wave
\( \lambda_i \) Wavelength of incident wave
\( \rho \) Dynamic viscosity

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This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
In recent years, increased demands for sustainable exploitation of ocean resources had significant impact on the development of innovative coastal and offshore structures. Examples are mounds (Shaifiee et al. 2020; Mares-Nasarre et al. 2020; Ehsani et al. 2020; Akbari and Taherkhani 2019; Klironomos et al. 2020) and breakwaters (Peng et al. 2013; Loukogeorgaki et al. 2014; Rahman et al. 2006) for use at ports, marinas and dockyards. For example, Loukogeorgaki et al. (2014) experimentally studied the structural response and showed that the structural response of the floating breakwater depends strongly upon the incident wave period. They analysed the effect of the incident wave period and height on the floating body’s structural response and showed that the structural response of the floating breakwater depends strongly upon the incident wave period. The classic surveys of Richey and Nece (1974), and Jones (1971) recognise more than 60 breakwater configurations. A comprehensive review of those demonstrates that the reliable estimation of wave transmission coefficient in real conditions is key from an assurance perspective. Thus, research focuses on developing semi-empirical formulae for application in design as well as the development of advanced fluid–structure interaction (FSI) models for the evaluation of hydrodynamic performance in real conditions. For example, Zhang and Li (2014) introduced a semi-empirical formulae for permeable rubble mounds and pile-type breakwaters through the application of modified Boussinesq wave equations. Building up from this work, Van der Meer and Daemen (1994) introduced practical design formulas and graphs and D’Angremont et al. (1996) studied the specialist case of low-crested breakwaters. Experimental research to validate the latter is still ongoing. Yet, the laboratory experiments of Melito and Melby (2002), Kramer et al. (2005), Calabrese et al. (2008), Peng et al. (2009), Laju et al. (2011) and Hur et al. (2012) demonstrate that the methods of Van der Meer and Daemen (1994) are well applicable to rubble mound breakwaters Ji et al. (2015, 2016, 2017). compared linear hydrodynamic theory and experiments to show that a cylindrical floating breakwater consisting of a flexible mesh cage and rigid cylinders have better hydrodynamic performance than a more traditional double pontoon type structure. Liu and Wang (2020) investigated the hydrodynamics of moored box-type FBs with different configurations. Their results show that hydrodynamic performance is primarily affected by the wave conditions and immersion depth. The work of Ji et al. (2018) and Cho (2016) shows that unique design characteristics such as porosity and deep side plates may also be significant as they reduce the influence of hydrodynamic loads. Recently, rectangular floating breakwater (RFB) and trapezoidal floating breakwater (TFB) have been broadly studied by some researchers (e.g. Liu and Wang 2020; Jeong and Lee 2014; Bin Abd Razak 2014; Hornack 2011; Masoudi and Zeraatgar (2017); Nikpour et al. 2019).

FBs are broadly used primarily because of their reduced cost, flexible installation requirements and ability to dissipate the wave energy without constraining under-water flow in areas with tidal variations (Dai et al. 2018; Stuart 2018; Rafic and Pascal 2009). Despite recent advances, a fast and efficient method for the evaluation of wave transmission coefficient on their hydrodynamic performance is not available. To address this problem, we present a fast-fictitious domain method-volume of fluid method (FFD – VOF)-free surface tracking numerical algorithm for the evaluation of hydrodynamic efficiency of FBs in real wave conditions. Key FSI
results are utilised within the context of a hybrid cuckoo optimisation algorithm and a least square support vector machine (CS-LSSVM) model with the aim to suggest a procedure for the optimum aspect ratio (AR) and sidewall angle of FBs.

2. Theory

A 2D numerical wave tank (NWT) model was used to generate Airy and irregular waves and simulate FSI. The FB was positioned 6.0 m downstream of a piston wavemaker located at the left lateral boundary of this system. A mooring was used to constrain FB oscillations. A schematic of the problem setup with the relevant dimensions are shown in Figure 1; Figure 2 illustrates the steps of the numerical procedure.

2.1. Numerical wave tank

Fluid motions were assumed viscous, turbulent incompressible. The fluid flow was assumed to be two-dimensional. According to Saghi (2019), the governing equations were defined as follows:

\[ \nabla \cdot V = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  

(1)

\[ \rho \left( \frac{\partial V}{\partial t} + (V \cdot \nabla)V \right) = -\nabla p + \rho g \]  

\[ + \nabla \cdot ((v + u_i)p(\nabla V + \nabla V^T)) \]  

(2)

The standard \( k - \varepsilon \) model (Saghi and Ketabdari 2014) was also considered in the developed model as:

\[ \frac{\partial k}{\partial t} + \frac{\partial (u_k)}{\partial x} + \frac{\partial (v_k)}{\partial y} = \frac{\partial}{\partial x} \left( v_k \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_k \frac{\partial k}{\partial y} \right) - G_S - \varepsilon \]  

\[ \frac{\partial \varepsilon}{\partial t} + \frac{\partial (u_k \varepsilon)}{\partial x} + \frac{\partial (v_k \varepsilon)}{\partial y} = \frac{\partial}{\partial x} \left( v_k \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_k \frac{\partial \varepsilon}{\partial y} \right) - C_{e1} G_S - C_{e2} \frac{\varepsilon^2}{k} \]  

\[ \nu = \frac{v_j}{\sigma_e} \cdot v_k = \nu + \frac{v_j}{\sigma_k} \cdot v_l = \frac{C_\mu k^2}{\varepsilon} \]  

\[ G_S = v_j \left[ 2 \left( \frac{\partial u}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right] \]  

(3)

The values of parameters \( C_\mu, C_{e1}, C_{e2}, \sigma_e \) and \( \sigma_k \) are summarised in Table 1.
The simplified marker and cell method was used to solve the Navier-Stokes equations (Saghi et al. 2012). Young’s VOF method was used for free surface tracking (Ketabdari and Saghi 2013). Thus, the interface within the cells was approximated by straight lines of different orientations. The initial condition for pressure was assumed hydrostatic. At the bottom of the domain, zero normal velocity and horizontal no-slip conditions were implemented. In way of the cell boundary, where the computational cell is adjacent to the tank bottom, the no-slip wall boundary condition was used to idealise the fluid velocity vector. In way of outflow, boundary condition was assumed open (Dean and Dalrymple 1991). In way of inflow, the fluid velocity was calculated by a piston type wave maker at each time step. The velocity conditions in the input boundary (i.e. in way of the wavemaker location) were assumed linear (Saghi et al. 2012):

\[
U_{\text{wavemaker}} = \frac{2k_i H_w + \sinh(2k_i H_w)}{2(\cosh(2k_i H_w) - 1)} a_i \omega \cos(\omega t) \tag{4}
\]

The wave velocity directed out of the domain (Saghi et al. 2012) was defined as follows:

\[
U_{\text{OpenBoundary}} = g \eta \frac{k_i}{\omega} \tag{5}
\]

The length of the incident wave was calculated by the dispersion relation of Liu and Li (2013):

\[
\frac{2\pi}{T_i} = \sqrt{\frac{2\pi}{\lambda_i} \tanh \left( \frac{2\pi}{\lambda_i} H_w \right)} \tag{6}
\]

To generate the random amplitude irregular waves, the prescribing inflow velocities were defined as (Li et al. 2000):

\[
U_{\text{wavemaker}} = \sum_{nf=1}^{M} AMP_{nf} \cos \left( \omega_{nf} t - 2\pi \epsilon_{nf} \right) FRF_{nf} \tag{7}
\]

where

\[
AMP_{nf} = \sqrt{2S_f(\omega_{nf})\Delta \omega} \tag{8}
\]

\[
\omega_{nf} = \omega_{nf - 1} + \omega_{nf} \frac{2}{\Delta \omega} \tag{9}
\]

\[
\Delta \omega = \frac{\omega_{max} - \omega_{min}}{M} \tag{10}
\]

\[
FRF_{nf} = \omega_{nf} \frac{\sinh(2k_{nf} H_w) + 2k_{nf} H_w}{4\sinh^2 k_{nf} H_w} \tag{12}
\]

where \( k_{nf} = \frac{2\pi}{\lambda_{nf}} \).

2.2. Fast fictitious domain method

VOF and FFD methods were coupled to model FB motions. The method assumed that the total angular and linear momentum in the solid body are conserved at each time step by using a scalar parameter \( \phi_{FB} \) defined as (Mirzaii and Passandideh-Fard 2012):

\[
\phi_{FB} = \begin{cases} 
0 & \text{between 0 and 1} \\
1 & \text{out of solid} \\
1 & \text{solid boundary} \\
1 & \text{within the solid} 
\end{cases} \tag{13}
\]

Figure 3. Different states of a moored floating body, (a) Case a, (b) Case b, (c) Case c, (d) Case d (Cheng and Lin 2018). (This figure is available in colour online.)
In turn, the viscosity and density in each cell was defined as follows:

\[ \mu_{ij} = F_{ij}\mu_w + (1 - F_{ij} - \phi_i)\mu_{air} + \phi_{FB}\mu_{FB} \]  

(14)

\[ \rho_{ij} = F_{ij}\rho_w + (1 - F_{ij} - \phi_i)\rho_{air} + \phi_{FB}\rho_{FB} \]  

(15)

Mirzaii and Passandideh-Fard (2012) showed that \( \mu_{FB} = 100\mu_w \) is appropriate for the idealisation of solid body movement. This is because high viscosity implicitly imposes a no-slip boundary condition on the interface of liquid and solid. The FB was assumed to be homogeneous and solid with \( \rho_{FB} = 0.75\rho_w \) (Teh and Ismail 2013). The average angular and translational velocities were evaluated by applying the conservation law of the angular and linear momentum as:

\[ I_s\ddot{\omega}_j = \int_{solidzone} r \times \rho Vd\mathcal{V} \]  

(16)

\[ M_s\bar{V}_j = \int_{solidzone} \rho Vd\mathcal{V} \]  

(17)

The velocity in the solid zone was estimated at each time step as:

\[ \bar{V}_{solidzone} = \bar{V}_s + \ddot{\omega}_s \times r \]  

(18)

2.3. Mooring line dynamics

Based on the position of the centre of gravity of the FB, different mooring line states (cases a, b, c, d) were considered (Figure 3).

![Flow chart of CS–LSSVM model. (This figure is available in colour online.)](image.png)
The horizontal \((F_{xm})\) and vertical \((F_{ym})\) mooring forces acting on the FB were calculated for different states as per Cheng and Lin (2018):

\[
F_{xm} = \begin{cases} 
0 & \text{case a} \\
\rho g a_m & \text{case b} \\
\rho g a_m \ e \Delta \cos \theta & \text{case c} \\
\rho g a_m \ e \Delta \sin \theta + \rho g L_M & \text{case d} 
\end{cases} \tag{19}
\]

\[
F_{ym} = \begin{cases} 
\rho g l_m & \text{case a} \\
\rho g l_m & \text{case b} \\
F_{xm} \tan \theta & \text{case c} \\
\rho g l_M & \text{case d} 
\end{cases} \tag{20}
\]

In cases \(b\) and \(c\), the parameter \(a_m\) being estimated by Newton’s iteration method as:

\[
L_M - S = \sqrt{H_W^2 + 2a_m H_W - a_m \text{arccosh} \frac{H_W + a_m}{a_m}} \tag{21}
\]

\[
\frac{H_W - L_M^2}{2a_m} = 1 - \cosh \frac{S}{a_m} \tag{22}
\]
The transmission coefficient \( K_t \) was used to evaluate hydrodynamic performance of both RFB and TFB. It was evaluated as:

\[
K_t = \frac{H_{tra}}{H_t}
\]

(23)

In regular waves, the above equation parameters \( H_{tra} \) and \( H_t \) are estimated based on the wave profile upstream and downstream of the FB. In irregular waves, they are estimated based on the spectrum of the incident and transmitted waves (Koley 2019). To achieve this, at first, the cut off spectrum frequencies in the range \([\omega_l, \omega_h]\) were identified. Then, the angular frequency range was partitioned into \( N \) intervals, namely, \([\omega_1, \omega_2], [\omega_2, \omega_3], ..., [\omega_i, \omega_{i+1}], ..., [\omega_{h-1}, \omega_h]\), and an average angular frequency was calculated for each range as \( \omega_{av}^i = \frac{\omega_i + \omega_{i+1}}{2} \) \( (i=1,2, ..., h-1) \). The incident and transmitted wave heights of the regular wave components were estimated as...
follows:

\[ H_{i,i} = 2\sqrt{2\int_{0}^{\infty} S_l(\omega^m)d\omega} \]  
\[ H_{tr,i} = 2\sqrt{2\int_{0}^{\infty} S_T(\omega^m)d\omega} \]

Finally, the incident and transmitted wave heights were estimated for all components as follows:

\[ H_I = 2\sqrt{\int_{0}^{\infty} S_l(\omega^m)d\omega} \]  
\[ H_{tr,I} = 2\sqrt{\int_{0}^{\infty} S_T(\omega^m)d\omega} \]

2.5 Intelligent hybrid model

The main objective of this study has been to introduce a simplified model for the estimation of the transmission coefficient of rectangular and trapezoidal FBs operating in typical regular wave condition. To achieve this an LSSVM model was used (Suykens et al., 2002). LSSVMs are least-square versions of support-vector machines (SVM) originally proposed by Suykens and Vandewalle (1999). The algorithm is less complex and computationally less expensive in comparison to a standard backup vector machine method. It is also useful in the solution of nonlinear problems (Anandhi et al. 2008). The regression relation between the input

Table 2. Procedure of hydrodynamic performance of moored RFB and TFB in the regular and irregular waves.

| Step | Description |
|------|-------------|
| 1    | Change the AR and choose the suitable one based on \( K_c \) criterion for Airy wave (see Section 4.1) |
| 2    | Change the AR and choose the suitable one based on \( K_c \) criterion for Irregular wave (see Section 4.1) |
| 3    | Change the sidewall angle and select the suitable one based on \( K_c \) criterion for Airy wave (see Section 4.2) |
| 4    | Change the sidewall angle and select the suitable one based on \( K_c \) criterion for Irregular wave (see Section 4.2) |
| 5    | Evaluation of floating breakwater location (water depth) (see Section 4.3) |
| 6    | Application of the hybrid CS–LSSVM model to predict the transmitted coefficient of RFB and TFB (see Section 4.4) |

Table 3. Case setting in the simulation of moored RFB.

| Case name | \( H_w \) (m) | \( H_{inc} \) (m) | \( T_i \) (s) | \( A_b \) (m\(^2\)) | \( b_0 \) (m) | \( h_0 \) (m) | AR |
|-----------|---------------|-----------------|-------------|----------------|-------------|-------------|----|
| 1         | 0.40          | 0.01            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
| 2         | 0.40          | 0.02            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
| 3         | 0.40          | 0.04            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
| 4         | 0.60          | 0.01            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
| 5         | 0.60          | 0.02            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
| 6         | 0.60          | 0.04            | 1.2         | 0.0225–0.09    | 0.15–0.75   | 0.15–0.50   | 1.00–6.00 |
and output of the model is defined as:

\[ y' = \sum_{i=1}^{n} w_i K(I, I_i) + b \]  

(28)

The risk bound is minimised by:

\[ \text{Min:} \psi(W, e) = \frac{1}{2} W^T W + \frac{1}{2} C \sum_{i=1}^{N} e_i \]  

(29)

\[ e_i = y_i - y_i' \]  

(30)

The structure of an LSSVM with Kernel-based Radial Basis Function (K) that may be used to predict the transmission coefficient of the FB is shown in Figure 4. The different steps of the CS–LSSVM used to estimate FB hydrodynamic performance are described in Figure 5.

In the next step, Cuckoo search (CS) was used for optimisation of the model (Payne, 2005). This method is based on the Cuckoo’s deceptive behavior when laying its eggs in other birds’ nests (Yang and Deb 2009). The cuckoo symbol in this algorithm oversees the local search, and each cuckoo egg indicates a solution that is placed inside the nest of other birds (host bird). So that if this host bird is aware of the presence of unknown eggs, it will either leave the nest or discard the cuckoo eggs. Based on this behaviour, which is the symbol of the global search in this algorithm, poor quality answers are discarded. In general, CS has three general rules:

1. Each cuckoo lays an egg only once at a time and lays it in a randomly selected nest.
Figure 15. (a) Time history of the transmitted wave for the RFB with AR = 4, (b) The energy spectrum of the transmitted wave for the RFB with AR = 4, (c) The parameter $K_t$ of the RFBs with different AR in NWT with an Irregular wave. (This figure is available in colour online.)

Figure 16. The transmitted wave height downstream of the moored TFBs with different sidewall angles: (a) Case 2, (b) Case 5. (This figure is available in colour online.)
The best nests and the highest quality eggs are passed on to the next generation.

The number of host nests available is constant and cuckoo eggs will be identified by the host bird with a Pa probability.

3. Validation of the wave–body interaction modelling

The validity of the Navier–stokes (NS), VOF and the couple of NS-VOF solvers was evaluated by using some benchmark tests including lid-driven cavity, constant unidirectional velocity field, and breaking dam tests (Saghi et al. 2012). Herein, the validity of NWT solver was evaluated including in regular and irregular wave conditions. At first, an Airy wave of 2 cm amplitude and 1.2 s period was generated in the NWT for different mesh sizes. Figure 6(a) confirms mesh size independency in the x and y directions for \(N_x = 80\) per wavelength (PWL), and \(N_y = 2\) per wave height (PWH), respectively. Model validation was achieved on the basis of wave maker theory, and the results are shown in Figure 6(b). Based on modelling experience, dynamic time steps that satisfy the Courant–Friedrichs–Lewy number of 0.3 were used (Nichols et al. 1980). A comparison of irregular waves is demonstrated in Figure 7.

To validate the coupled VOF–FFD solver both a free-floating and a moored FB have been considered. In case of a free-floating body, an FB of 0.3 m length, 0.2 m height and 500 kg/m³ density was positioned at 3.35 m downstream the wave maker. The heave and sway motions of the body were estimated by using the developed model and results compared well to Ren et al. (2015) (see Figure 8).

For the validation of the mooring model, the experimental results by Cheng and Lin (2018) corresponding to the case of a floating box of 0.3 m length, 0.18 m height and 750 kg/m³ density positioned at 3.35 m downstream a wave maker were used to validate the approach. In this model, each mooring line had vertical and horizontal (parameter S in Figure 1) lengths of 0.91 and 0.79 m, respectively. At first, a regular wave train of period \(T = 1.55\) s and wave height \(H = 0.07\) m was assumed propagating from the left boundary. Heave/sway motions and the time series of mooring forces were evaluated, and satisfactory comparisons are shown in Figures 9 and 10, respectively.

As a final step, the prediction of the wave transmission has been validated against the experimental results of Cui et al. (2020). An RFB with length \(h_0 = 0.5\) m and height \(h_0 = 0.2\) m was modelled in an NWT with length \(L_T = 40\) m and water depth \(H_w = 0.6\) m. An Airy wave with 0.1 m amplitude and different wavelengths was generated, and the estimated transmission coefficient was compared against the experimental results (see Figure 11).

4. Application

The hydrodynamic performance of moored RFB and TFB in regular and irregular waves was studied based on the procedure of Table 2.

4.1. Case 1: RFB

Airy waves with different heights and wave lengths were generated in the NWT for different water depths \((H_w = 40\) and \(60\) cm). The hydrodynamic performance of FBs for different area \((A_b = 225, 400, 625,\) and \(900\) cm²) and varying dimensions positioned 6 m away from the wave maker was assessed (see Figures 1 and 2). The incident and the transmitted wave heights 2 m downstream the FBs were used to estimate \(K_t\) and comparisons for different FB-dimensional configurations helped to identify the suitable width / height AR. Indicative results are demonstrated in Table 3 and Figure 12.
The result shown in Figure 12 indicates that the transmitted wave height is nearly constant after $t = 17$ s (see Figure 12). So, the average of the wave height after this time can be considered as the transmitted wave height. In the next step, $K_t$ was estimated for different cases by using Equation (23), and the results are shown in Figures 13 and 14. In general, FBs have better performance when $K_t$ is lower. In this regard, the results shown in Figures 13 and 14 demonstrate that the transmission coefficient of the FBs with different cross-sectional areas is maximum when the AR is in the range of 2–3. It means FB has the minimum performance. When increasing the AR, the transmission coefficient decreases irrespective to the cross-sectional area so that the $K_t$ for FBs with $AR \geq 4.5$ is minimum, and therefore the efficiency of the FBs is at maximum.

The energy spectrum of irregular waves was calculated by FFT and $K_t$ was estimated for the FBs with $A_b = 900$ cm$^2$ and different AR by using Equation (23) (see Figure 15). Results show that treatment an FB of $3.5 \leq AR \leq 4.5$ bears minimum $K_t$ in irregular waves. Furthermore, an FB with $AR \geq 4.5$ has the minimum $K_t$ in Airy waves. Hence $AR = 4.5$ can be considered suitable for an RFB operating in regular or irregular wave conditions.

**4.2. Case 2: TFB**

A single moored TFB with 900 cm$^2$ area, $AR = 4.5$, and different sidewall angles was positioned 10.0 m from the wave makers side of the NWT with 60 cm water depth (see Figure 1(b)) and an Airy wave with different heights was generated (see Figure 16). The transmitted wave height was estimated downstream of the moored TFBs with different sidewall angles (see Figure 17).

**Figure 19.** Velocity fields of the water flows downstream of the FBs at different moments for case 5; top / bottom pictures in (a) and (b) display optimum RFB / TFB flow patterns. (This figure is available in colour online.)

**Figure 20.** Transmitted wave for the RFBs and TFB for an irregular wave. (This figure is available in colour online.)
As shown on Figure 17, when the sidewall angle decreases from 90° to 75°, the transmission coefficient is also decreasing. This means that a TFB would be more efficient than an RFB (for which the sidewall angle is kept constant at 90°; see section 4.1). Minimum transmission coefficient of the TFB is obtained when the sidewall angle is in the range of 65° to 75°. A comparison of RFB and TFB for case 5 (see Table 3) is shown in Figures 18 and 19. It was found that the TFB decreases the transmitted elevation and velocity field relative to RFB. Results in irregular waves show that the average transmitted wave height downstream of the TFB are lower compared to the RFB (see Figure 20).

4.3 Evaluation of floating breakwater location (water depth)

The effectiveness of the suggested RFB and TFB in different water depths (shallow, transition and deep waters) was evaluated. To do this, the RFB and TFB with 900 cm² area were used in an Airy wave with 2 cm height in an NWT with different water depths. The obtained results of transmission coefficient (see Figure 21) were considered to find the optimum location (water depth) of FB. Results demonstrate that the effect of the RFB and TFB on the transmitted waves depends on the location of the FB (water depth). For example, the obtained results of the transmitted wave show that FB has the best efficiency (minimum $K_t$) at the depth of $H_w/\lambda_i = 0.4$. This is close to the boundary between shallow and deep water ($H_w/\lambda_i = 0.5$). A comparison between the RFB and

![Figure 21](image)
*Figure 21. The parameter $K_t$ of the optimum RFB and TFB in a numerical wave tank with different water depths. The vertical line in way of $H_w/\lambda_i = 0.5$ demonstrates the boundary between shallow and deep water. (This figure is available in colour online.)*

![Figure 22](image)
*Figure 22. The estimated transmission coefficient of the models relative to the observed one (estimated by using the developed model) in the training (a) and testing (b) step. (This figure is available in colour online.)*

![Figure 23](image)
*Figure 23. The prediction error distribution of the models: (a) training step, (b) testing step. (This figure is available in colour online.)*
TFB also shows that the $K_t$ of optimum TFB is always less than for the optimum RFB. Therefore, the operation of the TFB is better than the RFB against the incident wave.

4.4 CS –LSSVM results

To estimate the transmission coefficient of RFB, the developed numerical model (see Sections 2.1–2.4) was used to generate data. In this regard, 185 data were generated, 80% of which were used to train the model, and 20% to test it. The estimated transmission coefficient of the models relative to the observed one (estimated by using the developed model) in the training and testing steps are shown in Figure 22(a,b), respectively. The input and output parameters of CS–LSSVM model were defined as shown in Figure 4 as

\[ r_i = \{r_{i1}, r_{i2}, r_{i3}\} = \left\{ \frac{H_i}{H_w}, AR, \sqrt{\frac{A_b}{H_w}} \right\} \text{ and } u = K_i. \]

Based on the results shown in Figure 22, the correlation between the observed data and the estimated data in the training and testing steps are 0.78 and 0.68, respectively. The prediction error of the model in the training and testing steps were estimated by using Equation (31), and the results are shown in Figure 23. The results shown in Figure 23 indicate that maximum error in the training and testing steps are 16% and 26%, respectively. However, the most errors are less than 10% that is an acceptable result.

\[ \text{Error} = 100 \frac{K_i(\text{LSSVM-CS}) - K_i(\text{exp})}{K_i(\text{exp})} \quad (31) \]

The developed model was applied to estimate the transmitted coefficient of the RFB. To evaluate the efficiency of the LSSVM-CS model, transmission coefficient was estimated for some cases, and compared with results of the numerical model (Exp) in Table 4. Results show the acceptable accuracy of the model. It is mentioned as $r_i = \{r_{i1}, r_{i2}, r_{i3}\} = \left[ \frac{H_i}{H_w}, AR, \sqrt{\frac{A_b}{H_w}} \right]$ and $u = K_i$. Similarly, 80% of the generated data was used to train the model, and 20% of the data was used to test it. Two cases (see Table 5) were considered to evaluate the model ability to predict $K_i$. Based on the results shown in Figure 24, there is a good agreement between the results obtained with the CS-LSSVM and the numerical model. Furthermore, the results show that the estimated parameter $K_i$ for two cases (defined in Table 5) has similar behaviour compared to other cases shown in Figure 17 so that it is minimum for the side-wall angles in the range of 65° to 75°. Therefore, the optimum side-wall angle of a TFB can be suggested in the range of 65°–75°.

5. Conclusions

This paper presented a novel two-dimensional numerical model for the idealisation of the effects of regular and irregular waves on moored RFB and TFB. A VOF-FFD method was used to evaluate motions. By conducting a range of numerical tests, it was confirmed that the FSI model presented may be used to understand the influence of wave transmission parameters on hydrodynamic performance. The application of a simplified procedure for the selection of suitable dimensions of FB designs leads to the conclusion that depth ($H_w/\lambda$), side-wall angle ($\theta$) and dimensional AR may influence hydrodynamic performance. Results confirm that CS –LSSVM may be used for the prediction of wave transmission coefficients. Notwithstanding, before unifying conclusions for use in design standards the model presented should be extended to idealise advanced design features (e.g. multiple mooring lines, porosity, material properties, etc.) and results should be validated by extensive model tests.

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