Conference Paper, Published Version

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Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.
2 - 5 August 2010

ROLE OF ELASTICITY ON FORCES AND DEFLECTIONS OF A SUBMERGED ELASTIC PLATE IN WAVES

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Abstract: *Experimental investigations were carried out to study the forces and deformations of a submerged elastic plate subjected to regular waves. The wave forces and the deflections of the submerged elastic plate were investigated experimentally for a range rigidity of the plate, in order to understand the influence of rigidity on the wave- structure interaction process. The studies indicate that the plate with lower rigidity experiences lower force and as the depth of submergence increases the force decreases. Deflections are almost similar in both sides of the plate with respect to the longitudinal axis of the plate. The results indicate that, elastic plates with suitable rigidity may have beneficial effects to floating and offshore systems. Also, the experimental results would be helpful in understanding the fluid-structure interaction process as a function wave and structure parameters.*

Keywords: *Elasticity; forces; deflections; submerged plate.*

INTRODUCTION

Fluid structure interaction problems have been of common interest for a long time because of their engineering applications. The hydrodynamic forces exerted on rigid and elastic plate immersed in water are a problem of interest to naval architects as well as ocean engineers. Many researchers have investigated the submerged horizontal plate using either theoretical approach or model study. The presence of the plate reduces the lower part of the wave motion (Yueh, 1987). It was also found that a reduction in wave lengths, as well as wave heights in the region behind the plate was possible. Also, this kind of structure does not hinder the water exchange between the open sea and the protected area nor the view over the open sea. So, such a plate could be used as a wave filter for controlling the wave motion. The basic mechanism and physics of the flow around the plate would give a better idea on the cost effective design. But the flow around the plate is complex because of the presence of both unsteady flow and oscillatory motion.

Patarapanich (1984) studied the behavior of the thin plate subjected to waves. It was found that the vertical force and moment generally decrease with increasing d'/d and d/L ratios. The magnitude of horizontal force has been shown to be negligibly low because of the small

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thickness of the plate. Yamamoto et al (1995) investigated the feasibility of an oscillating fin propulsion control system as a vehicle actuator. It was concluded that the research outcomes can be widely applied to the propulsion system of various vehicles, such as ships, underwater vehicles, artificial fishes, and several types of robots. Such system is especially useful for an actuator of a quiet cruising demanded area, a slow speed cruising area, and a hovering area.

Most of the researchers have investigated by treating horizontal rigid plate as a wave absorber/ controller. There are very few researchers treated the plate as a hydrofoil or oscillating foil. Freymuth (1990) conducted experiments on a small airfoil which is operated in combined harmonic plunging and pitching motions to generate thrust in a still air environment. It has been shown that an airfoil in generic hovering can produce large thrust coefficients by full utilization of dynamic stall vortices for thrust generation. Read et al (2003) conducted an experiment on an oscillating foil to access its performance in producing large forces for propulsion and effective maneuvering. Experiments on a harmonically heaving and pitching foil were performed to determine its propulsion efficiency under conditions of significant thrust production, as function of the principal parameters: heave amplitude, strouhal number, angle of attack, and phase angle between heave and pitch.

The literature review reveals that the studies pertaining to the performance characteristics of a submerged elastic plate to the action of water waves are scarce. The purpose of this research is to investigate the interaction of 2D regular waves with the submerged elastic plate using wave flume experiments. In order to understand the influence of elasticity on motion control, tests were conducted on plates with different rigidity. A comprehensive experimental program, in order to cover a range of wave parameters and structural parameters are involved in this study.

EXPERIMENTAL INVESTIGATIONS

The wave flume experiments have been conducted to study the performance of the elastic and rigid plate for intermediate to deep-water conditions. Dimensional analysis was carried out before the experimental program and the same is presented herein. The dimensional analysis and details of wave flume studies are presented below.

Dimensional Analysis

In order to determine the non-dimensional parameters for the hydrodynamic investigations, a dimensional analysis was carried out using Buckingham's π theorem. The vertical force and horizontal forces of a rigid submerged horizontal plate can be expressed in terms of the following independent variables. Based on the non-dimensional analysis, vertical force, horizontal force and deflection is given by

$$\begin{bmatrix} F_V \\ F_H \\ \delta \end{bmatrix} = f\left(\frac{B}{L}, \frac{H}{L}, \frac{d'}{d}, \frac{d}{L}, \frac{RB}{\rho g (HLd')^2}\right) \quad (1)$$

Where,

$\frac{B}{L}$ = Relative plate width; $\frac{H}{L}$ = Wave steepness; $\frac{d}{L}$ = Relative water depth; $\frac{d'}{d}$ = Submergence ratio; $\frac{RB}{\rho g (HLd')^2}$ = Wave-structure parameter;

Test facility

The experimental investigations were carried out in a *30m* long, *2.0m* wide, and *1.7m* deep wave flume in the Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai. The details of the flume, position of the model and the wave gauges used to measure the wave elevations in front and rear of the model are shown in Figure.1.

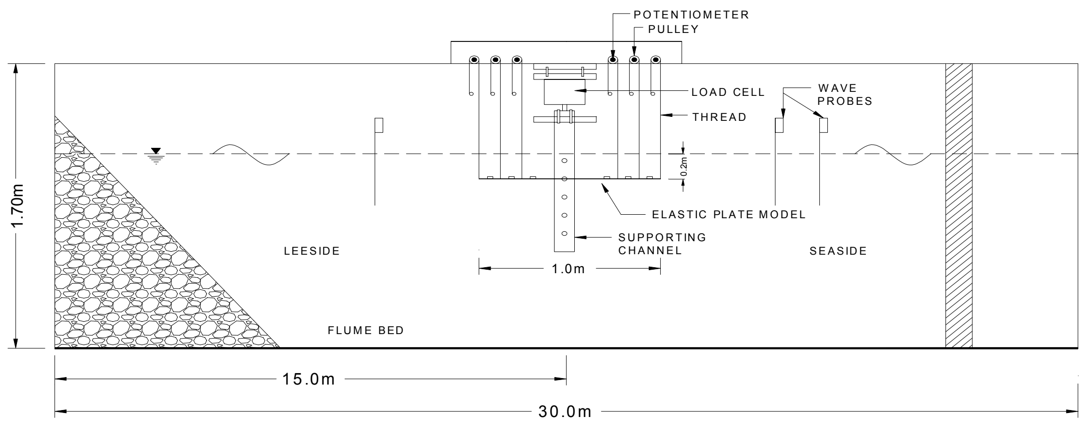

Fig.1. View of the model in the wave flume

A computer controlled piston type wave maker installed at one end of the flume is capable of generating regular waves of different heights and frequencies as well as random waves of pre-defined spectral characteristics. The other end of the flume is provided with a rubble mound. A constant water depth of 1m was chosen for the present study. The model was placed at a distance of 15m from the wave maker.

Instrumentation

For the present physical model study, a piston type wave-generator is used since a coastal wave climate is to be simulated. This wave generator can generate both regular and random wave trains through a servo actuator. One personal computer is connected to a servo actuator, for providing inputs such as wave height and wave period to the wave generator and also used for data acquisition of the signals from the wave probes, potentiometer and load cells through an amplifier. The water surface elevation is measured using wave probes. Two-component load cell was used to measure the vertical and horizontal forces. The load cell can measure the vertical force in the range of ± 500N and the horizontal force of ± 100N. The calibration was done for each set of experiments to minimize the errors in the experiments.

Details of the model

The submerged elastic plate models are made up of polymer sheets of size 1600 mm x 1000 mm x 1.5 mm stiffened all around by the aluminum flat of size 30 mm x 3 mm using bolts and nuts to make it horizontal. The submerged rigid plate model is made up of acrylic material with 1600mm x 1000mm x 10 mm. The plate model is kept across the wave flume which is supported by two channel sections on both sides of the plate that are hanging from the platform, which is placed on top of the wave flume. The model is hinged at the centre and allowed to hang from the top in such a way that the depth of the immersion can be varied by its support. The supporting channel ISMC 100 has five holes at one side. Each hole is spaced at a distance of 100mm. These supporting frames hanged from the load cells at both sides which are connected by bolts and base plates. The base plate is connected to the frame which is kept across the flume.

Experimental procedure

A series of tests were carried out by varying the depth of submergence of the plate (d') for different wave periods with different wave heights. The details of the non-dimensional parameters used in the present study are listed in Table 1. The plate model during test is shown in Figure.2.

Table 1.Non-dimensional parameters considered

Parameters	Range
Submergence ratio $\left(\frac{d'}{d}\right)$	0.10 – 0.40
Plate width to wave length ratio $\left[\frac{B}{L}\right]$	0.192 -1
Relative water depth $\left(\frac{d}{L}\right)$	0.192-1
Wave steepness $\left(\frac{H}{L}\right)$	0.019 - 0.05
Wave-structure parameter $\left(\frac{RB}{\rho g (HLd')^2}\right)$	0.004 - 209.21

Fig.2 Model plate in the wave flume

The depth of submergence was varied from 0.1-0.4m using the supporting channels. Three different wave heights were chosen for the present study. The wave period was varied form 0.8s-2s. For each plate 84 runs were carried out in the wave flume. A total of 336 runs with different rigidity, submergence, wave periods and wave heights were conducted for regular waves. The experiments were carried out for different plates with various rigidity. The plate was fixed horizontally with the particular depth of submergence at a distance of 15m from the wave generator. All the tests were carried out in a water depth of 1m.

RESULTS AND DISCUSSIONS

The plate models as described above were subjected to the action of regular waves, the characteristics of which has been reported earlier. Once the wave maker is started, the time histories of the wave elevation from the wave probes were acquired simultaneously. Typical time history from the vertical and horizontal transducer, potentiometer and the incident wave is shown in the Figure 3(a), 3(b),3(c),3(d) &3(e).

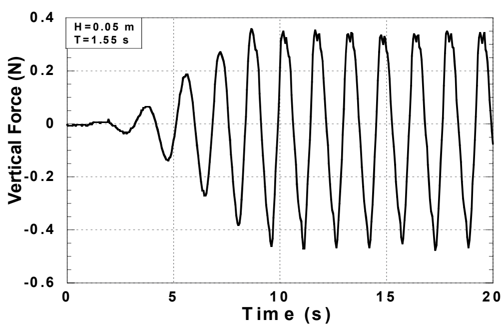

Fig.3(a). Typical response from the vertical transducer of the load cell

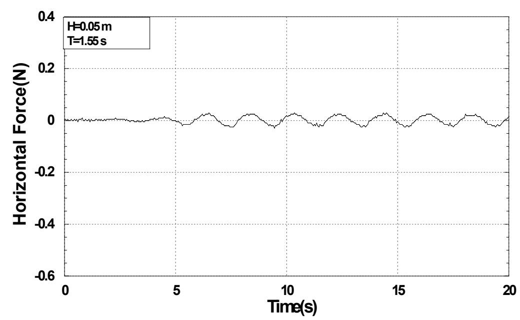

Fig.3(b). Typical response from the horizontal transducer of the load cell

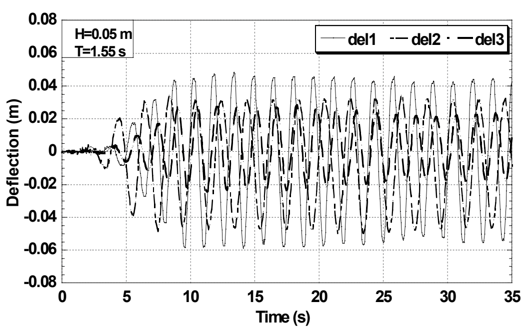

Fig. 3(c). Typical response from the potentiometers in the seaside

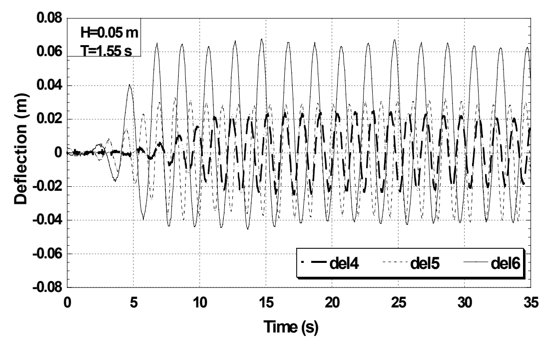

Fig.3 (d). Typical response from the potentiometers in the leeside

The elastic plate was fixed at a submergence depth of 0.1m. A constant water depth of 1m was used for the study. For a particular depth of submergence, the wave height and the wave period were varied and the time histories were recorded.

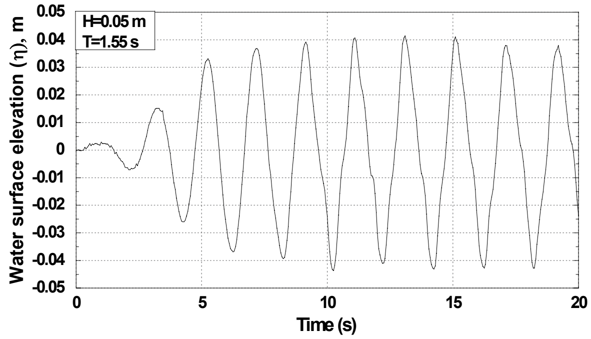

Fig. 3(e). Time series of the incident wave for the elastic plate

Role of elasticity on Vertical and Horizontal forces

Figure.4(a) & 4(b) shows the variation of vertical and horizontal forces with respect to the relative width of the plate (*B/L)* for four different plates. The plate was kept at a submergence of 0.1m and the wave steepness varied from 0.01-0.05. The Acrylic plate with 10mm thickness is considered as a rigid plate and the plate with 1.5 mm thickness is considered as an elastic plate. Plates with different rigidity values were tested in the flume by varying the depth of submergence. The results indicate that the plate with lower rigidity experiences lower force. Vertical and horizontal forces are less for the elastic plates compared to the rigid plate. The plate which is more elastic experiences very less force. Appreciable reduction in vertical forces is obtained for the most elastic plate. The reduction in vertical force is about 15% for B/L =1 and about 30-40% for B/L=0.4. Significant reduction in horizontal forces is obtained for the most elastic plate. The improvement is being about 40-50% for entire range of B/L. It is inferred from the plots that, the vertical force experienced by the elastic plates are nearly 33.33% as that of the force experienced by the rigid plate. And, the horizontal force experienced by the elastic plates is nearly 25% as that of the force experienced by the rigid plate. The elasticity in the plate has significantly improved the performance of the horizontal barrier in the lower B/L region where the rigid plate is not effective.

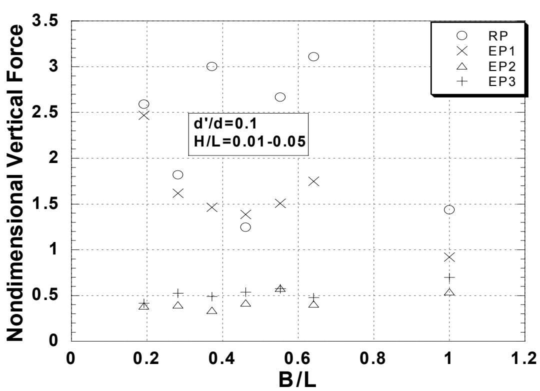

Fig.4(a) Non-dimensional vertical force four different plates with respect to B/L

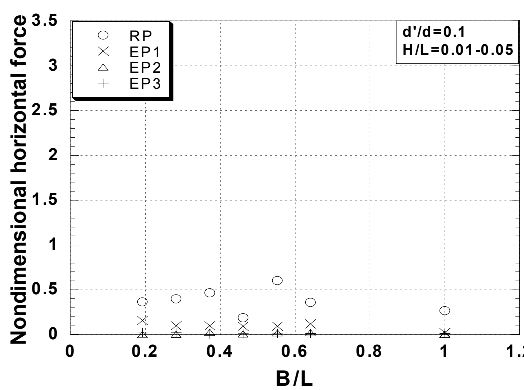

Fig.4(b).Non-dimensional horizontal force for four different plates with respect to B/L

Influence of depth of submergence (d'/d) on Vertical and Horizontal forces

During the wave flume experiments, the depth of submergence has been varied from 0.1m – 0.4m. The tests were repeated for the four different plates to study the effect of depth of submergence. The variation of vertical and horizontal forces for four different water depths with *B/L* ratio for a rigid plate and elastic plate are shown below. Figure.5(a) & 5(b) shows the variation of vertical and horizontal forces with *B/L* for a rigid plate for the range of d/L considered. Maximum vertical and horizontal forces are obtained when the plate is at 0.1m submergence.

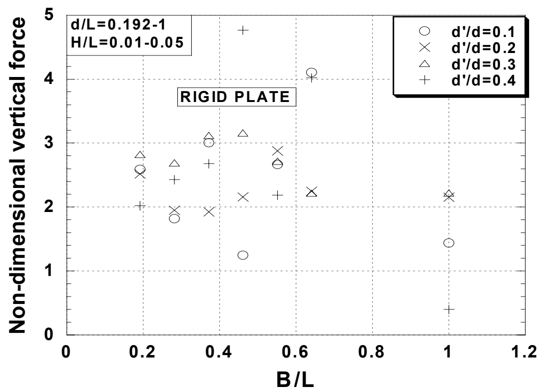

Fig.5(a).Non-dimensional vertical force for four different depths with B/L for rigid plate

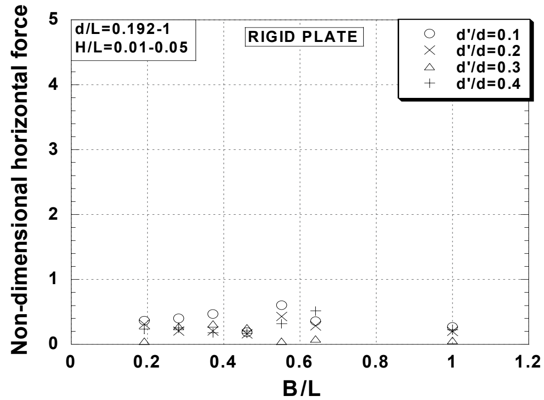

Fig.5(b). Non-dimensional horizontal force for four different depths with B/L for rigid plate

Figure.6 (a) & 6(b) shows the variation vertical and horizontal forces for most elastic plate (EP3). It is inferred from the plot that the vertical fore decreases with the increase in depth of submergence.The vertical and horizontal forces decrease with the increase in the depth of submergence. The reduction in vertical force is nearly 30-40% for the polyethylene plate (EP3).

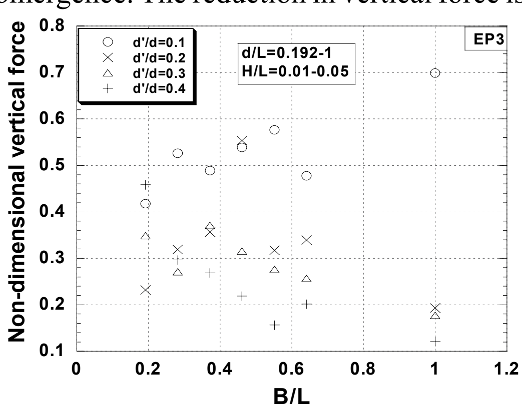

Fig.6(a) Non-dimensional vertical force for four different depths with B/L for elastic plate

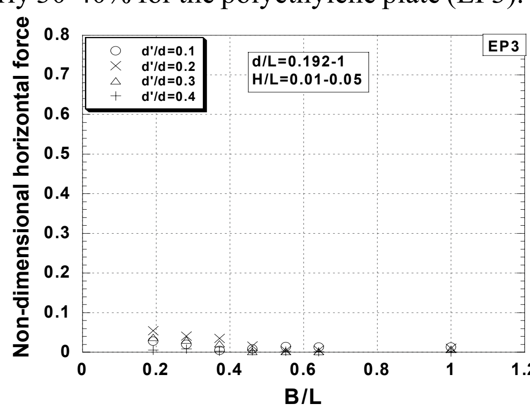

Fig.6 (b). Non-dimensional horizontal force for four different depths with B/L for elastic plate

Effect of wave-structure parameter on vertical and horizontal forces

Figure.7(a) & 7(b) shows the variation of vertical and horizontal forces with wave-structure parameter for four different plates. The plate with 10mm thickness is considered as a rigid plate and the plate with 1.5 mm thickness is considered as an elastic plate. Plates with different rigidity values were tested in the flume by varying the depth of submergence. The plot shows the variation of vertical and horizontal force for four different plates for a particular wave length with respect to wave-structure parameter.

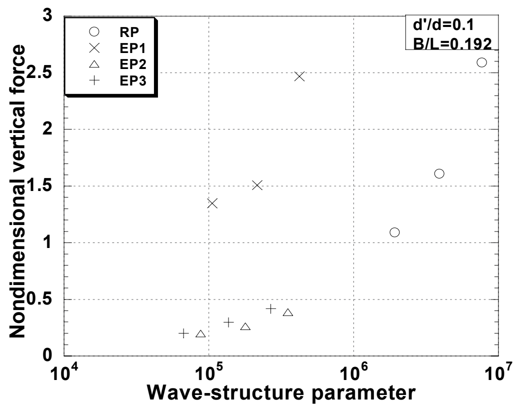

Fig.7(a) Non-dimensional vertical force four different plates with respect to WSP

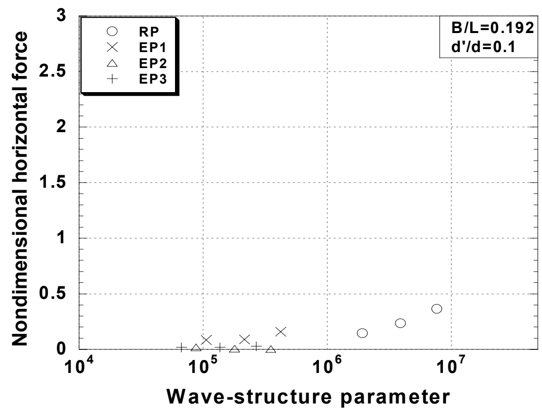

Fig.7(b).Non-dimensional horizontal force for four different plates with respect to WSP

The plates with less wave-structure parameter experience lesser vertical and horizontal force. 25-30% increase in the flexural rigidity causes nearly 30-40% reduction in vertical force and 40-50% reduction in horizontal force.

Influence of depth of submergence on deflection of the plate

Figure.8 (a) & 8(b) shows the variation of deflections (δ1, δ6) of the elastic plate (EP3) with the H/L range of 0.01-0.05 and the submergence ratio of 0.1, 0.2, 0.3 and 0.4 which are on seaside and leeside respectively.

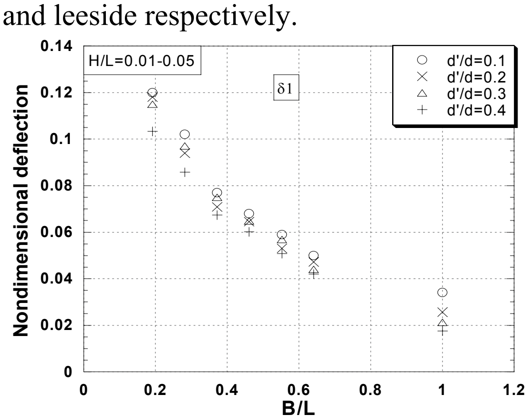

Fig.8(a) Deflection at the seaward edge of the elastic plate (EP3) at with respect to B/L

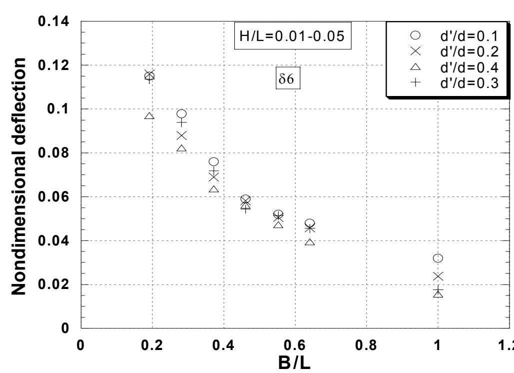

Fig.8 (b). Deflection at the leeward edge of the elastic plate (EP3)at with respect to B/L

It is plotted with respect to the variation of the relative plate width (B/L). It shows the maximum deflection of the plate which is experienced at the edges of the plate. It is inferred from the graph that, the deflections follow the same trend in all the cases. The deflections are almost similar on both sides with respect to the longitudinal axis of the plate. Also, the deflections decrease with increase in the B/L ratio. The deflection is more when the plate is kept at a submergence of 0.1m and the deflection decreases with increase in depth of submergence ratio.

Influence of wave-structure parameter on deflection of the plate

Figure.9 (a) shows the variation of deflection for four different plates with respect to the wave-structure parameter. It was inferred from the graph that, the deflection decreases with increase in the wave-structure parameter. The plate with less rigidity value undergoes more deformation compare to the other plates. Figure.9 (b) shows the deflection at the six different places with respect to wave-structure parameter. When the wave-structure parameter increases, the deflection decreases. Also, the deflections are similar in both sides of the plate with respect to the longitudinal axis of the plate. The rigid plate experiences less deflection and the deflection decreases with increase in the wave-structure parameter value for all the four plates.

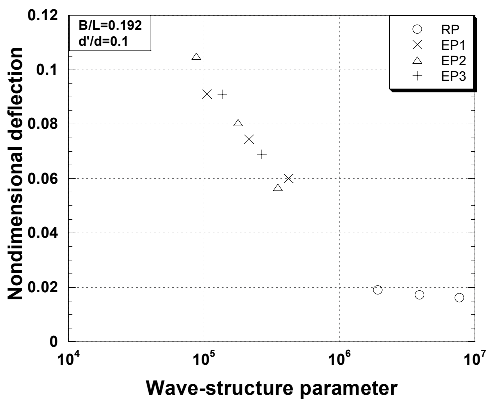

Fig.9 (a). Deflection of four different plates with respect to WSP for a B/L of 0.192

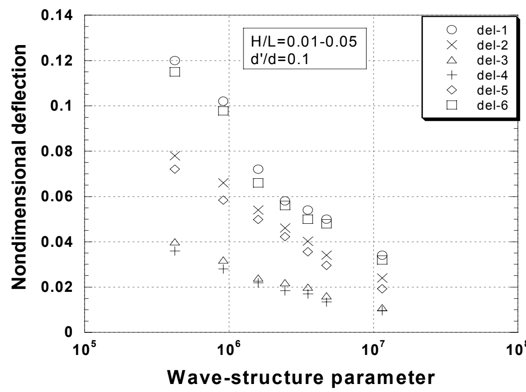

Fig.9(b).Deflection at six different locations for the elastic plate EP3

CONCLUSIONS

Experimental investigation of hydrodynamic forces of rigid and elastic plates in waves was carried out with different depth of submergence. The elasticity in the plate has a favorable effect on the engineering characteristics. Vertical and horizontal forces are less for the elastic plates compared to the rigid plate. The plate which is more elastic experiences very less force. Appreciable reduction in vertical forces is obtained for the most elastic plate. The reduction in vertical force is about 15% for B/L =1 and about 30-40% for B/L=0.4. Significant reduction in horizontal forces is obtained for the most elastic plate. The improvement is being about 40-50% for entire range of B/L. The elasticity in the plate has significantly improved the performance of the horizontal barrier in the lower B/L region where the rigid plate is not effective. The results indicate that the vertical and horizontal forces increase with the increase the wave-structure parameter. The plate with high wave-structure parameter experiences maximum force. Maximum vertical and horizontal forces are obtained when the plate is at 0.1m submergence. The vertical and horizontal forces decrease with the increase in the depth of submergence. 25-30% increase in the flexural rigidity causes nearly 30-40% reduction in vertical force and 40-50% reduction in horizontal force. Hence, it is inferred the elasticity in the plate has significantly improved the performance of the horizontal barrier in the lower *B/L* region where the rigid plate is not effective.

Nomenclature

B	Breadth of the plate
B/L	Plate width to wave length ratio
d	Water depth
d'	Depth of submergence
d'/d	Submergence ratio
d/L	Relative water depth
F	Force
F_x	Horizontal force
F_y	Vertical force
G	Acceleration due to gravity
H	Wave height
H/L	Wave steepness
L	Wave Length
PE	Polyethylene plate
PP-1	Polypropylene plate with more stiffeners
PP-2	Polypropylene plate with fewer stiffeners
R	Relative Rigidity
T	Wave period
t	Thickness of the plate
ρ	Density of water

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