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Wave forces on a vertical cylinder defenced by a perforated vertical and inclined barriers

S. Neelamani & M. G. Muni Reddy

Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai—600 036, India
[E-mail: sneel@pallava.iitm.ernet.in]

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Wave forces on a vertical cylinder defensed by a perforated vertical and inclined barriers with 45° angle of inclination were experimentally investigated. The relative wave height, (H_i/d) varied from 0.114 to 0.429 and the porosity was kept constant with 12%. The force ratios were found reducing with increase of H_i/d. It is estimated that on an average, the reduction of force on the vertical cylinder is about 35% due to perforated vertical barrier and is about 30% due to sloped barrier. Incident wave steepness, (H_i/L) varied from 0.007 to 0. 080 and the force ratios were also found reducing with increase of wave steepness. The force ratios are less sensitive for the scattering parameter (ka).

[**Key words** : Wave forces, vertical piles, wave barriers, energy dissipation]

Most of the structures offshore and in coastal region like jetties, approach trestles, ocean bridges, etc are supported on vertical piles, whose design is dictated by the severe wave forces. The *in situ* rectification of piles damaged by extreme wave forces is not economical. Simple cost effective ways to reduce the forces on the partially damaged pile is required. Perforated vertical sheet piles can be driven around the partially damaged piles to prevent it from further severe loading. This combined structure also can be used for scour reduction around the pile bottom. Load reduction on the load bearing structure will also enhance the life of the structure. Such applications have motivated the authors to investigate on the wave forces on a vertical cylinder defensed by vertical and inclined barriers. One of the main objectives of this study is to propose predictive formulae to estimate the wave force as a function of input parameters, when the vertical cylinder is defensed by the perforated vertical and sloped plate barrier.

The study of wave forces on an isolated slender vertical pile has been one of the main research areas, which attracted the attention of many researchers. Morison *et al*.[1] have proposed a simple empirical equation to estimate the velocity dependent drag force and acceleration dependent inertia force. Selection of appropriate wave theory for the estimation of the water particle velocity and acceleration and the corresponding drag and inertia coefficient is very essential in the usage of Morison equation. McCamy & Fuchs[2] have provided an analytical solution for the problem of wave diffraction by a large vertical cylinder by using the linear wave theory conditions. Sarpkaya & Isaacson[3] have solved this problem by source distribution technique. Dissipation of wave energy is a primary feature of wave interaction with porous structure and has been considered previously by many authors. Jarlan[4] originally suggested the fixed porous wall breakwaters and presented experimental data. The related problem of thin permeable breakwaters has also been reported[5-7] The breakwater is assumed to be thin only with respect to the wave diffraction problem so that matching conditions are applied across the breakwater, in which the flow through the porous breakwater is taken to be proportional to pressure gradient. The extension of the above methods to Jarlan type breakwaters involving the combination of porous barrier and impermeable back wall has been reported[8-10].

However, little work has been reported on the effect of porous vertical barrier on the isolated vertical cylinder and in particular, effects of the inclined barrier on the vertical cylinder. Darwiche *et al*[11]. have solved the problem of wave interaction on a vertical cylinder encircled by a semi porous circular caisson. Linearized potential flow condition is assumed and the coupled problem of flow in the interior and exterior fluid region is solved by an eigenfunction expansion approach. Such conditions can not provide the information for higher wave steepness and higher relative wave heights, which are essential for design conditions. Govaere *et al.*[12] presented an analytical solution for the evaluation of wave kinematics caused by piles with porous protection at their bases. They developed a mathematical model, assuming linear wave theory and neglecting the breaking waves. Neelamani *et al.*[13] experimentally investigated the water surface fluctuations around a structure consisting of a vertical cylinder encircled by a perforated square caisson and presented simple predictive equations to estimate the forces on and water surface fluctuations around the vertical cylinder protected by porous caissons. Mathematical and numerical modeling, assuming linearized boundary conditions are difficult to deal with the present wave-structure interaction problem. Hence, the experimental investigation was carried out. Richey & Sollitt[14] illustrated the practical use of protecting a main structure by using another defense structure for rehabilitation of a bridge wall.

Material and Methods

The experimental investigations were carried out in the wave flume (Leichtweiss-Institute for Hydraulics and Coastal Engineering, Technical University of Braunschweig, Germany).

The dimensions of the flume and the characteristics of the waves used for the study are:

Flume length	:	90 m
Flume width	:	2.0 m
Flume depth	:	1.2 m
Water depth, (d)	:	0.70 m
Waves used in this study	:	Monochromatic
Incident wave height, (H_i)	:	8 to 30 cm
Wave periods, (T)	:	1.5 to 4.5 sec
Diameter of the vertical cylinder, (D)	:	0.15 m
Porosity of the barrier, (P%)	:	12%
Inclination of the barrier	:	45^o and 90^o to horizontal

The different ranges of the normalized hydrodynamic parameters obtained are:

Incident wave steepness, (H_i/L)	:	0.007 to 0.08
Relative water depth, (d/L)	:	0.06 to 0.22
Scattering parameter, (ka)	:	0.04 to 0.15
Relative wave height, (H_i/d)	:	0.114 to 0.43
Keulegan-Carpenter number, [KC ($KC=U_{max}\ T/D$)]	:	1.89 to 8.49
Reynolds number, [Re ($Re=U_{max}\ D/\gamma$)]	:	21846 to 88793
Ursell parameter, [Up ($Up=HL^2/d^3$)]	:	2.268 to 46.46

The definition sketch showing the interaction of a incident gravity wave train with a single, vertical cylindrical impermeable pile of diameter, 'D' protected by a porous vertical and inclined barrier for a constant water depth, 'd' is shown in Fig. 1. The reason for wide use of vertical circular member is that they are blend and attracts less wave loads compared to the other forms like rectangular or square cylinders. The wave load is also independent of wave direction on circular vertical members unlike other forms. The system is subjected to train of monochromatic waves of height, H_i , wave period, T propagated from the deep ocean. When the wave reaches the protective barrier, some energy reflects back to sea, some energy dissipates due to partial breaking, flow contraction and expansion into the pores and turbulence and the remaining energy transmits towards the lee side of the barrier through the pores. This transmitted wave energy propagates further in waveforms and acts on the vertical cylinder. The designer looks for better energy dissipation or more energy reflection in order to avoid significant wave transmission. More transmission of wave energy increases the force on the vertical cylinder. It is to be kept in mind that significant wave reflection also causes more wave force on the defense barrier. In the present work, the scope is limited to the investigation of wave force on the rear cylinder and further work on wave force on the barrier is required.

In general, the force on the vertical cylinder protected by a perforated barrier, F_{x1} depends on the following parameters:

$$F_{x1} = f(H_i, T, d, D, P\%, \theta, l, \rho, g, \nu) \quad \dots (1)$$

In the present study, F_{x1} represents the force on the cylinder protected by vertical perforated barrier and F_{x2} represents the force on the cylinder protected by

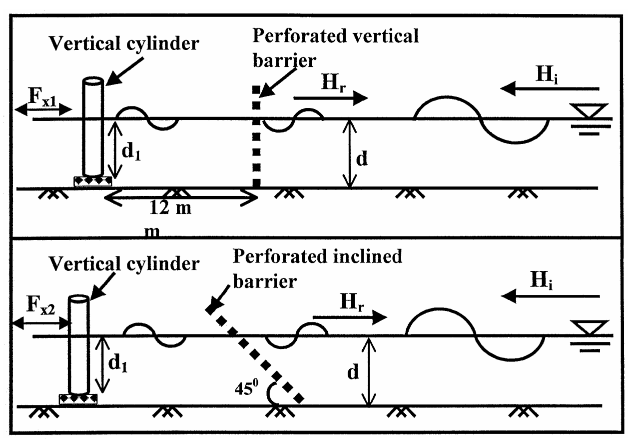

Fig. 1 — Definition skecth.

inclined perforated barrier, where H_i = incident wave height, T = wave period, d = local water depth, D = cylinder diameter, P% = porosity of the barrier, θ = inclination of the barrier with seabed (θ = 45° and 90° is used), l = distance between the toe of the barrier and the cylinder, ρ = mass density of the water, g = gravitational acceleration and ν = kinematic viscosity of water at the flume water temperature.

The present investigation was made for a constant porosity of 12% only. The distance between the toe of the barrier and the cylinder is kept at 12 m, which is more than one wavelength of the longest wave used in the present investigation. Hence it is assured that the pile is placed in a zone where the influence of evanescent wave mode of wave generation on the barrier is negligible. Hence eliminating the porosity (P%) and distance between the toe of the barrier and cylinder 'l' from the above equation, the following normalised form can be obtained:

$$F_{x1} /(\rho\, g\, H_i\, D\, d) = f\ \{ H_i /L \text{ or } H_i /d,\ d/L\ ,\ ka \text{ or } D /L,\ Re,\ \theta\} \qquad \ldots (2)$$

where 'a' is the cylinder radius, (H_i/L) is normally used for deep and intermediate water and (H_i/d) is used in shallow water conditions. Since the present investigation is in the inertia-dominated region, the effect of Re can be neglected. Hence the Eq. (2) can be written as :

$$F_{x1}/(\rho\, g\, H_i\, D\, d) = f\{H_i/L \text{ or } H_i/d,\ d/L,\ D/L,\ \theta\} \qquad \ldots (3)$$

For better understanding of the effect of barrier on the force on the vertical cylinder, force ratio in the form of F_{x1}/F_x and in the form of F_{x2}/F_x is used, where F_x is the force on the cylinder without any protection.

For measuring the in-line force and the corresponding moments on the structure, a force balance was fabricated by using 3 load cells, each of capacity 5 KN. One load cell measures directly the total in-line force and other two measures the reaction induced by the in-line moments. The load cells are burster, Type: 85041-5-6I, IP 68. The accuracy of the measurements was 1.56 ± 1.16 %. The reference supply for the instrument was 10 V_{DC} and the resonance frequency of the load cell was 2 kHz. The overloading capacity was 150 %. The force balance was calibrated for few times and the calibration constants were found to be repeating.

Standard Capacitance type (two parallel wires with 2 cm distance between them) wave probes are used for the measurements of incident wave fields. The average incident wave heights were estimated from the four wave probes placed at a distance of 37.56, 37.81, 38.38 and 39.47 m from the wave paddle. The accuracy of the measurement of wave height is about 0.2 % (accuracy of wave generation is ± 5 %). The wave gauges were calibrated each time, when the experiments repeated. The repeatability of the wave gauge calibration constants were good.

A personal computer records the time history of wave heights and wave forces on the vertical cylinder. Regular waves were generated for 100 sec and the data were collected for 200 sec at a sampling rate of 40 Hz. The time series corresponding to the clear repetition of the regular occurrences of the events and before any re-reflected wave influences the wave field around the vicinity of the structure was selected (a time window with an average of 25 to 35 sec out of a total measured duration of 200 sec) for analysis and the rest of the time series were discarded. Time domain analysis was carried out on these data. The average of maximum seaward and maximum shoreward force is used for the normalisation purpose.

The present experimental investigations were carried out in the inertia-dominated region. The details of the force measurement, analysis and presentations are available in Neelamani *et al*[14]. For the purpose of immediate reference, the method of estimation of force coefficient (Inertia coefficient, C_m if Inertia force is considered and C_T, if the total force is considered) is given below:

The present experimental investigations are carried out in the inertia-dominated regime. Hence the assessment of the inertia coefficient from the experimental investigations is reliable, whereas the estimation of drag coefficient is not reliable. The inertia coefficient due to in-line force, C_m is estimated by using the inertia part of the Morison equation:

$$C_m = F_{I\,max} / R1 \qquad \ldots (4)$$

where

$$R_1 = \pi\, D\, E\, (D/H_i)\, \tan h\, (kd)\, [1 - \{\sin h\, k(d - d1)/ \sin h\, (kd)\}] \qquad \ldots (5)$$

F_{Imax} = Maximum inertia force, [N]; E = incident wave Energy ($\rho g\, H_i^2/8$), [N-m]; k = wave number (2π/L), [m^{-1}], L = wave length [m] and d1 = depth of water from the SWL to the bottom of the cylinder, 0.45 m (the cylinder was fixed on a force balance, which is 250 mm high).

The above equations were obtained by integrating the inertia force from the bottom of the cylinder to the mean water level. The maximum inertia force, $F_{I\,max}$ is estimated as follows: The force magnitudes corresponding to the zero down crossing and up crossing of the in-phase water surface is equal to the maximum shoreward and seaward inertia forces respectively. These forces are picked up for as many times as they occur in the time window of 25 to 35 sec. The average of all the shoreward and seaward forces are calculated. Then the average of the absolute values of the shoreward and seaward forces are estimated and are used in Eq. 4. Since the present work is in the inertia-dominated regime, the maximum inertia force is almost equal to the absolute maximum force on the cylinder. For the purpose of estimating the total force coefficient, the maximum measured force values are also used. The maximum force will be greater than the maximum inertia force. The difference between the total force coefficient and inertia force coefficient gives qualitative information of the drag force contribution.

Results and Discussion

In the present investigation, the main attention is to explore the force reduction on a vertical cylinder placed behind a vertical and inclined perforated plate. The effect of Keulegan-Carpenter number (KC), Reynolds Number (Re) on inertia coefficient and total force coefficient are given in Fig. 2A and the effect of Ursell parameter (H_iL^2/d^3) and wave steepness (H_i/L) on Inertia coefficient and total wave force coefficient is provided in Fig. 2B. This plot is provided to understand the difference between the inertia coefficient and the total force coefficient on wave interaction with the vertical pile in the inertia-dominated regime. The average value of the inertia coefficient is 2.71 and the standard deviation is 0.22. The average value of the total force coefficient is 3.17 and the standard deviation is 0.47. It is important to note that these force coefficients should be used along with the water particle kinematics predicted by linear wave theory. This plot should be used in conjunction with Fig. 3 to 6 for the estimation of force on the vertical cylinder defensed by perforated plate barrier.

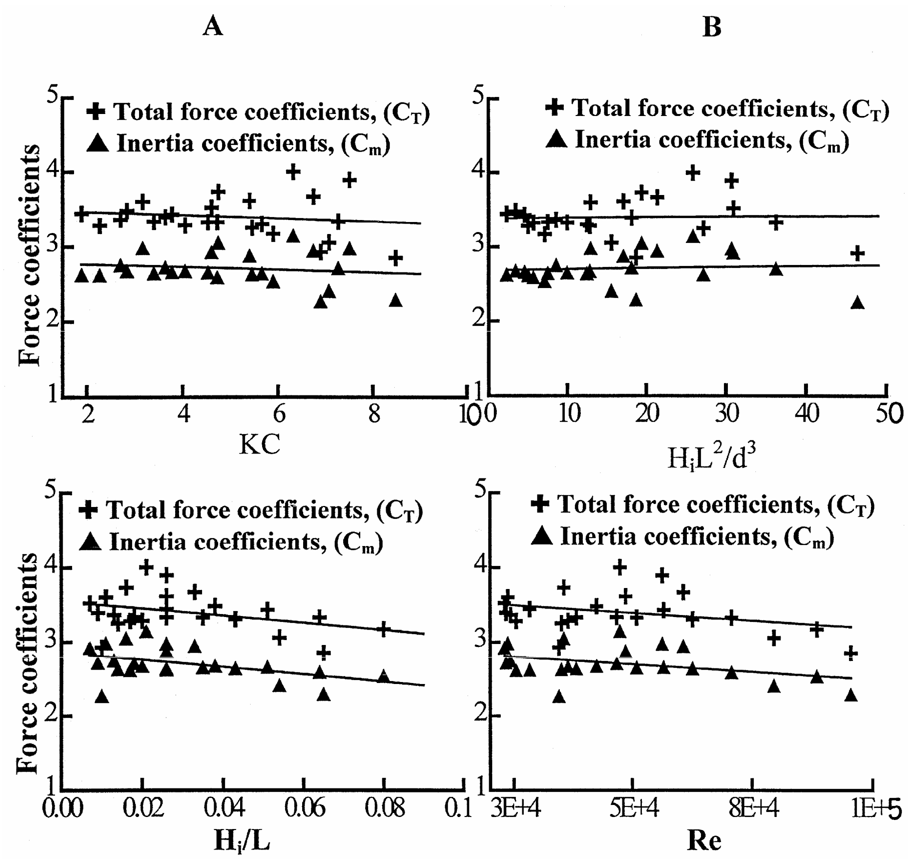

Fig. 2 — Effect of Keulegan-Carpenter number, Ursell parameter, incident wave steepness and Reynolds number on the force coefficients on a vertical cylinder without perforated barrier

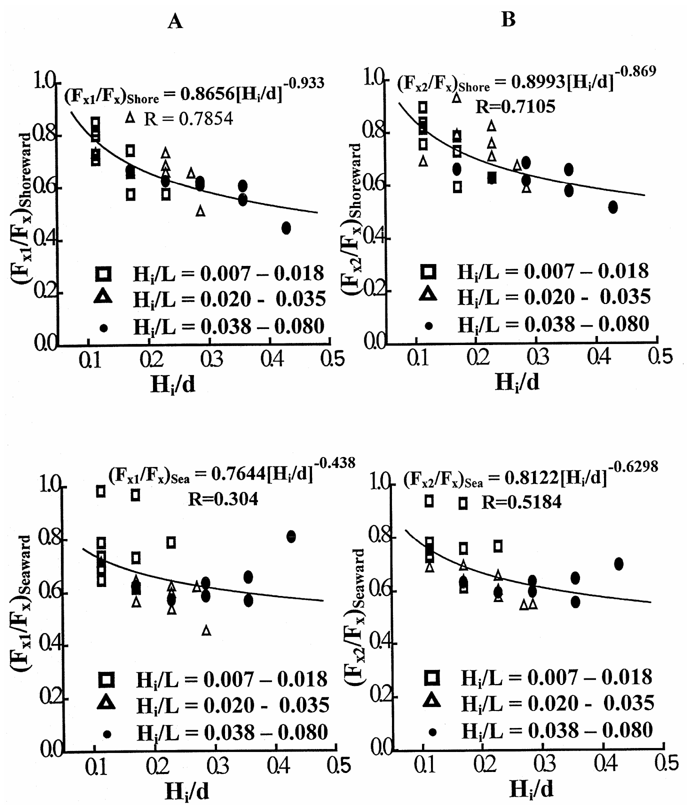

Fig. 3 — Effect of H_i/d on wave force ratio for (A) vertical barrier and (B) inclined barrier.

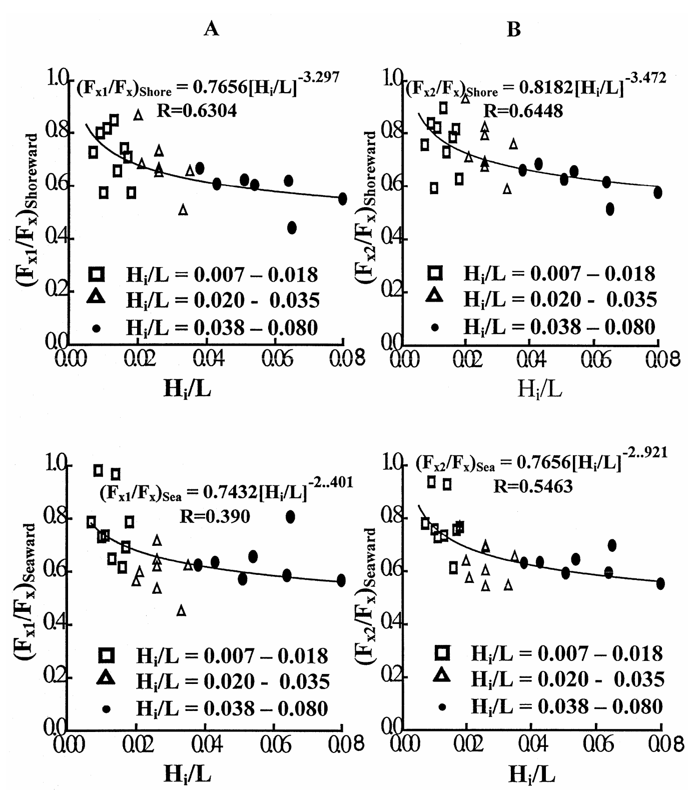

Fig. 4 — Effect of H_i/L on wave force ratio for (A) vertical barrier and (B) inclined barrier.

Forces on the vertical cylinder defensed by the perforated vertical and inclined barrier

First the effects of the important non-dimensional input parameters like H_i/d, H_i/L, D/L and d/L on the force ratios were studied. Based on this study, it is found that the most important predictor parameter is H_i/d and the inclusion of rest of the non-dimensional input parameters are found to be not effective significantly in the reliability of the prediction of the force ratios.

The effect of the relative wave height, H_i/d on the force ratios, F_{x1}/F_x and F_{x2}/F_x is presented in Fig. 3A and 3B. The effect of relative wave height directly indicates the effect of wave height for a constant water depth in the present investigation. The force ratio was found reducing with the increase in H_i /d values. The reason for this is more dissipation of energy by the perforated barriers with increased wave height. Increased wave height means increased velocity of the flow through the pores of perforated barriers. Increase in velocity through pores results in increase of energy loss, which is proportional to the square of the flow velocity. The wave attenuating mechanisms in these porous structures are energy loss in partial breaking, viscous damping, jet mixing, disruptions of orbital motions and out-of-phase relationships between the water surfaces lee-side and sea-side of the perforated barrier. These losses are expected to dominate, when the incident wave height is high. This reducing trend of wave force ratio with increase of H_i/d is very favorable for the design, because the structural design is governed by high values of H_i/d. The force ratio (shoreward) reduced from 0.88 to 0.45 for vertical barrier case and was found reducing from 0.92 to 0.50 for the case of sloped barrier protection. Similarly, the seaward force ratio varied from 0.97 to 0.45 for the vertical barrier and from 0.92 to 0.55 for sloped barrier case respectively. Overall, it is seen that a vertical and sloped barrier of 12% porosity was capable of reducing the force on the vertical cylinder resting on

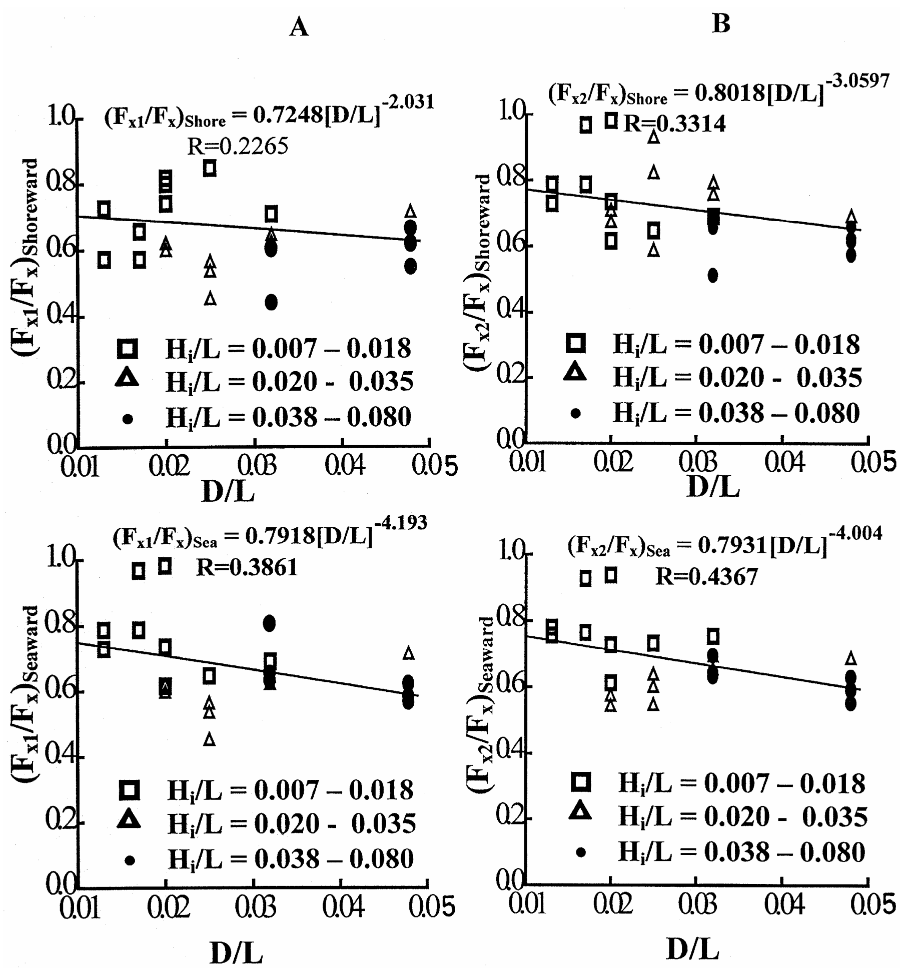

Fig. 5 — Effect of D/L on wave force ratio for (A) vertical barrier and (B) inclined barrier.

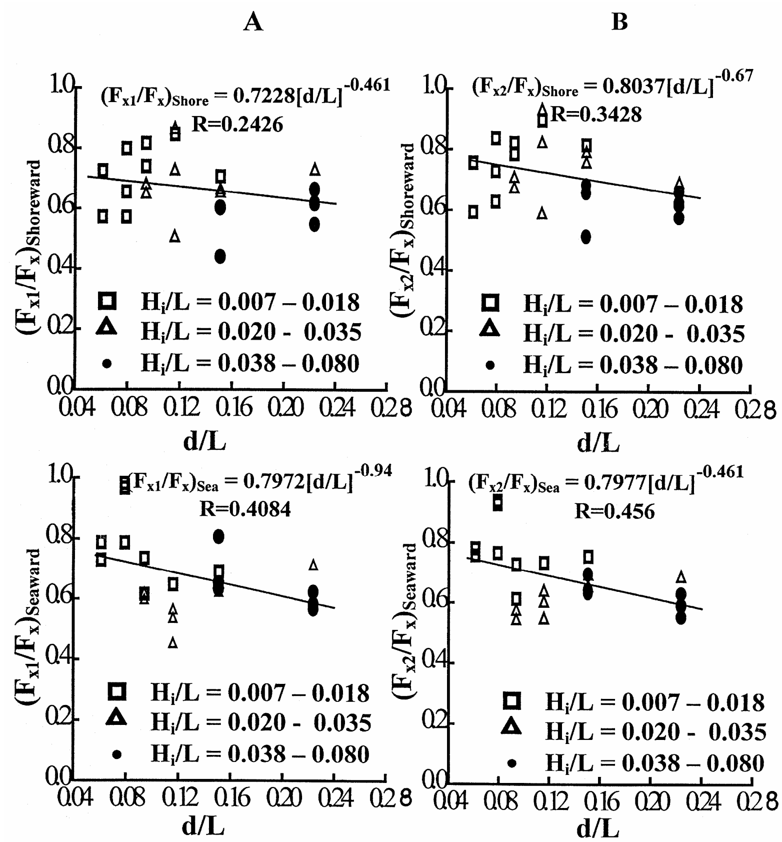

Fig. 6—Effect of d/L on wave force ratio for (A) vertical barrier and (B) inclined barrier.

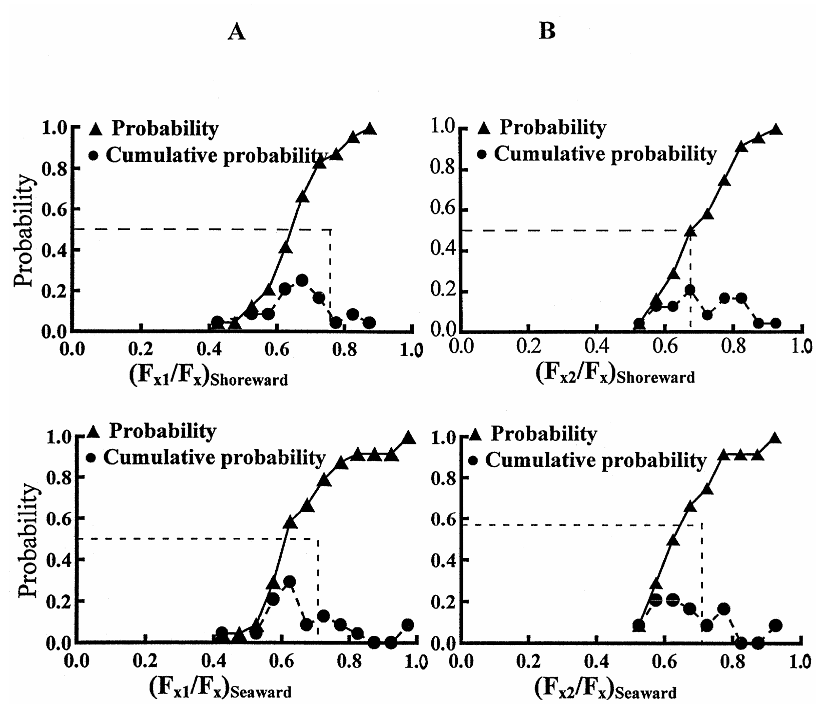

Fig. 7—Probability and Cumulative probability of force ratio of (A) vertical barrier and (B) inclined barrier.

Table 1 — Probablity information of wave force ratio on vertical pile

Description	Average value	Standard deviation	Median	Mode
Vertical barrier and shoreward force	0.67	0.10	0.64	0.68
Vertical barrier and seaward force	0.67	0.13	0.61	0.63
Inclined barrier and shoreward force	0.71	0.11	0.68	0.68
Inclined barrier and seaward force	0.68	0.11	0.63	0.62

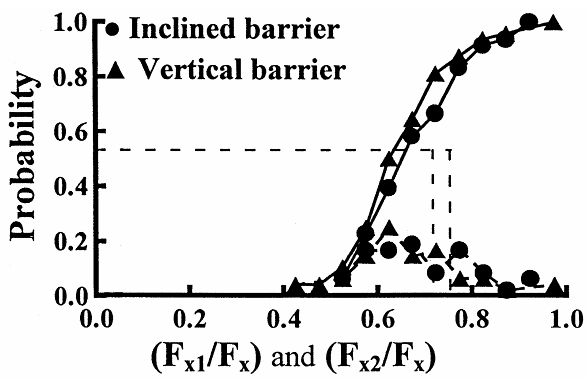

Fig. 8 — Combined probability and cumulative probability of shoreward and seaward force ratio for (▲) vertical barrier and (●) inclined barrier.

the lee-side to an average extent of about 35% and 30% respectively. This is encouraging and the results can be used for estimating the force reduction required on partly damaged vertical piles from the point of protecting them from further direct wave loading.

The effect of incident wave steepness on the force ratios is given in Fig.4A for the pile protected by vertical porous barrier and in Fig.4B for the pile protected with inclined porous barrier respectively. The trend of variation of force ratio with increased wave steepness is similar to Fig.3A and 3B. It can be confirmed that the force ratio is minimum (of the order of 0.5 to 0.6) when steeper waves (wave steepness of the order of 0.06 and above) are acting on the structure. This is an encouraging result since the design is for steeper wave action only. It is to be noted that for normal wave action (wave steepness up to 0.04), the force ratio is about 0.7 to 0.8. The predictive equations for force ratios are also included in this plot by incorporating the wave steepness as predictor parameter.

The effect of D/L on F_{x1}/F_x and F_{x2}/F_x is presented in Fig. 5A for the pile protected by vertical porous barrier and in Fig. 5B for the pile protected with inclined porous barrier respectively. In general the force ratio is showing a mild reducing trend, but the scattering of points is very significant about the trend line. This clearly indicates that it is not worth including D/L as a parameter in the predictive equation.

The effect of relative water depth, d/L on F_{x1}/F_x and F_{x2}/F_x is presented in Fig. 6A for the pile protected by vertical porous barrier and in Fig. 6B for the pile protected with inclined porous barrier respectively. In general, the force ratio is showing a mild reducing trend, similar to Fig. 5A and B. The scattering of force ratio points is significant about the trend line. Hence, it can be concluded that it is not worth including d/L as a parameter in the predictive equation.

Predictive formulae for the wave force ratios on the vertical cylinder

Multiple Regression Analysis (MRA) was carried out on the measured average maximum shoreward and seaward forces. The basic MRA with H_i/d, H_i/L, D/L and d/L as independent variables and force ratios as the depedent variables shows that the influence of relative wave height, H_i/d and H_i/L is significant when compared to that of D/L and d/L. The regression coefficient of the predictive equation is better with H_i/D compared to H_i/L. The prediction is better for shoreward force ratio compared to seaward force ratio.

Statistical analysis of wave force ratio

Statistical analysis was carried out to find the probability, p and cumulative probability, P of the force ratios. Figure 7A shows the probability density and cumulative probability (or probability of non-exceedence) of wave force ratios for both shoreward and seaward forces and for vertical barrier case and Fig. 7B shows the probability and cumulative probability for inclined barrier cases. It is found that for the case of vertical cylinder protected by vertical barrier, the probability of shoreward and seaward force ratio peaks (mode) at 0.68 and 0.63 respectively. The probability of the shoreward force for the case of vertical cylinder protected by inclined barrier does not have a single peak. One peak is obtained around 0.68 and other one is around 0.8. However the probability of seaward force ratio peaks at 0.62. The median value of the shoreward force ratio is 0.64 and the seaward force ratio is 0.61 (Fig. 7A). Similarly, the median value for the seaward force for cylinder and sloped barrier system (Fig. 7B) is 0.68 and the median value of the seaward force ratio is 0.63. These statistical informations are required for decision making in the design.

The shoreward and seaward force ratios are combined (average shoreward and seaward force ratios are used) and the probability and the corresponding cumulative probability are given in Fig. 8. The cumulative probability of the vertical cylinder protected by vertical perforated barrier has an edge over inclined barrier. For example, for the case of vertical barrier, 80% of the measured force ratio did not exceed 0.7. Whereas for the case of inclined barrier, only 70% of the force ratio values did not exceed 0.7. The details of the probability analysis is given in Table 1.

Overall it was observed that the vertical perforated barrier is better in reducing the wave force on the cylinder, when compared to the sloping barrier of the same porosity. The disadvantage of this structure is that it should be designed for large wave force. In the present study, only one porosity is considered. A study on the performance of the barriers with different porosities and angle of inclinations are needed.

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