

Wave loads on open sea mooring dolphin with vertical cylinders due to regular waves

*S. Neelamani

Coastal Engineering and Air Pollution Dept, Environmental and Urban Development Division,
Kuwait Institute for Scientific Research, P.O. Box : 24885, 13109 Safat, Kuwait

and

Cheduluri R Chandra Rao & S. Narasimha Rao

Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai – 600 036, India

*[E-mail: nsubram@kisir.edu.kw / sneel@iitm.ac.in]

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Mooring dolphin is one of the components of open sea marine terminal. A thorough knowledge on wave forces on this mooring dolphin is essential for its design. Experimental investigations were carried out on wave loads on an open sea mooring dolphin with vertical slender cylinders and deck in 0.60 m water depth. The deck slab was placed at nine different elevations above and below the still water level (emerged and submerged conditions) to study the effect of deck elevation on wave loads on mooring dolphin due to regular waves. A study on single cylinder is also carried out to compare the forces on mooring dolphin with the forces on single cylinder. Wave force on single cylinder can be calculated by using Morison equation. There is no theoretical method to calculate wave forces on slender cylinders with deck, especially when the deck is in submerged condition. It is found that the in-line and transverse forces are more when the bottom of deck slab is exactly at still water level and reduce significantly when it is submerged or emerged. Mooring dolphin receives maximum slamming force when the deck is in submerged condition.

[**Key words**: Deck slab, in-line force, mooring dolphin, slamming pressure, transverse force, vertical slamming force]

Many harbours around the world are congested due to increase in traffic flow. The demand for liquid cargoes like crude oil, Naphtha, LNG, LPG, ammonia etc are increasing steadily. Liquid cargoes can be handled by using open sea marine terminals during fair to moderate weather windows (Ex: in east coast of India, the wave heights are less than 1 m for about 250 days per year). A typical open sea marine terminal consists of pile supported structures like approach trestle, jetty head, berthing dolphins and mooring dolphins. An open sea mooring dolphin consists of circular members that are connected together in various planes. Mooring dolphin is normally designed for mooring forces, if it is situated inside the harbour. For the case of open sea mooring dolphin, the severe loads due to waves may dictate the design. During severe sea state, the marine terminal experiences extremely high environmental loading from the gravity waves, which is not studied systematically. In order to achieve a safe and economic design of the open sea mooring dolphin, the wave forces and slamming pressures on the bottom of deck slab should be evaluated. The deck slab of mooring dolphin may be submerged during high tidal

variation and severe cyclone conditions. It is important to select the appropriate air gap (vertical distance between the still water level, SWL and bottom of deck slab) to avoid severe wave slamming loads. Theoretical estimation of wave loads on mooring dolphins is cumbersome, especially when the deck is exposed and submerged. Therefore, the present work was carried out to investigate wave forces (in-line, transverse and slamming forces) and slamming pressures on mooring dolphin with a deck slab and nine vertical slender cylinders arranged in a square pattern for different relative deck levels covering complete immersion of the deck in water and exposure to air.

Many researchers around the World have investigated the hydrodynamics of fluid flow phenomena around the slender and large cylinders¹⁻⁹. The wave hydrodynamics of pile groups are not fully understood because of the complex nature of the flow around the pile groups and variation of phase. From the available literature¹⁻⁹ there is not much work carried out in the field of wave-induced forces on group of slender cylinders with deck used as an open sea mooring dolphin. Hence, there is a definite need

for a detailed investigation of hydrodynamic forces on group of slender cylinders with deck slab. Wave force measurements were carried out on open sea mooring dolphin with nine vertical cylinders in a square pattern under regular waves. The main objectives of the present study are,

- ◆ To measure the wave-induced forces (In-line, Transverse and Slamming forces) and slamming pressure on Open Sea mooring dolphin with 9 vertical cylinders and with different deck elevations and with constant water depth due to regular waves.
- ◆ To examine the effect of deck elevation of mooring dolphin on wave forces and slamming pressure.
- ◆ To measure the wave forces on a single cylinder for comparing the wave loads on mooring dolphin with different deck elevations.
- ◆ To study all the above referred parameters for regular waves of different combinations of wave height, wave period and for constant water depth.

Material and Methods

Mooring dolphin was fabricated with 63 mm PVC pipes and 10 mm thick PVC sheets at a model scale of 1:20. Nine PVC pipes were fixed to 0.60 m × 0.60 m × 0.010 m size bottom plate. 14 mm holes were drilled in bottom plate for fixing the model with six component force balance plates and 5 mm holes were drilled in pipes at 5 cm interval to place the deck slab at different elevations. Deck slab of size 0.60 m × 0.60 m × 0.10 m was made with 10 mm thick PVC sheets.

The present experimental investigations were carried out in a 30 m long, 2.0 m wide and 1.7 m deep wave flume. Piston type wave maker provided at one end of 2 m wave flume was used for generation of waves. The wave height and period to be generated are controlled by a personal computer. The other end of the flume is provided with a rubble mound absorber to effectively absorb the incident waves. The details of the flume, position of the model and the wave gauge used to register the wave elevations near the model are shown in Fig. 1.

The parameters measured were wave forces and pressures acting on the mooring dolphin model of 1:20 scale under the action of regular waves. The mooring dolphin model is fitted to six components force balance provided in the 2 m pit available at the flume bottom. The schematic diagram of experimental setup is shown in Fig. 2. The force balance is capable of measuring six components of forces (X , Y_1 , Y_2 , Z_1 ,

Z_2 and Z_3). The range of X , Y_1 and Y_2 force transducers are ± 200 kgf and for Z_1 , Z_2 and Z_3 are ± 800 kgf. The force balance measures the forces using strain gauge measuring principles. The change in the strain of the strain gauge fixed on steel rods are converted into change in voltages and recorded. The force balance is designed and fabricated for measurement of wave induced forces on ocean structure models by HBM, Germany. In-line, transverse, vertical slamming force and the corresponding moments were calculated from the six components of forces measured. Pressure transducer of 0.5 bar capacity was fixed at the bottom of the deck slab for measuring the slamming pressure on deck slab. The pressure transducers (P11 type) are diaphragm type (HBM, Germany) for measuring the underwater dynamic pressure variations. The displacement of the diaphragm due to the dynamic pressure variation is transferred by a LVDT housed inside the pressure cell housing and this signal is converted into voltages for the purpose of recording. The model is placed at the centre of the force balance

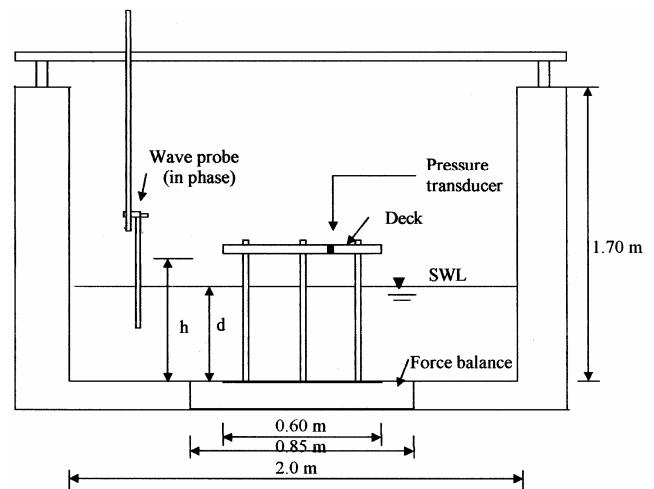


Fig. 1 — Cross sectional details of wave flume, positions of mooring dolphin model and wave probes (Not to scale)

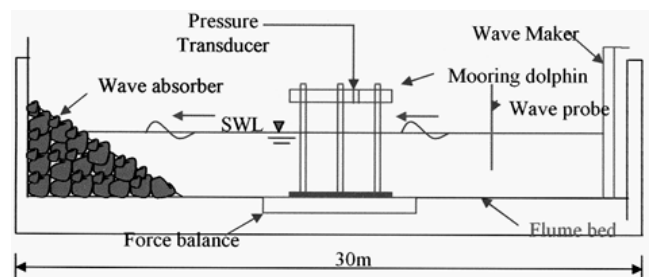


Fig. 2 — Longitudinal section of 2 m Wave flume with mooring dolphin model

plate and subjected to the action of regular waves with wave height, H ranging from 0.05 m to 0.25 m with an interval of 0.05 m. For each wave height, eleven wave periods, T ranging from 1.0 sec to 3.0 sec with an interval of 0.2 sec was used. Experiments were done at a constant water depth of 0.60 m and for nine different deck elevations. The deck slab was placed at nine different elevations (h=0.40 m to 0.80 m with an increments of 0.05 m) by putting nails in the holes drilled in pipes. Tests were carried out for nine different conditions based on the position of deck slab with reference to the flume bed:

- a. Deck submerged (4 conditions) (h/d<1)
- b. Deck bottom at SWL (h/d=1)
- c. Deck emerged (4 conditions) (h/d > 1)

where ‘h’ is the vertical distance between bottom of deck slab and flume bed and ‘d’ is the local water depth. The wave forces and moments were computed from the six components of forces measured by using the following formulae:

In-line force, $F_x = X$
 Transverse force, $F_y = Y_1 + Y_2$
 Vertical slamming force, $F_z = Z_1 + Z_2 + Z_3$
 In-line moment, $M_x = (Z_3 - Z_1 - Z_2) * B/2$
 Transverse Moment, $M_y = (Z_2 - Z_1) * B/2$
 Moment about vertical axis, $M_z = (Y_1 - Y_2) * A/2$

where A=800 mm and B=900 mm
 A=center to center distance of Y₁ and Y₂ force transducers
 B=center to center distance of Z₁ (or Z₂) and Z₃ force transducers

The range of normalised parameter obtained for regular waves are given in Table 1.

For uncertainty analysis the measurements were carried out using 12 bit data acquisition card and the measuring range is -10 volts to + 10 volts. The uncertainty of the measured parameters is as follows:

- Wave height : 0.1%
- Wave pressures : 0.2%
- Wave forces : 0.5%

Table 1 — Range of normalised parameters obtained

Parameter	Range
Wave steepness, H/L	0.01 - 0.18
Relative water depth, d/L	0.086-0.390
Relative deck level, h/d	0.667 –1.333
Wave height ratio, H/d	0.167-0.333

Results and Discussion

Maximum wave force and pressure values were obtained by using threshold-crossing analysis for regular waves. WS4 software package [Danish Hydraulic Institute, Denmark] was used to perform the time domain analysis. The wave forces and pressures are normalized by using appropriate input parameters.

Wave forces on mooring dolphin

In the field, the mooring dolphin has to cross different water depths, wave height and periods. It is essential to understand the effect of these parameters on wave forces on open sea mooring dolphin for safe and economic design.

In-line force

From the investigation with single vertical cylinder, it is found that the average value of force coefficient $F_x (s)/(\rho g H D d)$ is 0.80 and the standard deviation is 0.2. The maximum value is 1.4. This information is required for force estimation on mooring dolphin.

Effect of relative deck level, h/d on the in-line force ratio

The effect of variation of relative deck level, h/d on the in-line force ratio ($F_x (md)/F_x (s)$) for two relative water depths, d/L=0.390 and 0.086 and for relative wave height (H/d) of 0.250 is shown in Fig. 3. Here, ‘F_x (md)’ and ‘F_x (s)’ are the maximum in-line forces

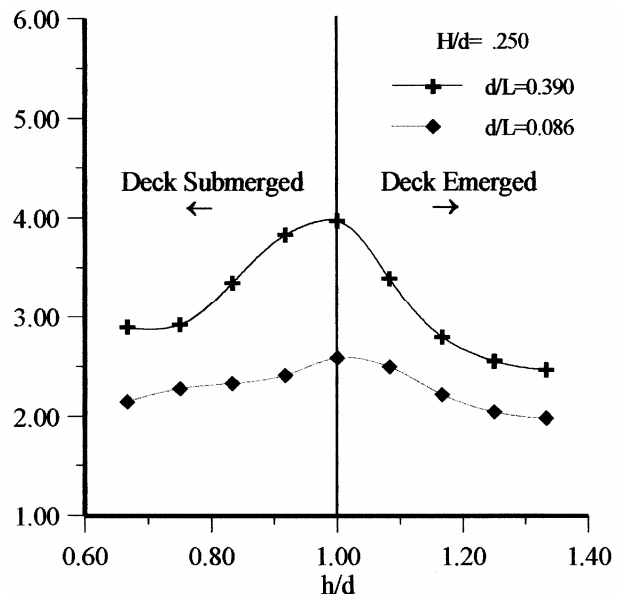


Fig. 3 — Variation of in-line force ratio with relative deck levels (h/d) for two different relative water depths (d/L)

on mooring dolphin and single cylinder respectively. It is seen that the maximum value of the force ratio is about 4.0 and reduced significantly when the deck slab is submerged or emerged. It was also observed that mooring dolphin receives more in-line force ratio when the bottom of deck is at still water level. This increase in force is due to more blockages to moving fluid. The deck may get submerged during strong surges combined with high tide levels. If the mooring dolphin is designed for $h/d=1.0$, it will be safe for other submerged and emerged conditions.

Effect of relative water depth, d/L on the in-line force ratio

The effect of relative water depth, (d/L) on in-line force ratio $[F_x(\text{md})/F_x(\text{s})]$ for three different h/d values is shown in Fig. 4 for relative wave height H/d of 0.250. The increase in relative water depth, d/L from 0.086 to 0.390 has resulted in increase of the in-line force ratios. Here again, it is found that the force ratio is consistently maximum for $h/d=1.0$. For $h/d=1.0$, the force ratio varies from 2.5 to 3.8 when d/L is varied from 0.086 to 0.390. In general short waves offer more wave force on the open sea mooring dolphin. Similar trends were obtained, when the tests were carried out with different wave height and wave period conditions.

Effect of wave steepness, H/L on the in-line force ratio

The effect of wave steepness on the in-line force ratio on the mooring dolphin with three different deck

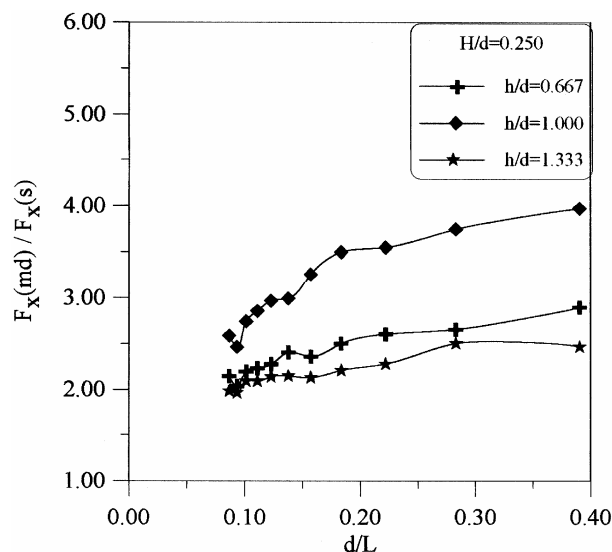


Fig. 4 — Variation of in-line force ratio with relative water depth for three different relative deck levels (h/d)

levels and for relative water depth (d/L) of 0.086 (Fig. 5) shows that there is an increase in the in-line force ratio with increase in wave steepness (H/L). An increase in H/L from 0.012 to 0.060 has resulted in an increase of wave force ratio from 2.0 to 3.5 for $h/d=1.0$. It is a critical condition from design point of view.

Transverse force

Transverse force on mooring dolphin is due to unsymmetrical vortex or eddy shedding formed around the cylinders during wave action. It acts in the direction perpendicular to the wave motion and the pile axis. Transverse force on the mooring dolphin can be estimated when the transverse force ratio is known. The maximum value of normalised transverse force on the single cylinder is found to be about 0.28 and the average value is only about 0.1. The standard deviation of the transverse force ratio $F_y(\text{s})/\rho g H d$ is about 0.02. These informations are required to estimate the transverse forces on the open sea mooring dolphin.

Effect of relative dock level on transverse force ratio

The variation of transverse force ratio $[F_y(\text{md})/F_y(\text{s})]$ with relative deck level, h/d for two different relative water depths ($d/L=0.390$ and 0.086) and for H/d of 0.250 is shown in Fig. 6. Here ' $F_y(\text{md})$ ' is the transverse force on the mooring dolphin and ' $F_y(\text{s})$ ' is the transverse force on the single cylinder. The transverse force ratio reduced significantly when the deck slab of mooring dolphin is either submerged or

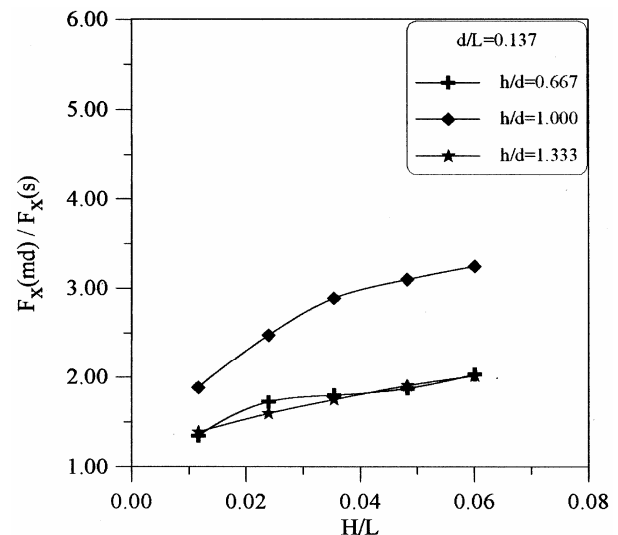


Fig. 5 — Variation of in-line force ratio with wave steepness (H/L) for three different relative deck levels (h/d)

emerged (i.e, h/d is less than or greater than 1). The mooring dolphin receives the highest transverse force when the bottom of deck is at still water level. The maximum value of transverse force ratio is 4.5.

Effect of relative water depth on transverse force ratio

The variation of transverse force ratio $[F_y(\text{md})/F_y(\text{s})]$ with relative water depth, d/L for three different relative deck levels ($h/d=0.667, 1.0$ and 1.333) and for relative wave height, H/d of 0.250 is shown in Fig. 7. Transverse force ratio increased with increase in relative water depth from 0.086 to 0.390 . As seen in

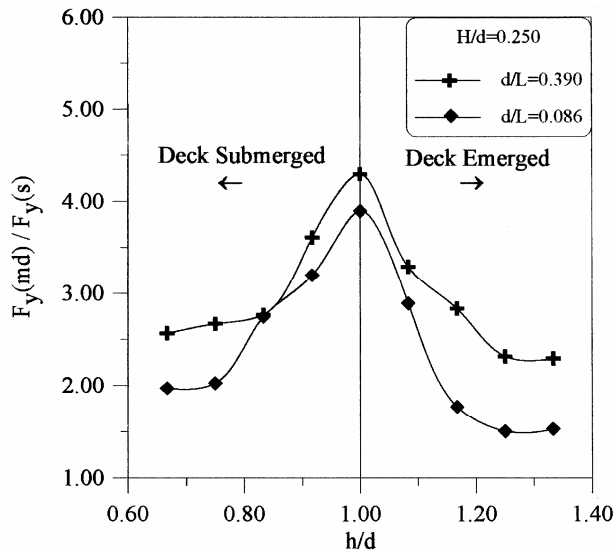


Fig. 6— Variation of transverse force ratio with relative deck levels (h/d) for two different relative water depths (d/L)

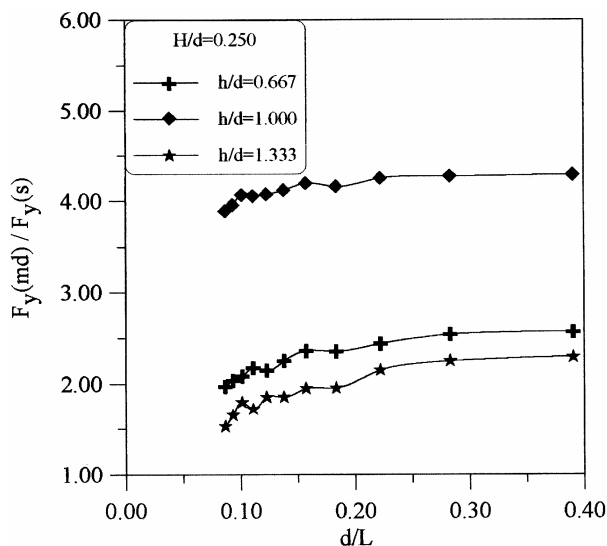


Fig. 7— Variation of transverse force ratio with relative water depth (d/L) for three different relative deck levels (h/d)

the earlier plots, deck bottom at still water level ($h/d=1.0$) is the critical case.

Effect of wave steepness in transverse force ratio

The variation of transverse force ratio $[F_y(\text{md})/F_y(\text{s})]$ with wave steepness, H/L for three different relative deck levels and for relative water depth, d/L of 0.086 is shown in Fig. 8. Transverse force ratio increased with increase in wave steepness from 0.012 to 0.060 . The maximum transverse force ratio of 4.3 occurred when the wave steepness is 0.060 .

Slamming force

Slamming force is the force acting on the deck of the mooring dolphin in vertical direction due to the water surface fluctuations around the deck slab of the mooring dolphin. Slamming force is normalized with $(\rho g a H/2)$, where ‘ ρ ’ is density of water, ‘ g ’ is acceleration due to gravity, ‘ a ’ is the plan area of deck slab and ‘ H ’ is the incident wave height. Normalized slamming force was plotted against different parameters like relative deck level (h/d), relative water depth (d/L) and wave steepness (H/L).

Effect of relative deck level on normalized slamming force

The variation of normalized slamming force $[F_z / (\rho g a H/2)]$ with relative deck levels (h/d) for two different relative water depths and for relative wave height, H/d of 0.250 is shown in Fig. 9. The normalized slamming force is less when the bottom of deck touches the still water level ($h/d=1.0$) compared to other deck conditions. It is due to the fact that the

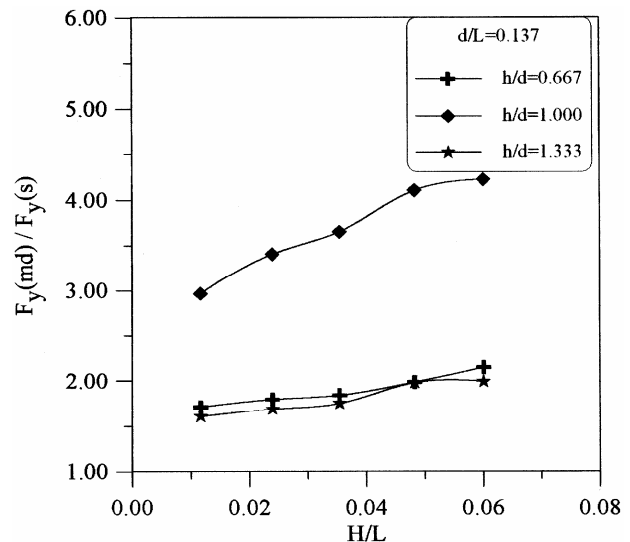


Fig. 8— Variation of transverse force ratio with wave steepness (H/L) for three different relative deck levels (h/d)

water mass moving above the deck slab imparts downward force and reduces the resultant upward loading. It is also observed that the normalized slamming force is more when the deck is in submerged condition. The normalized slamming force is minimum for exposed condition.

The effect of relative water depth on normalized slamming force

The effect of relative water depth on normalized slamming force $[F_z / (\rho g a H / 2)]$ for three different relative deck levels ($h/d=0.667, 1.000$ and 1.333) and for H/d of 0.250 is shown in Fig. 10. The normalized

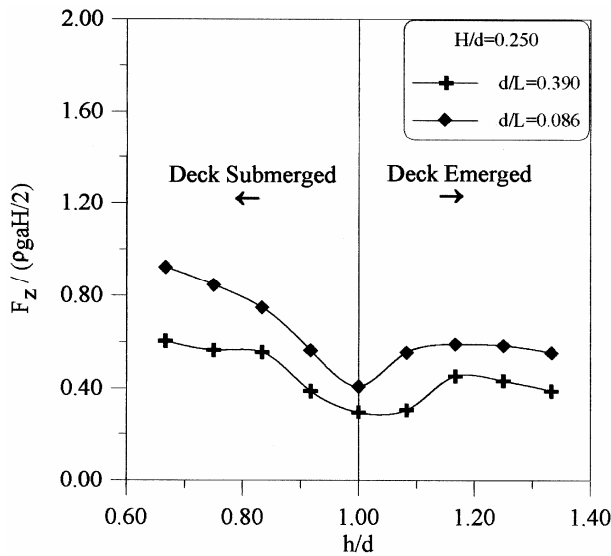


Fig. 9— Variation of normalized slamming force with relative deck levels (h/d) for two different relative water depths (d/L)

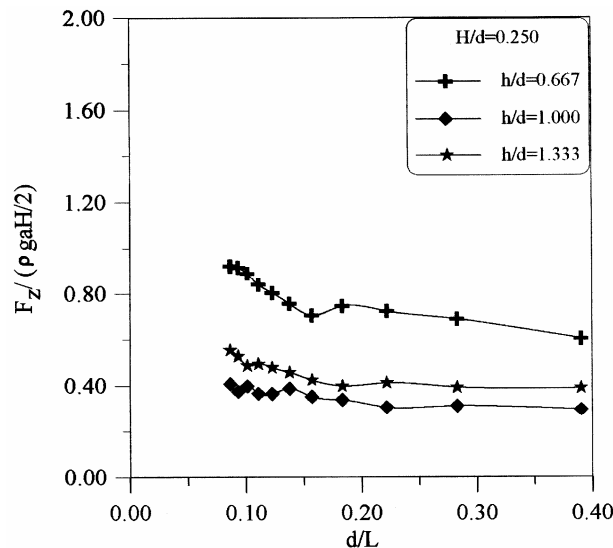


Fig. 10— Variation of normalized slamming force with relative water depth (d/L) for three different relative deck levels (h/d)

slamming force is found decreased with increase in relative water depth, d/L from 0.086 to 0.390 . The normalized slamming force is maximum for $h/d=0.667$. Relatively long wave offers high value of normalized slamming force.

Effect of wave steepness on normalized slamming force

The variation of normalized slamming force on the deck of mooring dolphin with wave steepness for three different deck levels and relative wave height, H/d of 0.250 is shown in Fig. 11. The plot that the normalized slamming force has increased with increase of wave steepness, the increment is noticeable for $h/d=0.667$ compared to other two cases.

Slamming pressure

Slamming pressure on the bottom of the deck slab was measured by using ± 1 bar capacity pressure transducer. The upward pressure is due to the hammering effect of water when the wave crest is acting on the deck slab. Slamming pressure is normalized with $\rho g H / 2$ where ' ρ ' is density of water, ' g ' is acceleration due to gravity and ' H ' is incident wave height.

Effect of relative deck level on normalized slamming pressure

The effect of relative deck level on normalized slamming pressure ($P/(\rho g H / 2)$) for two different relative water depths (d/L) and for relative wave heights (H/d) of 0.250 is shown in Fig. 12. The plot

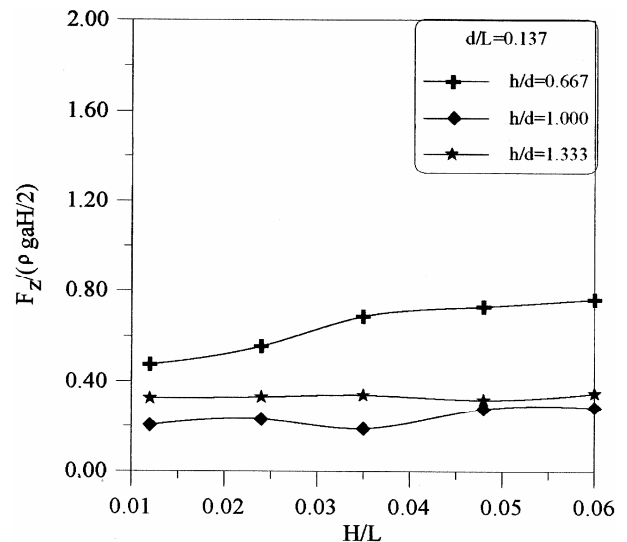


Fig. 11— Variation of normalized slamming force with wave steepness (H/L) for three different relative deck levels (h/d)

that the deck of the mooring dolphin receives more slamming pressure when its bottom at still water level and the normalized slamming pressure decreased with increase in relative water depth from 0.086 to 0.390. Slamming pressure was reduced when the deck is placed above or below still water level. The maximum value of the normalized slamming pressure is about 1.2.

Effect of relative water depth on normalized slamming pressure

The variation of normalized slamming pressure with relative water depth for two different relative deck levels ($h/d=0.667$ and 1.000) and for H/d of 0.250 is shown in Fig. 13. It is observed that the normalized slamming pressure decreased with increase in relative water depth, d/L from 0.390 to 0.086 . It is due to the fact that long period waves are more powerful than the short period waves.

Effect of wave steepness on normalized slamming pressure

The effect of variation of wave steepness on the normalized slamming pressure on the deck of mooring dolphin for three different deck levels and relative water depth, d/L of 0.137 is shown in Fig. 14. The normalized slamming pressure increased with increase of wave steepness. It is also seen that the normalized slamming pressure decreased when the deck of the mooring dolphin is above or below still water level.

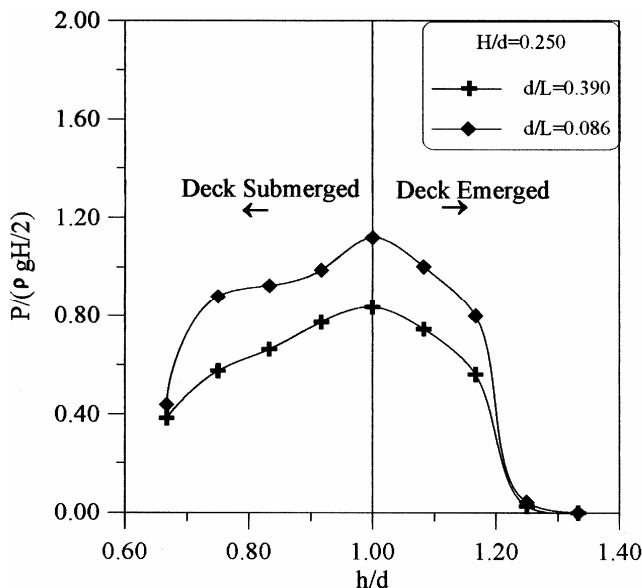


Fig. 12 — Variation of normalized slamming pressure with relative deck levels (h/d) for two different relative water depths (d/L)

Cross correlation analysis

A cross correlation of two events occurring at the same time is essential to understand their phase information in detail. This gives a picture of the variation of the correlation between different events like in-line force, transverse force and slamming force. It is achieved by using the correlation coefficient (C_c), which is defined as

$$c_c = \rho_{xy} = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sigma_x \sigma_y} \dots (4.1)$$

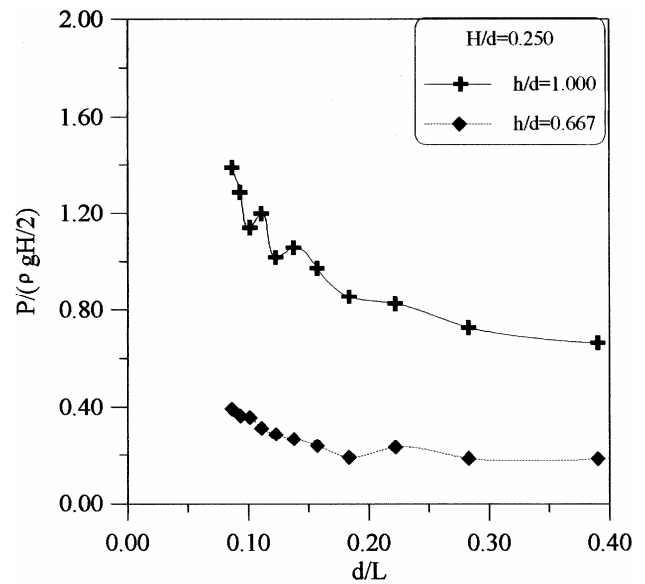


Fig. 13 — Variation of normalized slamming pressure with relative water depth (d/L) for two different relative deck levels (h/d)

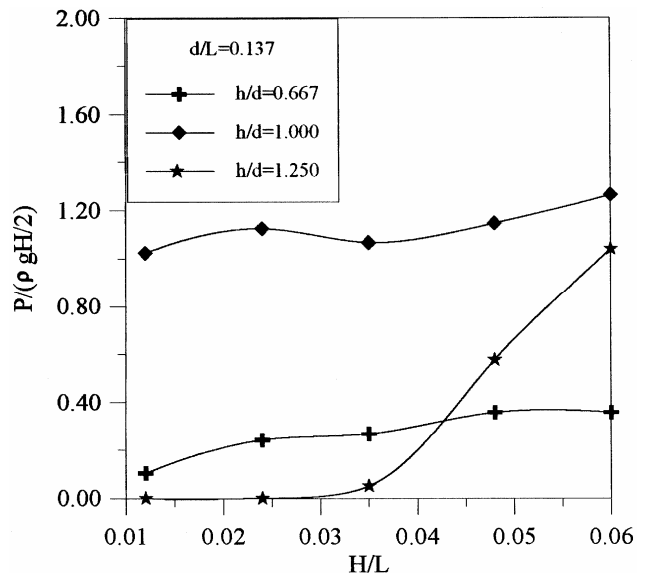


Fig. 14 — Variation of normalized slamming pressure with wave steepness (H/L) for three different relative deck levels (h/d)

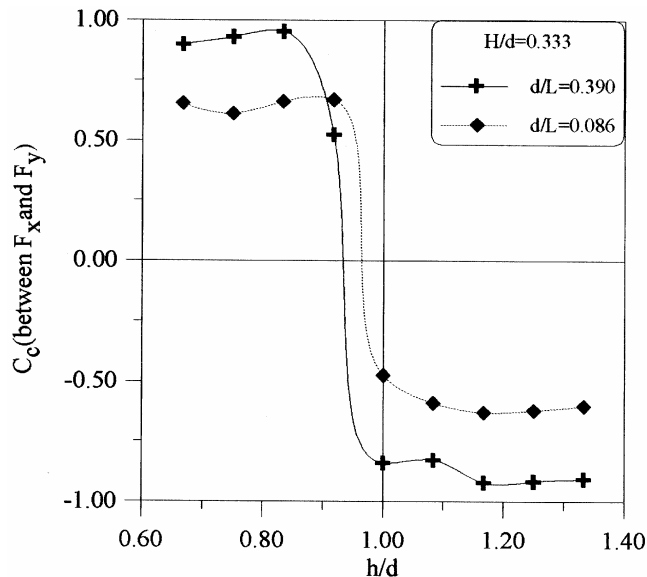


Fig. 15— Variation of coefficient of correlation (C_c) between in-line and transverse forces as a function of relative deck levels (h/d) for two different relative water depths

where x and y are the measured variable (events); \bar{x} and \bar{y} are the mean and σ_x and σ_y are the standard deviations of x and y respectively. The coefficient of correlation (C_c) generally ranges from -1 and $+1$. If the value is $+1$, the events are absolutely in phase with each other. C_c value of -1 indicates that the events are completely out of phase. For any value of C_c between -1 and $+1$, the average phase difference between two events can be understood.

Coefficient of correlation between in-line and transverse force

Cross correlation analysis was carried out between the in-line force (F_x) and transverse forces (F_y). The variation of cross correlation coefficient is presented against relative deck level for two relative water depths, d/L of 0.390 and 0.086 and H/d of 0.333 as shown in Fig. 15. It is seen that the correlation coefficient between in-line and transverse forces is close to $+1$ when the deck is submerged and close to -1 when the deck is emerged. These two forces are in the same phase when the deck is submerged and out of phase when it is emerged. The resultant force due to in-line and transverse forces dictate the design when the deck is submerged.

Correlation coefficient between in-line and slamming forces

The effect of relative deck level on cross correlation coefficient between in-line force (F_x) and slamming force (F_z) is presented for two different

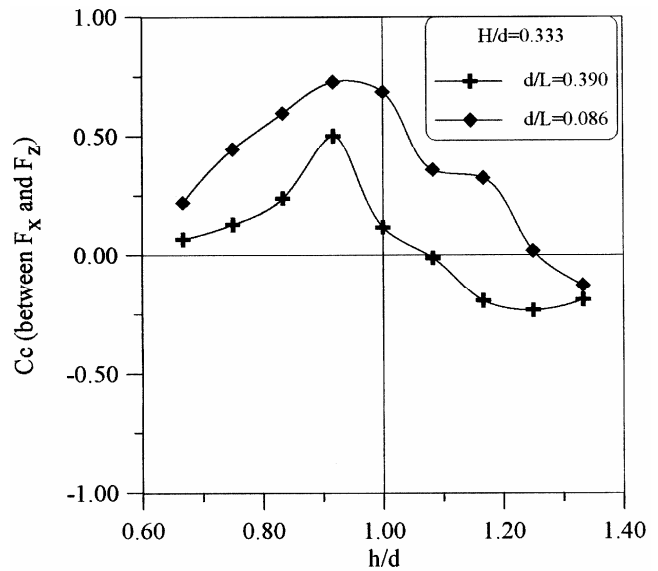


Fig. 16— Variation of coefficient of correlation (C_c) between in-line and vertical forces as a function of relative deck levels (h/d) for two different relative water depths

relative water depths, d/L and for relative wave height, H/d of 0.333 in Fig. 16. The in-line and slamming forces are almost in phase when the deck is just submerged (relative deck level (h/d) just less than 1). It is a critical deck condition from design point of view. The net tensile load on the seaside row of piles will be higher compared to the back row of piles when the deck is in submerged condition due to the simultaneous action of in-line and vertical forces. This understanding is necessary for designing the pile diameter and depth of penetration in the soil strata.

Conclusion

A comprehensive investigation on the wave forces and slamming pressures due to regular waves on a mooring dolphin with 9 vertical piles and with a deck slab at different elevations were carried out using physical model studies. The mooring dolphin is subjected to maximum in-line and transverse forces and minimum vertical forces when the deck slab bottom is at mean water level. Increase in relative wave height (H/d) causes increase in the in-line, transverse force ratio and normalized vertical force. Increase in relative water depth (d/L) increases the in-line and transverse force ratios and decrease in normalized vertical force. In-line, transverse and slamming forces occur simultaneously (since cross correlation coefficient is closer to 1.0) especially when the deck is just submerged. This situation is very critical and the designer should take this point into account for safe design.

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Nomenclature

- A = Plan area of deck slab
 C_D = Coefficient of Drag
 C_M = Coefficient of Inertia
 C_c = Coefficient of correlation
d = Depth of water
D = Diameter of the cylinder
d/L = Relative water depth
 F_x = n-line wave force
 F_y = Transverse wave force
 F_z = Vertical slamming force
g = Acceleration due to gravity
h = Vertical distance between bottom of deck slab and flume bottom
h/d = Relative deck level
H = Wave height
H/d = Relative wave height
H/L = Incident wave steepness
KC = Keulegan-Carpenter Number
L = Local wave length
P = Slamming pressure on the bottom of the deck slab
Re = Reynolds number
 ρ = Mass density of water
 γ = Specific weight of water