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Assessment of global wave forces and moments on porous vertical barriers in random wave fields

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Abstract. Experimental investigations were carried out to assess the global wave forces and wave induced moments on slotted vertical barriers (SVB). Fourty two different wave barrier configurations (5%, 10%, 20%, 30%, 40%, 50% and 60% porosities and 1 to 6 number of slotted walls) were tested in random wave fields of JONSWAP spectra for wide range of significant wave heights and peak periods. It is found that the wave force is very sensitive to the change in porosity of the SVB. It is also found that relatively long waves and low porosity on SVB results in the highest wave force and short waves and high porosity on the SVB results in the lowest wave force. For most of the conditions, the wave force on SVB is less than the wave force on a single impervious vertical wall and force reduction to an extent of 20% to 80% is possible for the range of porosity and number of porous walls studied. A predictive equation to estimate the wave induced significant moment is provided with high regression coefficient. The average lever arm for assessing the wave induced moment is 0.6145 times the local water depth.

Keywords: breakwater; experimental investigation; fluid structure interaction; stability; wave forces

1. Introduction

Natural rocks have been used for construction of marine structures like breakwaters for many decades (Van der Meer 1988). Normally, the construction of rubble mound breakwater (RMBW) consumes high volume of materials. At 4.0 m water depth, a typical rubble mound breakwater needs about 80 to 100 m^3 of rocks/m. Construction of offshore RMBW also requires a long span of calm weather window, sophisticated tools, divers and a range of construction logistics. For any potential environmental reason, removing the rubble is also a costly afire. Emerged offshore RMBW reduce free water circulation between sea and shore side and results in poor water quality on the lee side.

The seabed needs to have high bearing capacity to reduce the potential settlement of RMBW. Recently, quarrying of stones have become a serious environmental issue. Under these circumstances, innovating new wave damping structures have become inescapable. The innovation should take care of few things such as (a). Complete the construction with less volume of natural resources; (b). Easy to fabricate and install in the field; (c). Reduce the environmental effects etc.

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Literature shows that porous marine structures are built in many locations around the world. For example, porous barriers are used in Baie-Comeau Harbor and Chandler Harbor in Canada, Roscoff Harbor in France, Half Moon Bay Marina in New Zealand, and Plymouth Harbor in the United States (Mei *et al*. 1974, Gardner *et al*. 1986). However, it is not clear from the literatures, whether these wave barriers were optimally designed. Optimal design is termed, when the wave barrier consumes minimum natural resource and provides high hydrodynamic performance (i.e., reduced wave forces, moments and wave transmission). Hydrodynamic performance assessment is one of the main scientific aspect of any type of wave barriers. Some of the promising publications related to hydrodynamic performance of different types of wave barriers are by Terret *et al.* (1968), Hayashi *et al.* (1968), Urashima *et al.* (1986), Kriebel (1992), Isaacson *et al.* (1998), Isaacson et al (1999), Bergman and Oumeraci (1999), Liu and Li (2013), Suman and Hegde (2017), Barzegar and Palaniappan (2020). Using matched eigenfunction expansion, Liu and Li (2013) studied on the hydrodynamic performance including the wave forces on a composite breakwater with upper horizontal porous plate and lower rubble mound and suggestions are provided for engineering design. There are many studies on special type of wave barriers and perforated barriers based on numerical and physical modeling such as Koraim (2011), Huang *et al.* (2011), Ji and Suh (2010), Al-Khalidi *et al.* (2015a, b), Neelamani *et al.* (2016). Further analytical, numerical and physical model based studies on slotted vertical barriers (SVBs) are reported by Al-Salem *et al*. (2014), Molin and Remy (2015), Elbisy *et al*. (2016), Valizadeh and Rudman (2017), Liu and Li (2017), Alsaydalani *et al*. (2017), Zhao *et al.* (2018), Valizadeh *et al.* (2018), Vijay *et al.* (2019), Hussein and Ibrahim (2019), Ibrahim (2019), George and Cho (2020), Poguluri and Cho (2020), Vijay *et al.* (2020) and Mackay and Johanning (2020). In general, it is found from the literature that increasing the porosity of the wave barrier reduces the wave forces and moments. It is found from the literature review that the published study results on wave forces and moments were available only for a maximum of up to three slotted vertical barriers. There is no literature available on wave forces and moments on vertical slotted wave barriers with more than three vertical porous walls and for a wide range of porosity (up to 60%), especially based on experimental investigations in random wave fields. This is a critical knowledge gap, while studies on special type of wave barriers gained momentum during the last two decades. This has motivated us for the present research work. The present work is on measurement of global wave forces and moments on slotted zigzag type vertical wave barrier for a wide range of slotted walls, porosity and incident random wave conditions. The results of wave induced dynamic pressures on the vertical perforated barrier was already reported by Neelamani and Al-Anjari (2020), which can be used for the design of the panels of the slotted vertical barrier. The present work is on global wave forces and moments and is needed for a complete design of vertical slotted wave barrier systems encompassing the design of the wave barrier for horizontal sliding and overturning. Hence, a detailed experimental investigation is carried out to measure the global wave forces and moments; the data were analyzed and the important results are presented in this paper. A typical design example is also presented to emphasize the application of this study. Vertical slotted barriers can be prefabricated as concrete panels in a factory (Fernández-Ordóñez Hernández D. 2018). During good weather window, the panels of the slotted barrier can be moved to the construction site and quickly assembled. The slotted wave barriers also allow easy fish passage, sediment movement and help to reduce the project cost significantly (Koutandos 2009).

2. Methodology

Table 1 Flume dimension, model configurations, instruments, input conditions, normalized input parameter ranges and data collection details

Item	Details
Wave flume dimension	54.5 m long, 0.6 m wide and 1.2 m high
Wave maker	Piston type with active wave absorption type
Number of vertical porous walls, n	1, 2, 3, 4, 5 and 6
Porosity of the vertical porous wall, P	0%, 5%, 10%, 20%, 30%, 40%, 50%, and 60%
Total number of wave barrier configurations studied	43 (One with 0% porosity and 42 porous barriers)
Horizontal distance between each barrier, B	0.20 m
Thickness of the wave barrier plate	1.0 cm
Material for model fabrication	Acrylic sheet of 10 mm thick
Wave spectrum used	JONSWAP
Significant incident wave height, H_{is}	5, 10 and 15 cm
Peak wave period, T_p	0.949, 1.066, 1.251, 1.624 and 2.837 s
Water depth at the model location, d	0.55 m
Far field water depth, d_1	0.70 m
C/C distance between the barriers	0.21 m
Range of wave length, L_p	1.7 to 7.0 m
Relative significant wave height, H_{is}/d	0.071, 0.142 and 0.214
Range of wave steepness, H_{is}/L_p	0.007 to 0.107
Relative water depth, d/L_p	0.1, 0.2, 0.3, 0.4 and 0.5
Force sensor	9105-TIF-OMEGA160-IP68 from ATI Industrial Automation, USA with horizontal force capacity of 2500 N and moment capacity of 400 N-m
Wave probe	Conductivity type, 60 cm long
Data collection duration	420 s
Sampling interval	40 samples/sec
Total number of runs	645

The wave forces and moments on SVB is assessed based on experimental investigations in a wave flume at Kuwait Institute for Scientific Research, Kuwait. The details of the model fabrication, input wave conditions, data acquisition and analysis, dimensional analysis etc. are provided in Neelamani and Al-Anjari (2020). A concise detail is provided in Table 1.

Fig. 1 shows the typical experimental setup at the model location.

In Fig. 1, WP1 is the wave probe for incident wave, WP2, WP3, and WP4 are the wave probes used for measuring wave histories for reflection analysis, WP5 is the wave probe for measuring wave run-up on the front panel and WP6 is used to measure the wave transmission. The results pertain to wave transmission, reflection and dissipation is fully reported in Neelamani and AlAnjari (2018) and hence they are not discussed in this paper.

Fig. 2 is a typical photo showing the model setup in the wave flume.

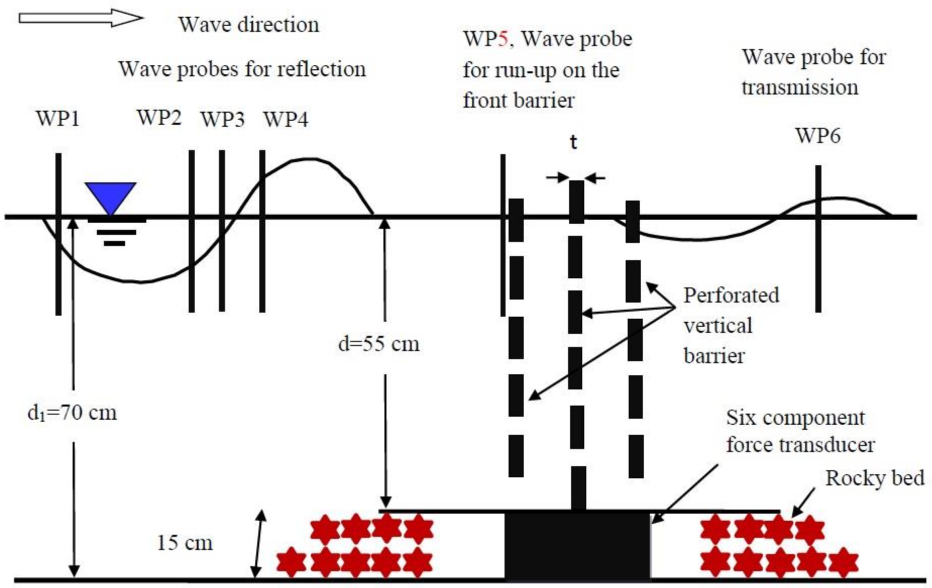


Fig. 1 Typical arrangement for measuring waves, wave force and moment on a vertical slotted barrier configuration

Fig. 2 Model setup in the wave flume.

The spectral analysis is carried out and the zeroth moment for the incident wave, total horizontal force and the moment is assessed for all the runs. The value of the significant wave height is estimated by multiplying the square root of the zeroth moment by 4. The significant wave force, F_{xs} and significant wave induced moment, M_{ys} is estimated by multiplying the square root of the zeroth moment by 2.

Based on the dimensional analysis, the normalized significant wave force, $F_{xs} / (0.5\ \rho\ g\ H_{is}\ d\ W)$ and the normalized significant wave induced moment, $M_{ys} / (0.5\ \rho\ g\ H_{is}\ d^2\ W)$ is expressed as follows

$$[F_{xs} / (0.5\ \rho\ g\ H_{is}\ d\ W),\ M_{ys} / (0.5\ \rho\ g\ H_{is}\ d^2\ W)] = f_1\ (d/L_p \text{ or } B/L_p,\ H_{is}/d \text{ or } H_{is}/L_p,\ n,\ P) \quad (1)$$

Since for every d/L_p there exist a constant B/L_p value, one can either use d/L_p or B/L_p value. From field application point of view, it is more appropriate if d/L_p is used, since the engineer selects the suitable slotted barrier for a specific water depth selected during project execution. The results of the present study can extensively be used for coastal engineering applications, it is appropriate to use H_{is}/d. Hence, the dimensional analysis yields

$$[F_{xs} / (0.5\ \rho\ g\ H_{is}\ d\ W),\ M_{ys} / (0.5\ \rho\ g\ H_{is}\ d^2\ W)] = f_1\ (d/L_p,\ H_{is}/d,\ n,\ P) \quad (2)$$

These non-dimensional values on are used to describe their effects on wave forces and moments.

3. Results and discussions

For the design of SVB, the main requirement is the accurate wave force acting on the structure and the next expectation is how to reduce the wave force on the structure. Reducing the wave force may be possible by reducing the number of slotted walls or by increasing the porosity of the structure. Hence, it is essential to know the wave force variation, when the porosity as well as the number of SVB is changed. First, typical wave force time series are presented. Then, the effect of all the input parameters are discussed.

3.1 Typical random wave force time series to understand the effect of porosity and number of slotted barriers on wave forces

The wave force on the vertical wall with 0% porosity is used as the reference case to understand how the wave forces on a single porous wall change when the porosity is increased from 0% to 60%. The wave force time series on a single wall are presented in Figs. 3(a) to 3(c) for P=0%, 10%, and 60%, respectively, for n=1, H_{is}=10 cm, and T_p=1.624 s. The time series plot is provided for 60 s only for clear visualization. It is found from Figs. 3a to 3c that the wave force is maximum for P=0%, and it decreases progressively with an increased porosity of the SVB. Increasing the porosity of SVB results in less projected area for wave action on the barrier and more penetration of wave energy through the slots, resulting in less wave force transfer on the SVB. Hence, to reduce the wave force, it is essential to increase the porosity of the SVB.

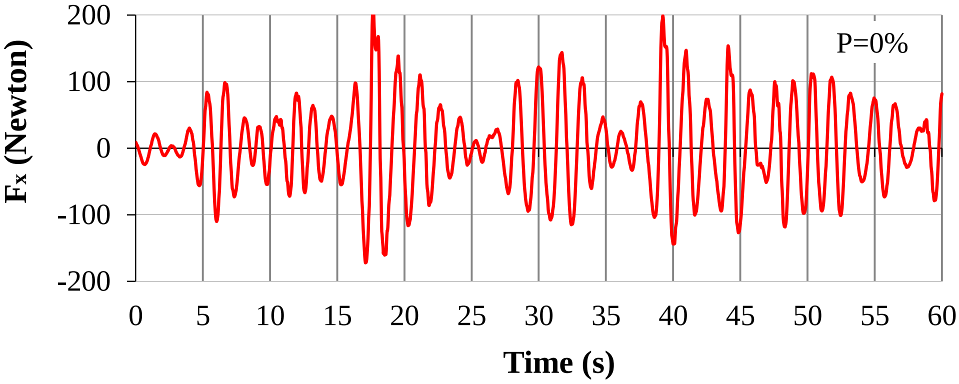
Figs. 4(a) to 4(c) are presented for n = 2, 4, and 6 respectively, for P=30%, H_{is}=10 cm, and T_p=1.624 s.

Among these three plots, the measured wave force value is minimum for n=2, and it gradually increases with increase in number of SVBs. Increasing the number of porous walls allows more interaction of waves on the SVBs and hence, resulting in the increase of the wave force magnitude. However, it is to be noted that the wave force increase is moderate, when the number of SVBs is increased from 4 to 6, which could be due to the phase lag of interacting waves as well as increased wave energy dissipation, when waves act on more number of porous barriers.

From these wave force time series plots, it is clear that the global wave force is more sensitive to the change in porosity and is less sensitive to the change in the number of slotted walls.

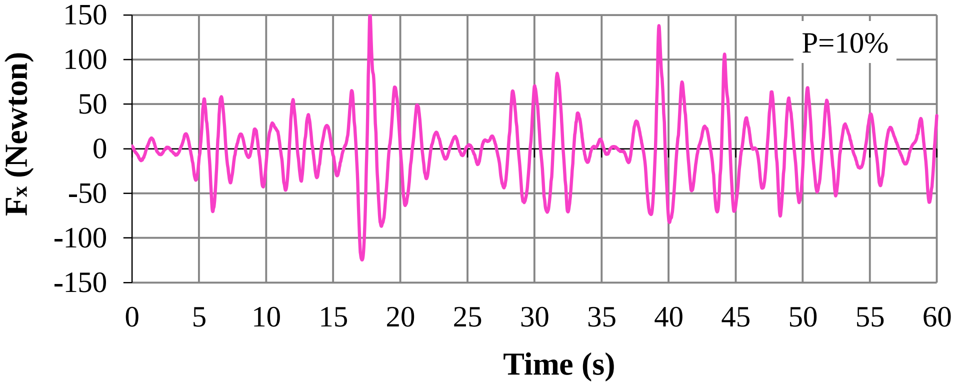
3.2 Effect of increase in significant incident wave height on change in wave force

Fig. 5 shows the variation of wave force coefficient (WFC) for three different H_{is}/d values, and for n=1 and P=10%. In general, interaction of higher significant wave height results in a higher WFC value, when compared to a low significant wave height. In general, the value of WFC is found to reduce with increase in d/L_p. Long waves (smaller d/L_p) results in higher WFC value than short

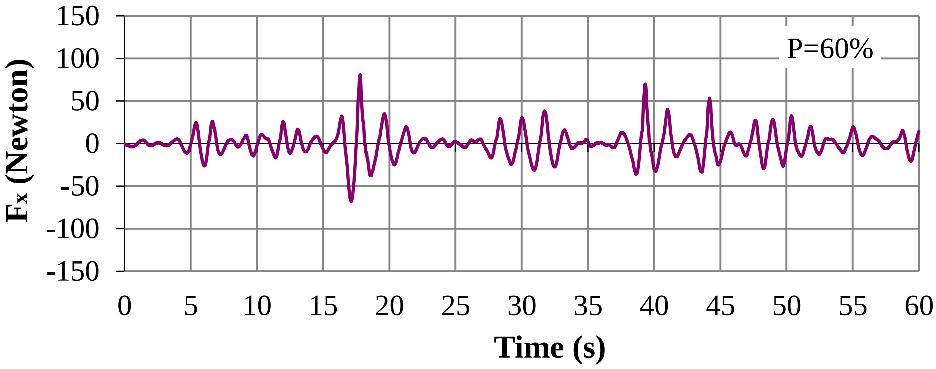


c

(a)

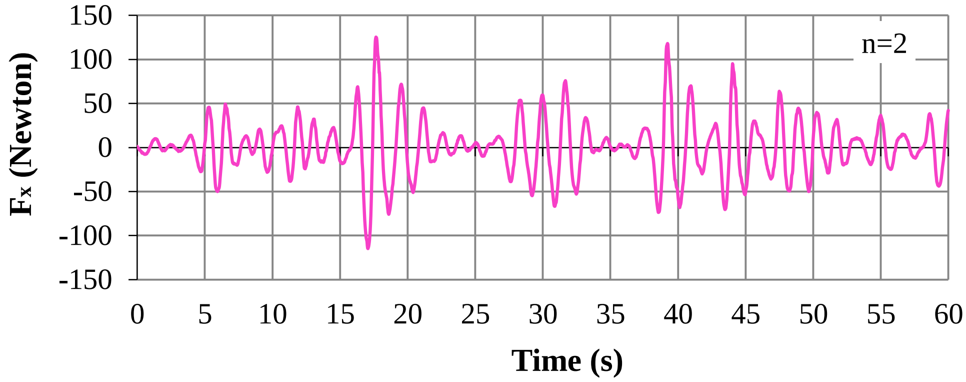


(b)

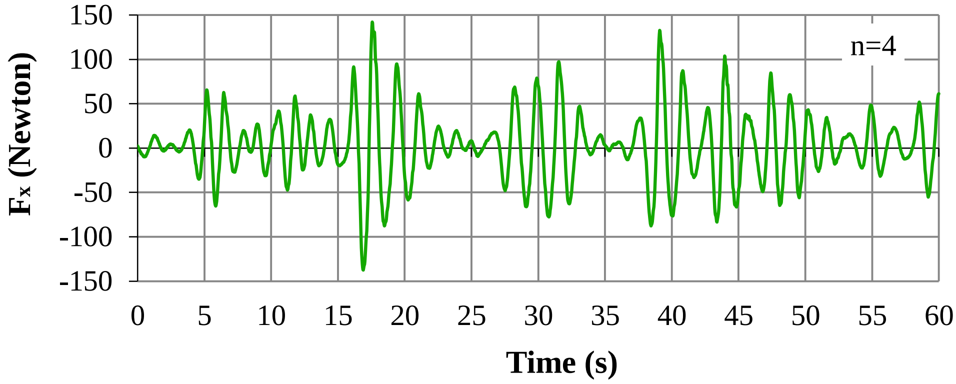


(c)

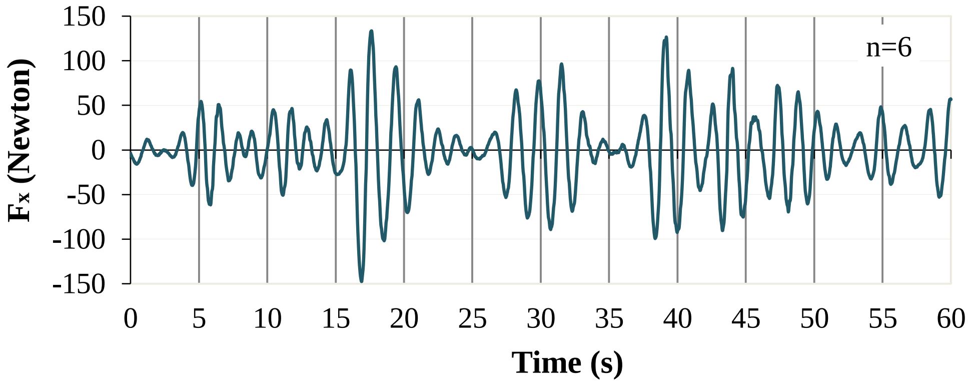
Fig. 3 (a) Measured inline wave force on a single vertical wall (P=0%, H_{is}=10 cm, and T_p=1.624 s), (b) Measured inline wave force on a single slotted wave barrier (P=10%, H_{is}=10 cm, and T_p=1.624 s) and (c) Measured inline wave force on a single slotted wave barrier (P=60%, H_{is}=10 cm, and T_p=1.624 s) waves (larger d/L_p). For d/L_p=0.1, with n=1 and P=10%, the value of the WFC is about 0.91, 0.83, and 0.69 for strong, moderate, and mild wave energy interactions. For d/L_p=0.5, the value of WFC is 0.46, 0.42, and 0.36, respectively, for strong, moderate, and mild waves interacting with SVB.



(a)



(b)



(c)

Fig. 4 (a) Measured inline wave force on slotted wave barrier (n=2, P=30%, H_{is}=10 cm, and T_p=1.624 s), (b) Measured inline wave force on slotted wave barrier (n=4, P=30%, H_{is}=10 cm, and T_p=1.624 s) and (c) Measured inline wave force on slotted wave barrier (n=6, P=30%, H_{is}=10 cm, and T_p=1.624 s)

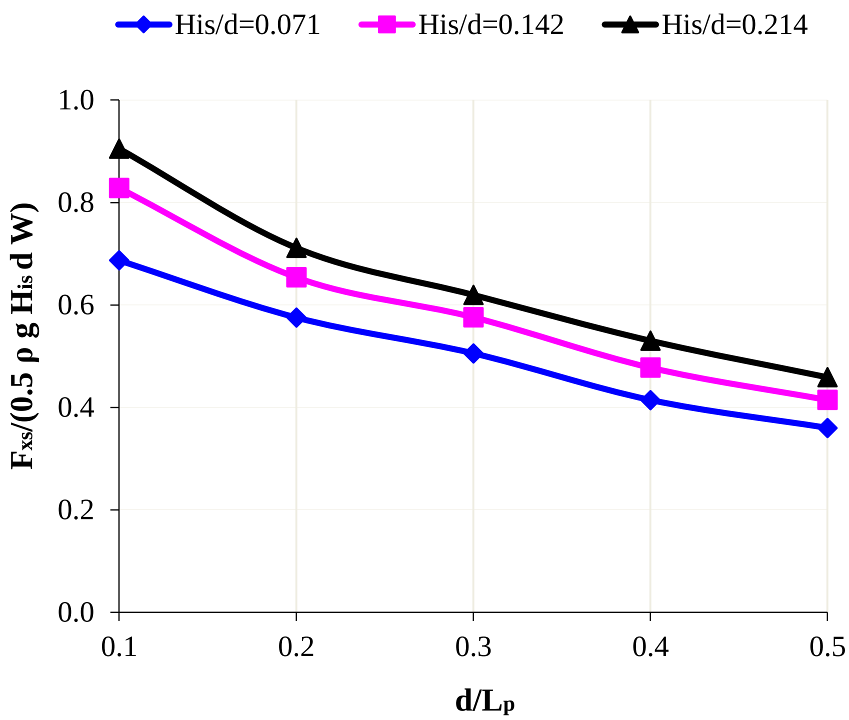


Fig. 5 Effect of change in significant wave height on wave force coefficient on slotted vertical barrier (n=1, P=10%)

Fig. 5 indicate the nonlinear behavior of the waves on wave forces. This character of the wave force on SVB needs to be noticed carefully for the correct field application of the study results.

3.3 Effect of porosity of the slotted vertical barriers on wave force variations

A clear understanding of the effect of the porosity of the SVB on WFC for different number of SVBs is needed for its cost effective design. Fig. 6 shows the effect of porosity of SVB on WFC for n=1 and H_{is}/d=0.142. It is found from this figure that increasing the porosity from 0% to 60% consistently reduces the value of WFC. For d/L_p=0.1 (long wave case), the value of WFC reduced from 1.25 to 0.35 when the porosity was increased from 0% to 60%. For d/L_p=0.5 (short wave case), the value of WFC reduced from 0.74 to 0.17 for same porosity variation. The reduction in the value of WFC is significant when the porosity is changed from 0% to 20%. When the porosity is more than 20%, the wave force reduction is marginal. Hence, varying the porosity from 0% to 20% is very sensitive for reducing the global wave force.

Similar plot for n=3 is provided in Fig. 7. The effect of porosity on WFC is similar to the previous case. However, changing n=1 to n=3 has increased the value of WFC. For d/L_p=0.10 (long wave case), the value of WFC changed from 1.14 to 0.59 when the porosity has increased from 5% to 60%. For d/L_p=0.5 (short wave case), the value of WFC reduced from 0.56 to 0.29 when the porosity has increased from 5% to 60%.

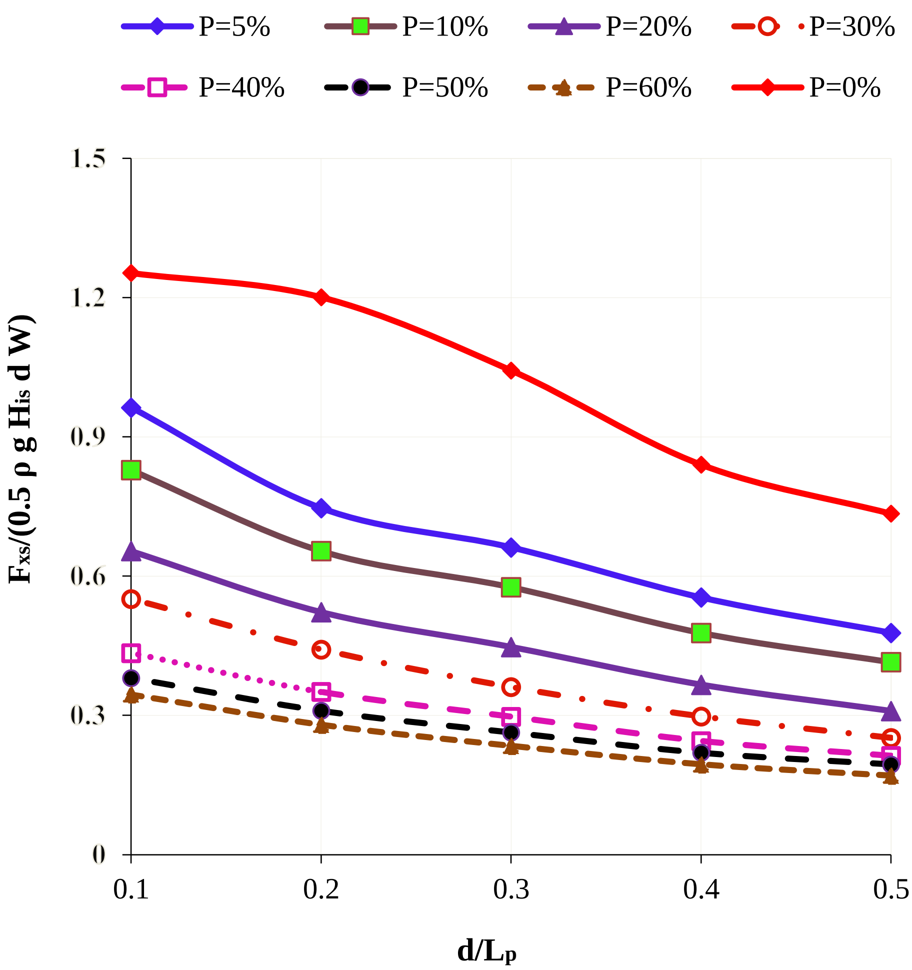


Fig. 6 Effect of the porosity of SVB on wave force coefficient (n=1, His/d=0.142)

Similar plots for n=6 are provided in Fig. 8. The effect of porosity on WFC is similar to the previous case. However, changing n=3 to n=6 resulted in higher WFC values. For d/L_p=0.10 (long wave case), the value of WFC reduced from 1.35 to 0.81 when the porosity was increased from 5% to 60%. For d/L_p=0.5 (short wave case), the value of WFC reduced from 0.47 to 0.24 when the porosity was increased from 5% to 60%.

Overall, it is found that increasing the porosity of SVB from 5% to 60% helps to reduce the WFC progressively. Long waves and low porosity results in the highest value of WFC (more than 1.2). Short waves and high porosity helps to reduce the value of WFC significantly (less than 0.3).

3.4 Effect of the increasing the number of SVBs from 1 to 6 on changes in wave forces

Fig. 9 shows the effect of the number of SVBs on WFC for P=10% and H_{is}/d=0.142. In general, it is found from this figure that increasing the number of SVBs from 1 to 6 increases the value of

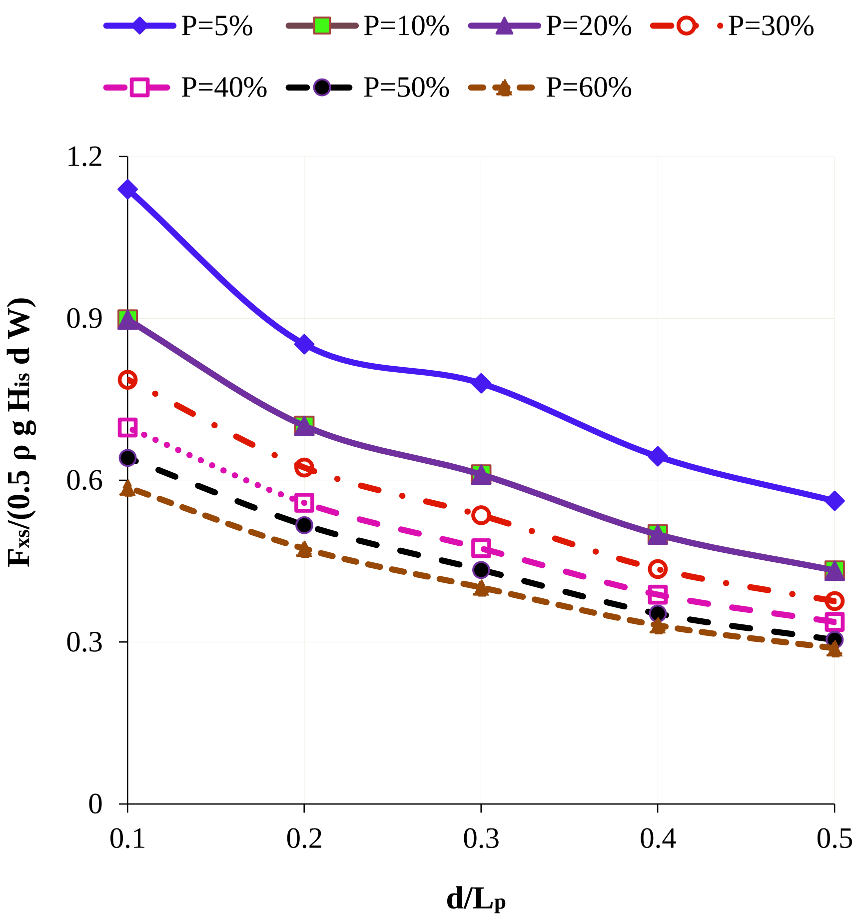


Fig. 7 Effect of the porosity of SVB on wave force coefficient (n=3, H_{is}/d=0.142)

WFC. However, the change in wave force is significant when the number of barrier is changed from 1 to 3. Further increase in number of wave barriers resulted in change, which are less significant. This could be due to less wave energy available when waves hit barrier 4 to 6 after dissipating significant energy while interacting with barriers 1 to 3. For d/L_p=0.1 (relatively long wave), the value of WFC increased from 0.83 to 1.28 when ‘n’ was increased from 1 to 6. For d/L_p=0.5 (relatively short wave), the change in the value of WFC is only from 0.42 to 0.55, which can be considered as insignificant, when n was increased from 1 to 6.

Similar plots for P=30% are provided in Fig. 10. The effect of changing ‘n’ on WFC is similar to the previous case. However, changing P=10% to P=30% resulted in the overall reduction of WFC. For d/L_p=0.10, the value of WFC increased from 0.55 to 1.03 when ‘n’ was increased from 1 to 6. For d/L_p=0.5, the value of WFC increased from 0.25 to 0.37 when ‘n’ was increased from 1 to 6. Similar plots for P=60% are provided in Fig. 11. As seen from Fig. 9, the change in wave force is quite significant when n is changed from 1 to 3 but not so significant when n is changed from 4 to 6 due to less wave energy available when waves hit barrier 4 onwards due to lesser energy of the wave while interacting with barriers 4 to 6.

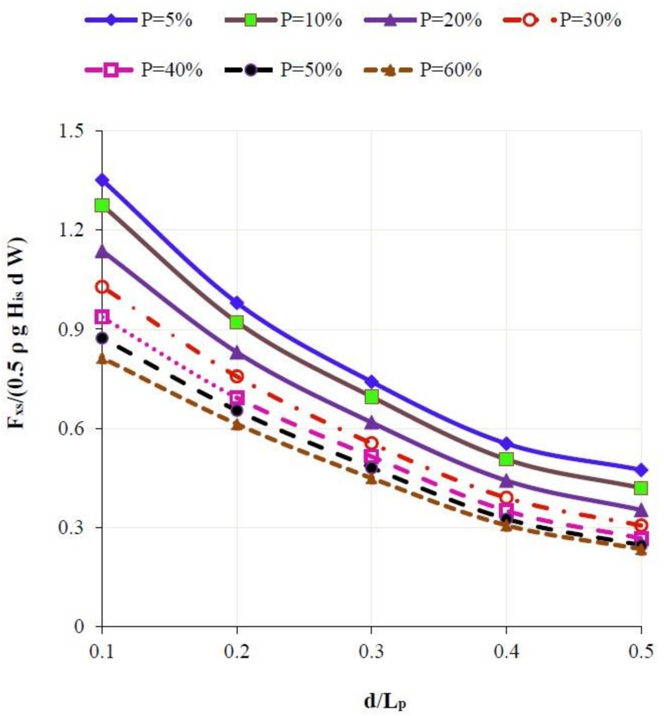


Fig. 8 Effect of the porosity of SVB on wave force coefficient (n=6, H_{is}/d=0.142)

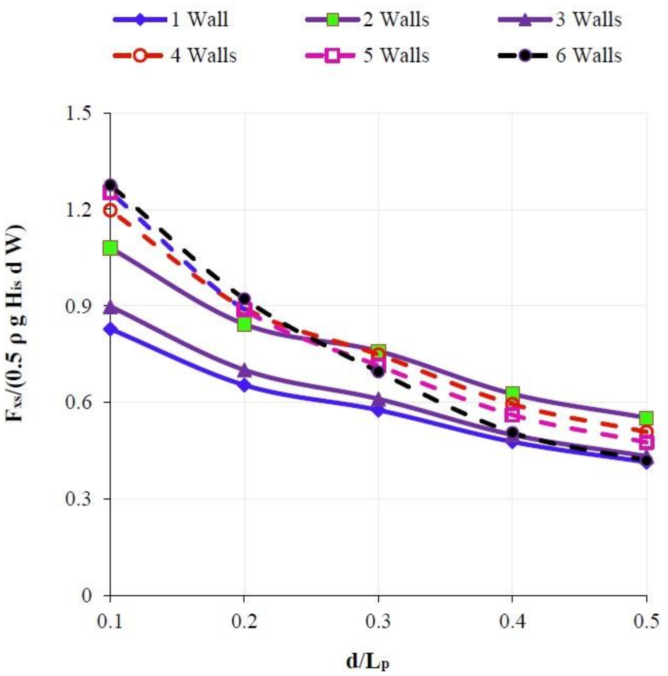


Fig. 9 Effect of the number of SVBs on wave force coefficient (P=10%, H_{is}/d=0.142)

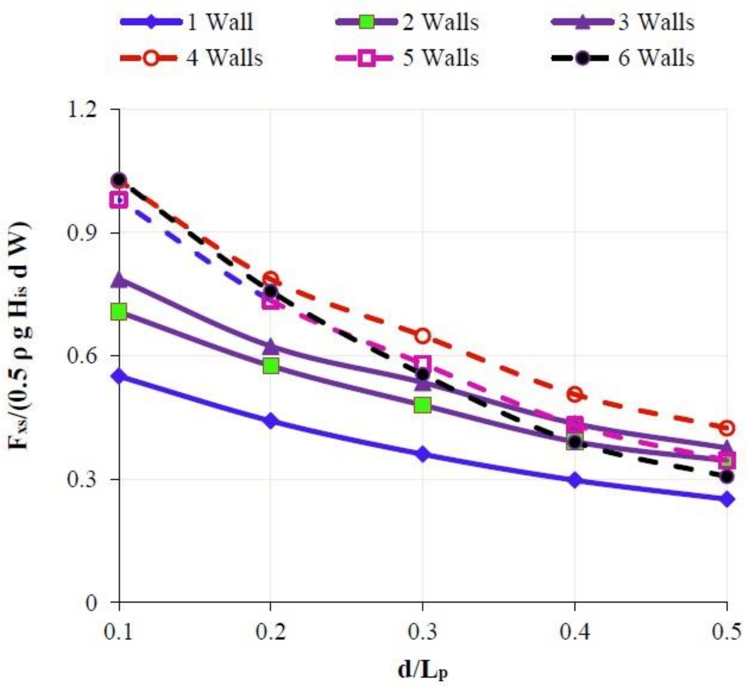


Fig. 10 Effect of the number of SVBs on wave force coefficient (P=30%, H_{is}/d=0.142)

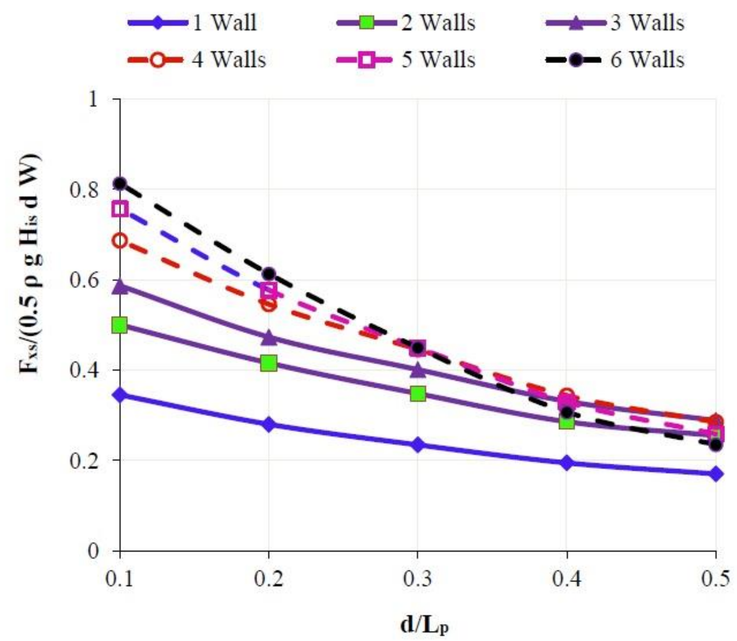


Fig. 11 Effect of the number of SVBs on wave force coefficient (P=60%, H_{is}/d=0.142)

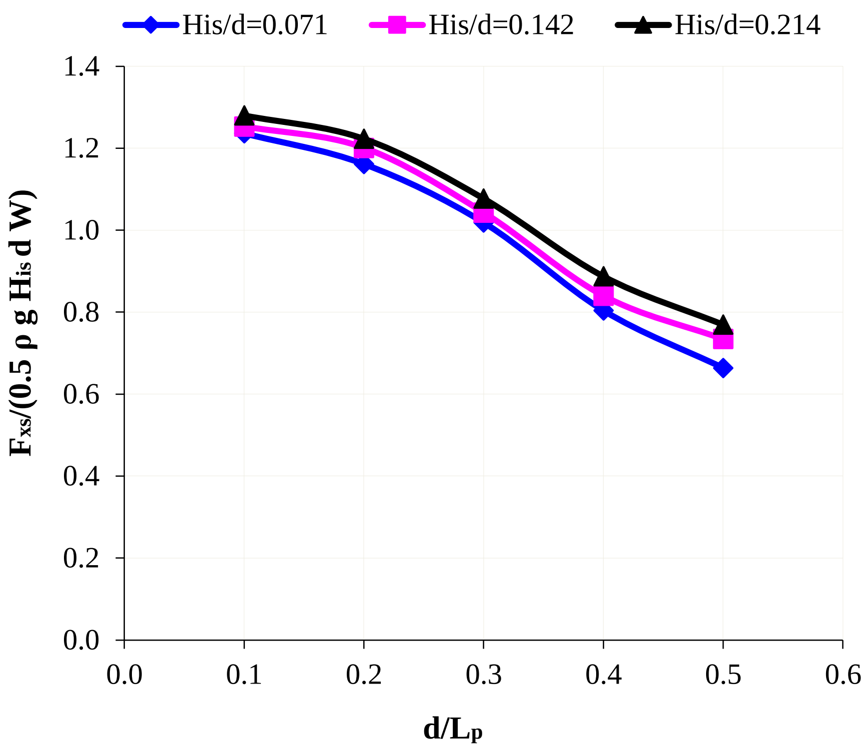


Fig. 12 Effect of wave height and wave period on the wave force coefficient on vertical barrier with zero porosity

It is clear that increasing the number of SVBs increases the wave force on SVB, especially for long waves. For short waves, increasing the number of SVBs does not increase the wave force significantly.

3.5 Effect of the slotted vertical barrier configuration on wave forces

As discussed earlier, the horizontal wave force was measured on 42 different SVBs and also on a vertical wall with zero porosity, as the reference case. It is our curiosity to know how much is the reduction (or) increase in wave force on these SVB configurations, when compared to the wave force on an impervious vertical wall. For coastal engineers, it is beneficial if the wave force on SVB is smaller than the wave force on impervious vertical wall. It is also important to know how much is the reduction in wave force on the SVB of different configurations compared to the wave force on an impervious wall. If the wave force on any SVB configuration is more than the wave force on an impervious vertical wall, then the SVB would not be a desired choice for field applications. Engineers look for a solution, where the wave force on SVBs is smaller than that on vertical wall with P=0%. This will help to prevent the horizontal sliding of the SVB structure with less investments. Since the wave force on an impervious vertical wall is the reference case, Fig. 12 is provided with d/L_p on the x-axis and measured force coefficient on the y-axis for three different H_{is}/d values. The measured normalized wave force value is about 1.25 for relatively long waves

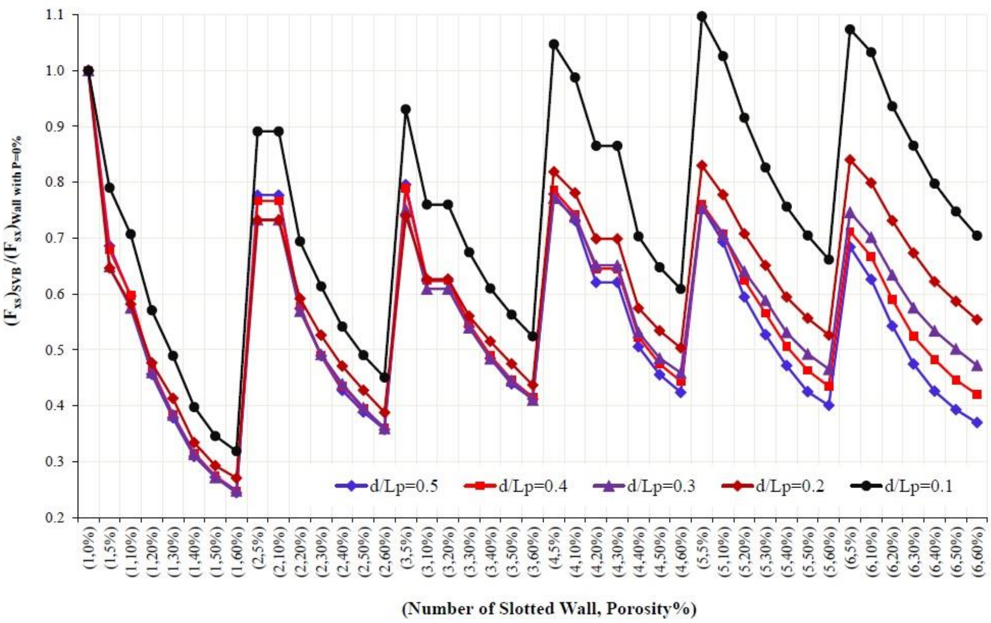


Fig. 13 Comparison of wave forces on the slotted vertical barrier of different configurations with an impervious vertical wall (H_{is}/d=0.214)

(d/L_p=0.1) and is about 0.7 for relatively short waves (d/L_p=0.5). It is found that increase in H_{is}/d increases the normalized wave force value to an extent of 5% to 10%, when H_{is}/d value is varied from 0.071 to 0.214. From this plot, once the design wave height, wave period, and water depth is known, the horizontal wave force can be accurately estimated on the impervious vertical wall. Now, it is important to know how the wave force varies on the SVB, when compared to the wave force on impervious vertical wall. The best way is to find out the ratio between the wave force on SVB and on the impervious vertical wall for the same input wave conditions. Such an estimate was carried out for all experimental runs.

Fig. 13 reveals the comparison of wave force ratios on the slotted vertical barrier of different configurations with an impervious vertical wall for H_{is}/d=0.214, the highest relative wave height conditions used in the experiment.

The x-axis is (No. of vertical wall, Porosity%) and the y-axis is the ratio between the wave force on different vertical barrier configurations to the wave force on the vertical wall with 0% porosity, $(F_{xs})_{SVB}$ / $(F_{xs})_{Wall\ with\ P=0\%}$. The y-axis value for (1.0%) is 1.0. The plot shows the result for five different d/LP values. Many interesting finding are available from this plot.

The wave force on slotted wave barrier is smaller than the wave force on a single impervious vertical wall for all configurations and for $d/L_p > 0.1$. Only for d/L_p=0.1 (long waves), and for 5% and 10% porosity and for 4, 5 and 6 porous walls, the wave force ratio has exceeded 1.0.

The wave force on the slotted barrier is minimum for 60% porosity whether it is one wall or six walls. For single slotted barrier, the lowest wave force ratio for 60% porosity is 0.24, whereas for two, three and four slotted barriers, the lowest value is 0.36, 0.40 and 0.42. For five and six barrier, the lowest value is 0.4 and 0.365. The lowest value of the wave force occurs for d/L_p = 0.5 (relatively short waves). As d/L_p reduced from 0.5 to 0.1, the force on the slotted barrier is found to increase.

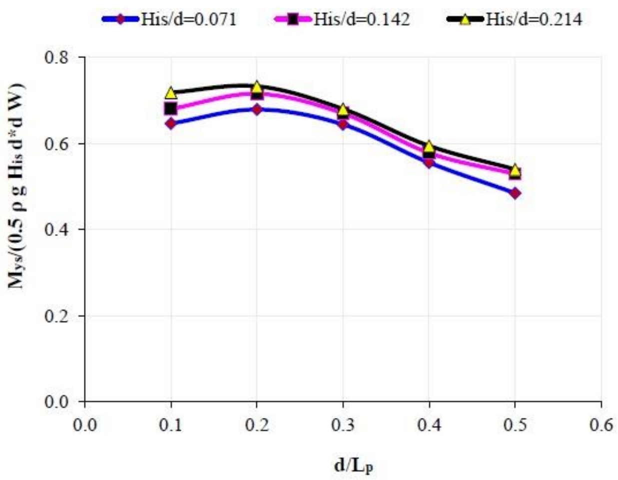


Fig. 14 Effect of wave height and wave period on wave induced moment on the vertical wall with zero porosity

It is also found from this figure that the wave force variation is sensitive for variation in d/L_p for six porous walls and less sensitive for single porous wall. For example, varying d/L_p from 0.1 to 0.5 for porous wall case (1, 60%) has varied the force ration from 0.24 to 0.32, whereas for (6, 60%), the force ration changed from 0.36 to 0.7. Fig. 13 along with Fig. 12 can be used to assess the actual wave force on any slotted wave barrier configurations for any d/L_p conditions within the range of 0.1 to 0.5.

3.6 Wave induced moment on the slotted vertical barrier

Similar to wave forces, the effect of wave height and wave period on the normalized wave induced moment on a vertical impervious wall is shown in Fig. 14. For relatively long waves (d/L_p=0.1), the normalized moment value is in the range of 0.7 to 0.77, whereas for relatively short waves ((d/L_p=0.5), it is about 0.54 to 059. The value of normalized moment is found to increases when H_{is}/d increases from 0.071 to 0.214.

The wave-induced moment is equal to the total horizontal wave force and the lever arm from the base of the wall. In general, if wave force increases, the wave induced moment also has to increase. Fig. 15 is prepared to correlate the normalized wave force and normalized moment by using all the measured data points. The correlation is found to be good with a correlation coefficient of 0.95. The equation obtained connecting the wave force and moment is y=0.6145 x, where y is the normalized moment and x is the normalized wave force. Hence, if the significant wave force on SVB is known, then the significant moment can be estimated using the following equation

$$M_{ys} = (0.6145\ d)\ F_{xs} \qquad (3)$$

3.7 Typical application of the present study

The application of the present study is illustrated through a workout example for a typical field conditions encountered in Gulf. The purpose is to check the stability of a vertical porous breakwater,

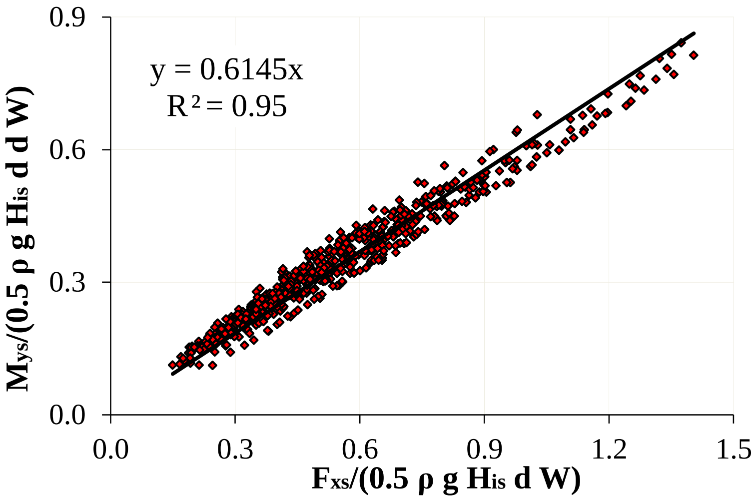


Fig. 14 Slotted vertical barrier with two walls and 10% porosity

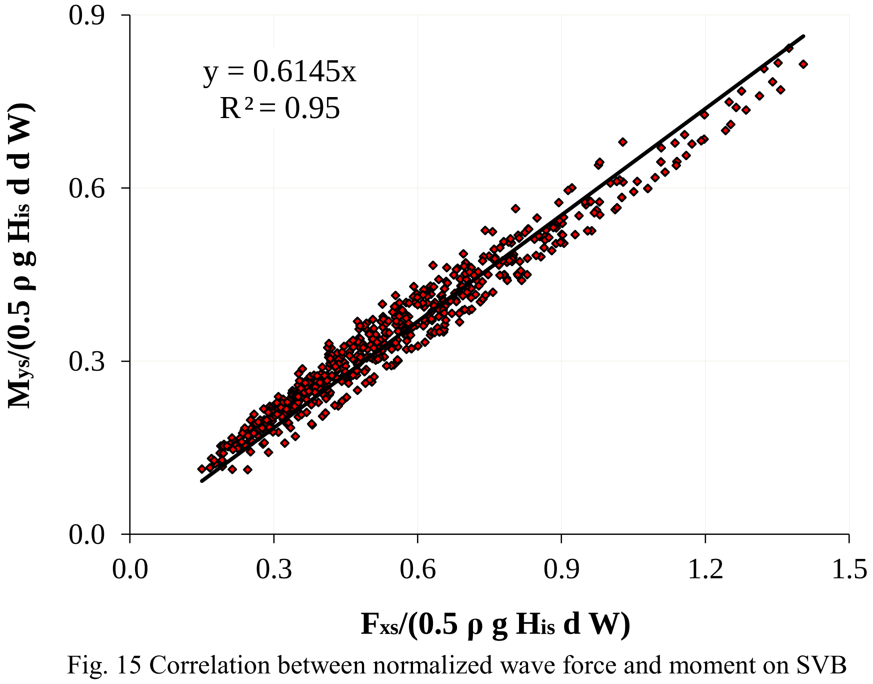


Fig. 15 Correlation between normalized wave force and moment on SVB

which consists of two porous walls of 10% porosity for a design condition with significant wave height, H_{is} of 1.0 m and a peak period, T_p of 4.23 s at water depth, d of 4.7 m. For H_{is}=1.0 m; T_p=4.23 s; d=4.7 m, the value of d/L_p is 0.2. The value of H_{is}/d is 0.214. For this d/L_p and H_{is}/d condition, from Fig. 13, the wave force coefficients F_{xs} /(0.5 ρ g H_{is} d W) for (n, P) = (2,10) is 0.732. Based on the structural design of the panel, the thickness required is 0.3 m for M50 concrete. The structural arrangement is as shown in Fig. 14.

The check for stability against horizontal sliding is carried out. A SVB of 1.0 m width is considered. Hence, W = 1.0 m. The value of F_{xs} /(0.5 ρ g H_{is} d W) is 0.732. Hence, F_{xs} is equal to 0.732 x 0.5 x 1.030 x 9.81 x 1.0 x 4.7 x 1.0 kN/m =17.38 kN/m. Cross-sectional area of the SVB structure is (4.0 x 0.5) + (2 x 7.2 x 0.3 x (1.0-0.1)), which is equal to 5.888 $m^{2.}$ Hence, the volume of concrete required/m run is 5.888 m^3. Assume the whole structure is submerged during the design wave action. Hence, the net submerged downward self-weight of the concrete structure, W_c is equal to 5.888 x (25 - 1.03x9.81), which is 84.82 kN/m. Assume the seabed is sandy and the coefficient of friction between the concrete bottom slab and sand is μ=0.5. The factor of safety against horizontal sliding is μ W_c / F_{xs} = 0.5 x 84.82 / 17.38, which is 2.44. The factor of safety of 1.5 against horizontal sliding is enough. It is clear that 2.44 is on the higher side and hence, very safe. It is to be noted that the design is carried out for a significant wave force. The extreme wave force can be about 1.8 times the significant wave force, but it happens rarely. Still, the SVB is safe against sliding.

The check for stability against overturning is also carried out. The overturning moment, M_{ys} is (0.6145 d) F_{xs}, which is equal to 0.6145 x 4.2 x17.38 kN-m/m = 44.86 kN-m/m. The center of gravity of the SVB is 2.0 m from the toe. Hence, the restraining moment is 84.82 x 2.0 = 169.64 kN-m/m. The factor of safety against overturning is equal to Restraining moment / disturbing moment, which is 169.64 / 44.86 = 3.78. The factor of safety of 1.5 against overturning is enough. 3.78 is on the higher side and hence, very safe. Even if the extreme moment of 1.8 times the significant wave induced moment is considered, still the structure is safe against overturning. Scope for reducing the bottom slab thickness exists. This is a typical worked out example to illustrate the application of the present study. Similar calculations can be carried out for any field application for the range of parameters studied in this manuscript.

4. Conclusions

The important conclusions from the study on the wave forces and wave moments on slotted vertical barriers are as follows:

- The wave force coefficient, F_{xs} / (0.5 ρ g H_{is} d W) on slotted vertical walls can be reduced consistently with an increase in d/L_p from 0.1 to 0.5.
- On any slotted vertical wall configuration, for a fixed d/L_p value, the wave force coefficient increases with increase in H_{is}/d.
- The wave force on the vertical slotted wave barrier is very sensitive to the change in porosity of the SVB.
- For a fixed number of porous walls of the SVBs, the wave force coefficient progressively reduces with an increase in the porosity of the SVBs.
- The highest value of the wave force occurs on the SVB, when long waves interact with them with low porosity.
- The lowest value of the wave force occurs on SVB, when short waves interact with them with high porosity.
- The wave force on SVB can be reduced to an extent of up to 76%, depending on the porosity and number of SVBs. This character can be used for cost-effective design of SVBs against horizontal sliding.

- Only for few cases (4, 5 and 6 SVB and 5% and 10% porosity), the wave forces on the slotted vertical barrier is 5% to 10% more than the wave force on a single non-porous vertical wall. This condition can be avoided during design of such wave barriers.
- Increasing the number of SVBs increases the wave force coefficient on SVB, especially for long waves. For short waves, increasing the number of SVBs does not increase the wave force coefficient significantly.
- Wave force and wave induced moment on the slotted vertical barrier correlates positively with an equation $M_{ys} = (0.6145\ d)\ F_{xs}$ and with $R^2 = 0.95$.

Suggestions for future studies

The following are the suggestions for future studies:

- Effect of varying the horizontal distance between the slotted walls.
- Effect of progressively decreasing or increasing the porosity from the front wall to the rear wall.

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References

Alkhalidi, M., Neelamani, S. and Al Haj Assad, A.I. (2015a), “Wave forces and dynamic pressures on slotted vertical wave barriers with an impermeable wall in random wave fields”, *Ocean Eng*., **109**, 1-6.

Alkhalidi, M., Neelamani, S. and Al Haj Assad, A.I. (2015b), “Wave pressures and forces on slotted vertical wave barriers”, *Ocean Eng*., **108**, 578-583.

Al-Salem, K., Neelamani, S., Al-Essa, F. and Taqi, A. (2014), “Physical model study on wave reflection by harbor structures for validating KISR’s wave agitation model - Phase I”, Kuwait Institute for Scientific Research, Report No. KISR12252, Kuwait.

Alsaydalani, M.O., Saif, M.A.N. and Helal, M.M. (2017), “Hydrodynamic characteristics of three rows of vertical slotted wall breakwaters”, *J. Mar. Sci. Appl.*, **16**, 261-275. https://doi.org/10.1007/s11804-017-1427-5.

Barzegar, M. and Palaniappan, D. (2020), “Numerical study on the performance of semicircular and rectangular submerged breakwaters”, *Ocean Syst. Eng.,* **10**(2), 201-226. https://doi.org/10.12989/ose.2020.10.2.201.

Bergmann, H. and Oumeraci, H. (1998), “Wave pressure distribution on permeable vertical walls”, *Proceedings of the 26th International Conference on Coastal Engineering*, June 22-26, Copenhagen, Denmark.

Elbisy, M.S., Mlybari, E.M. and Helal, M.M. (2016), “Hydrodynamic performance of multiple-row slotted breakwaters”, *J. Mar. Sci. Appl.*, **15**, 123-135. https://doi.org/10.1007/s11804-016-1358-6.

Fernández-Ordóñez Hernández, D. (2018), “Early developments of concrete prefabrication”, (Eds., Hordijk D., Luković M.), High Tech Concrete: Where Technology and Engineering Meet. Springer, Cham.

Gardner, J.D., Townend, T.H. and Fleming, C.A. (1986). “The design of a slotted vertical screen breakwater”, *Proceedings of the 20th Coastal Engineering Conference*, ASCE, Taipei.

George, A. and Cho, I. H. (2020), “Hydrodynamic performance of a vertical slotted breakwater”, *Int. J. Naval Architect. Ocean Eng.*, **12**, 468-478. https://doi.org/10.1016/j.ijnaoe.2019.12.001.

Goda, Y. and Suzuki, Y. (1976), “Estimation of incident and reflected waves in random wave experiments”, *Proceedings of the 15th Coastal Engineering Conference*, Honolulu, Hawaii.

Hayashi, T., Hattori, M., Kano, T. and Shirai, M. (1968), “Closely spaced pile breakwater as a protect structure against beach erosion”, *Coast. Eng. Japan*, **11**, 149-160.

Huang, Z.H., Li, Y.C. and Liu, Y. (2011), “Hydraulic performance and wave loading of perforated/slotted coastal structures: A review”, *Ocean Eng.*, **38**, 1031-1053.

Hussein, K.B. and Ibrahim, M.I. (2019), “Wave interaction with vertical slotted breakwaters”, *Int. J. Eng. Res. Technol.*, **8**(7).

Ibrahim, M. (2019), “Hydrodynamic performance efficiency of perforated vertical barrier with circular or square slots”, *Al-Azar Univ. Civil Eng. Res. Mag*., **41**(1), 74-89.

Isaacson, M., Premasiri, S. and Yang, G. (1998), “Wave interaction with vertical slotted barrier”, *J. Waterway, Port, Coast. Ocean Eng.*, **124**(3), 118-126.

Isaacson, M., Baldwin, J., Premasiri, S. and Yang, G. (1999), “Wave interactions with double slotted barriers”, *Appl. Ocean Res.*, **21** (2), 81-91.

Ji, C.H. and Suh, K.D. (2010), “Wave interactions with multiple-row curtain wall-pile breakwaters”, *Coast. Eng.*, **57**(5), 500-512.

Koraim, A.S. (2011), “Hydrodynamic characteristics of slotted breakwaters under regular waves”, *J. Mar. Sci. Technol.*, **16**, 331-342. https://doi.org/10.1007/s00773-011-0126-1.

Koutandos, E.V. (2009), “Hydrodynamics of Vertical Semi-Immersed Slotted Barrier”, *WSEAS T. Fluid Mech*., **4**(3), 85-96.

Kriebel, D.L. (1992), “Vertical wave barriers: wave transmission and wave forces”, *Proceedings of the 23rd Coastal Engineering Conference*, ASCE, Venice.

Kundapura, S. and Hegde, A.V. (2017), “Current approaches of artificial intelligence in breakwaters – A review”, *Ocean Syst. Eng.*, **7**(2), 75-87. https://doi.org/10.12989/ose.2017.7.2.075.

Liu, Y. and Li, H.J. (2013), “Hydrodynamic performance of a composite breakwater with an upper horizontal porous plate and a lower rubble mound”, *Ocean Syst. Eng.*, **3**(1), 55-70. https://doi.org/10.12989/ose.2013.3.1.055.

Liu, Y. and Li, H.J. (2017), “Iterative multi-domain BqM solution for water wave reflection by perforated caisson breakwaters”, *Eng. Anal. Bound. Elem.*, **77**, 70-80.

Mackay, E.D. and Johanning, L. (2020), “Comparison of analytical and numerical solutions for wave interaction with a vertical porous barrier”, *Ocean Eng.*, **199**, 107032.

Mansard, E.P.D. and Funke, E.R. (1987), “On the reflection analysis of irregular waves”, Technical Report TR-HY-017, NRCC No. 27522, National Research Council of Canada, Canada.

Mei, C.C., Liu, P.L.F. and Ippen, A.T. (1974), “Quadratic loss and scattering of long waves”, *J. Waterway, Harbors Coast. Eng. Div. –ASCE*, **100**(3), 217-239.

Molin, B. and Remy, F. (2015), “Inertia effects in TLD sloshing with perforated screens”, *J. Fluid. Struct.*, **59**, 165-177.

Neelamani, S., Taqi, A. and Al-Salem, K. (2016), “Method of Dissipating Water Wave Energy”, US Patent No.: US 9,447,554; Date of Patent issue: September 20, 2016.

Neelamani, S. and Al-Anjari, N. (2018), “Hydrodynamic Studies on Slotted Vertical Wave Barriers (EC097C)”, Final report submitted to Kuwait Foundation for Advancement of Sciences by Kuwait Institute for Scientific Research, Kuwait, Project code: 07-0818-007.

Neelamani, S. and Al-Anjari, N. (2020), “Experimental investigations on wave induced dynamic pressures over slotted vertical barriers in random wave fields”, *Ocean Eng.*, **220**(2021), 108482.

Poguluri, S.K. and Cho, I.H. (2020), “Analytical and numerical study of wave interaction with a vertical slotted barrier”, *Ships Offshore Struct.*, https://doi.org/10.1080/17445302.2020.1790299.

Terret, F.L., Osorio, J.D.C. and Lean, G.H. (1968), “Model studies of a perforated breakwater”, *Proceedings of the 11th Coastal Engineering Conference*. ASCE, London.

Urashima, S., Ishizuka, K. and Kondo, H. (1986). “Energy dissipation and wave force at slotted wall”. *Proceedings of the 20th Coastal Engineering Conference.* ASCE, Taipai, 2344–2352.

Valizadeh, A. and Rudman, M. (2017), “A numerical approach for simulating flow through thin porous media”, *Eur. J. Mech. Fluid.*, **65**, 31-44.

Valizadeh, A., Rafiee, A., Francis, V., Rudman, M. and Ramakrishnan, B. (2018), “An analysis of perforated plate breakwaters”, *Proceedings of the 28th International Ocean and Polar Engineering Conference*, Sapporo, Japan, June 10-15.

Van der Meer, J.W. (1988), “Deterministic and probabilistic design of breakwater armor layers”, *Proceedings ASCE, Waterway, Port, Coast. Ocean Eng.*, **114**(1), 66-80.

Vijay, K.G., Neelamani, S. and Sahoo, T. (2019), “Wave interaction with multiple slotted barriers inside harbour: Physical and numerical modeling”, *Ocean Eng.*, **193(**1), 106623. https://doi.org/10.1016/j.oceaneng.2019.106623**.**

Vijay, K.G., Nishad, C.S., Neelamani, S. and Sahoo, T. (2020), “Gravity wave interaction with a wave attenuating system”, *Appl. Ocean Res.*, **101**, 102206, https://doi.org/10.1016/j.apor.2020.102206**.**

Zelt, J.A. and Skjelbreia, J.E. (1992). “Estimating incident and reflected wave fields using arbitrary number of wave gauges”, *Coast. Eng. - ASCE*, 777-789.

Zhao, Y., Liu, Y. and Li, H. (2018), “Iterative analytical solution for wave scattering by multiple partially immersed slotted barriers”, *Proceedings of the 28th International Ocean and Polar Engineering Conference,* Sapporo, Japan, June 10-15.

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Nomenclature

B: The distance between the vertical slotted wave barriers
d_1: The far field water depth
d: Water depth at model location
d/L_p: The relative water depth
F_{xs}: The significant global wave force in the direction of wave propagation
g: The acceleration due to gravity
H_{is}: The significant incident wave height
H_{is}/d: The relative significant wave height
H_{is}/L_p: The wave steepness
L_p: The wavelength corresponds to peak period
M_{ys}: The significant wave induced moments on the vertical slotted wave barrier
n: The number of vertical slotted wave barriers
P: porosity of the wave barrier
RMBW: Rubble mound breakwater
SVB: Slotted vertical barrier
t: The thickness of the wave barrier
T_p: the peak period
W: The width of the wave barrier
WFC: Wave force coefficient
WP1, WP2, WP3, WP4, WP5 and WP6: Wave probes used for the study
ρ: The density of water