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Wave Interaction With Floating Wave Energy Caisson Breakwaters

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ABSTRACT

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Fixed oscillating water column (OWC) wave energy caisson is one of the promising devices for the extraction of power from ocean waves. But, however this device is not suitable for larger tidal variation, as the high tide results in excessive reflection of wave energy and low tide affects the efficiency. Fixed wave energy caisson will be very expensive in deeper waters and hence floating devices can be adopted. In the present work, an attempt is made to investigate the hydrodynamic characters like pneumatic efficiency, wave transmission, reflection and losses, dynamic response of the device and mooring forces of the OWC wave energy caisson in the moored condition under tidal effects, especially in deep water conditions. For the present experimental study, a 1:20 scale model of 6415 Ton displacement prototype OWC wave energy caisson was tested for three damping conditions at three different water depths (To represent the tidal effects) for a mooring configuration with six mooring lines for a scope of 4 under different wave climate. The experiments were carried out for the wave periods from 1 sec to 3.0 sec for three different wave heights of 0.05m, 0.075m and 0.1m. It is found that the tidal variation of about 10% to 15% of the water depth does not change the pneumatic efficiency significantly, unlike fixed OWC device. Increase in tidal level by 10% to 15% of water depth is found to increase the wave transmission by about 15% and reduces the reflection by about 15%. The salient results of this study can be used in the design of floating OWC devices for wave power conversion and as a floating breakwater in a tide and wave dominating sea.

ADDITIONAL INDEX WORDS: *Floating breakwaters, oscillating water column, pneumatic efficiency, wave transmission, reflection, dynamic response and mooring forces.*

INTRODUCTION

Energy is the key to industrial development and for the promotion of economic and social well being of the world population. The growth of world population, coupled with the rising material standard of living has escalated the growth of energy usage since the turn of this century. It took millions of years for the earth to fertilize and to store fossil fuels in convenient forms, but it takes only 300 or 400 years to use them up by the human being. The rapid depletion of fossil-fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources to meet out demands for immediate future and for generations to come. Of the many alternatives, ocean energy stands out as the brightest long-range promises toward meeting the continually increasing demand for energy. Considerable developments have taken place in the last decade or so in the field of wave energy. Out of numerous concepts which has been tested and designed, extraction of wave energy using the oscillating water column (OWC) principle is found to be the most promising. The OWC wave energy converter is a well-established means of extracting useful energy from water waves. It consists of a chamber with two orifices. One is open to the sea below the water lever and other is typically at the top of the chamber where the air turbine is mounted. Due to the action of waves on the device, an oscillating water column is formed in the chamber, which in turn forces air thus driving the air turbine. The rotary motion of the air turbine is transferred to a generator to generate electricity.

A combination of the wave power converter working on OWC principle and the caisson type breakwater is attractive as the construction cost for power generation can be jointly shared with the following facilities:

1. Breakwater cum berthing facility
2. Coastal protection against erosion
3. Calm water basin for cage culture.

Bottom standing caisson type OWC devices are alright for water depths of 8.0 to 10.0 m. But they will become prohibitively expensive for deeper waters, say 20.0 to 25.0 m. Here floating wave energy devices can be a financially viable option. Intercepting the waves in deeper water is also better, since the available wave power is higher in deeper water than that in shallow water due to loss of wave energy during wave propagation by breaking, bottom friction and percolation. Floating wave energy device is expected to attract lesser force since a part of the incident wave power is finally converted as electric power. Floating breakwater also has some of its inherent merits and demerits. The merits are: Free water circulation between the sea side and lee side is possible and lee side pollutant dispersion will be better. Fish migration between sea side and lee side is easy. Any type of foundation can be used. Since the floating structure rides over the wave, the forces and pressures will be less than that on a fixed structure. The floating wave energy device can be optimally oriented to take care of the seasonal wave directions, which is not possible in the bottom fixed devices. The demerits are that the floating breakwater is not efficient to prevent wave transmission like bottom standing breakwater, especially for long waves. Berthing of vessels at the rear side is restricted due to the wave energy transmission. Apart from all the merits listed above, floating moored OWC caisson has a major advantage compared to bottom standing OWC device. The bottom standing OWC device can be used in places where the tidal variations are less than say 0.5 m. If tidal variations are higher say more than 1.0 m, then it will affect the average pneumatic efficiency significantly. This is because, during high tide, more of the incident wave energy will be reflected and during the low tide, the air pressure inside the OWC chamber will be equal to the atmospheric pressure most of the time due to the exposure of the bottom of the lip wall and hence pneumatic efficiency will be very less. Floating moored caissons will raise and fall in the vertical direction along with the tide and hence this major technical problem is solved. However the effect of the tidal

Table 1. *Particulars of the Device.*

Description	Symbol	Unit	Model
Length	L	mm	1800
Breadth	B	mm	990
Height	H	mm	650
Draft	T	mm	450
Mass	M	kg	779
Centre of gravity above base	KG	mm	299
Transverse metacentric height	GM_T	mm	161.5
Radius of gyration for rolling	k_{xx}	mm	322
Distance between keel to			
Centre of buoyancy	KB	mm	225
Natural period in heave	T_z	sec	2.077
Natural period in roll	T	sec	1.763
Mooring chain			
Material	Steel		
Type	Open		
Proof Load	W_P	kg	13.04
Breaking Load	W_B	kg	18.26
Weight per meter	W_c/m	kg	0.1115

variation on pneumatic efficiency, wave transmission, reflection, loss of power, dynamic response and mooring forces are not known. This is the motivation for the present work.

LITERATURE REVIEW

For many years, scientists and engineers have been constantly working to develop an effective device for the utilization of ocean-wave energy. A variety of wave-energy extraction devices have been invented mainly in Japan, the UK, the USA, Norway, Portugal, Ireland and India. Reviews of much of this research are available in ELLIOT (1981), SHAW (1982), COUNT *et al*. (1983) and CARMICHAEL and FALNES (1992). The development of Multi-resonant oscillating water column from OWC, introduced by AMBLI *et al*. (1982) showed that the device is capable of absorbing incident wave energy effectively for a wide band width of wave frequency which

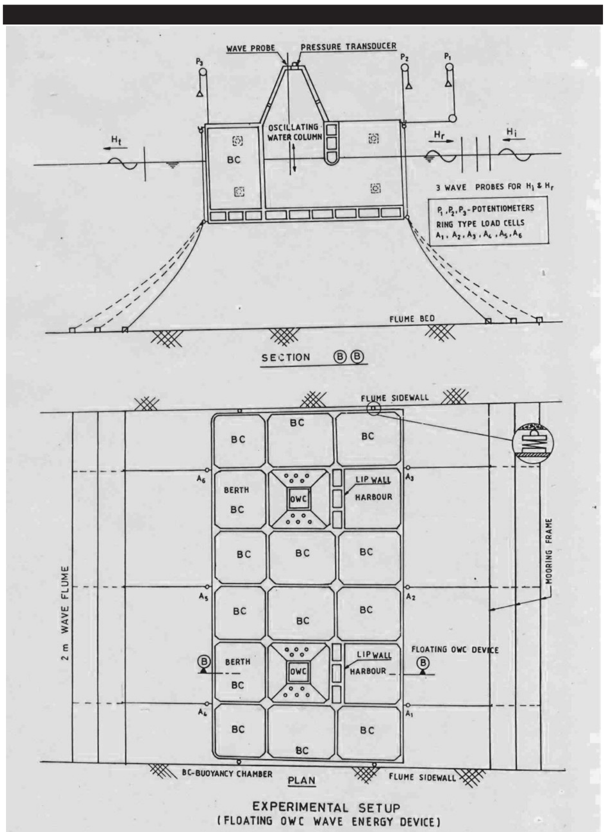

Figure1.Experimental setup of Floating wave energy device model.

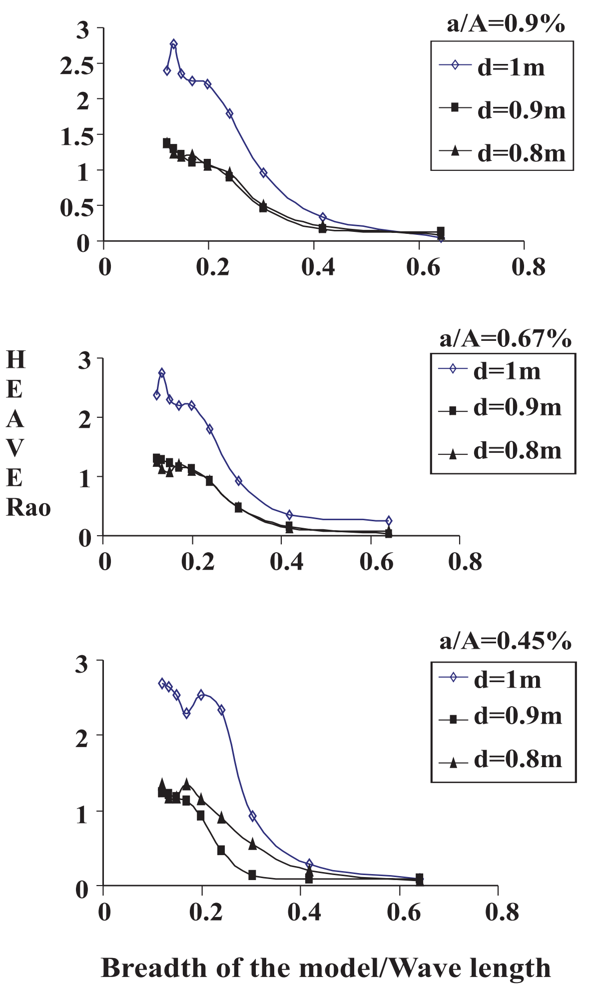

Figure 2. Heave RAO (H= 0.1m).

results in a more cost effective system. JAYAKUMAR (1994), THIRUVENKATASAMY and NEELAMANI (1997), VINOD (1998) has carried out experimental investigations for the development of Indian wave power plants and for future modification. TAKAHASHI (1988) has described the development of a wave power extracting caisson breakwater in Japan. MALMO and REITAN (1985) theoretically studied the hydrodynamic performance behavior of a MOWC in a channel using linear wave theory for different boundary conditions in the regions between absorber and channel wall. It is confirmed that MOWCs in an array were more efficient than in isolation. HITOSHI *et al*. (1995) reported on the floating wave power device "Mighty Whale" developed by JAMSTEC, Japan. The prototype is 50 m x 30 m x 12 m in overall dimensions. The device has a total draft of 8m and moored at 40 m deep water. The maximum value of the efficiency was found to be about 40% at the design wave period of 6 seconds.

From the detailed survey of the existing literature, it is evident that several OWC devices are now in operation worldwide but all the devices reported so far, except "Mighty Whale" and "Kaimei" are shore-based structures. Studies pertaining to the pneumatic efficiency of the floating OWC wave energy device especially with varying tidal levels are scarce. A detailed laboratory investigation is warranted to investigate on the pneumatic efficiency of the floating wave energy device under varied wave height, wave period and for different tidal levels. This is the main motivation for the present work. The present study has been programmed to carry out model experiments to get insight knowledge about the wave transmission, pneumatic efficiency, the motion response and line tension of a typical moored OWC for such an application, with special reference to the damping conditions defined by a/A ratio where a = Area of orifice opening, A = Projected area of Oscillating water Column and tidal effects simulated by different water depths, at a given mooring configuration of scope = 4 (Length of the mooring line/Water depth).

DESCRIPTION OF THE MODEL

Physical Modeling

In this study, a 1:20 model of the floating wave energy device as shown in Figure 1 was fabricated using Perspex sheet. The dimension of the OWC device is 1.8 m x 0.99 m x 0.65 m. The side plates of the model was stiffened with Perspex sheet stiffeners of 6 mm thick and 25 mm width and the bottom plate was stiffened with 18mm thick and 18 mm width Perspex stiffeners. An indigenous spring loaded frictionless single ball bearing was fixed on the sides of the floating wave energy device in order to reduce the friction between the sidewall of the flume and the caisson so as to reduce the error in the measurement of dynamic response & mooring loads during experimental investigations. The particulars of the device are given in Table 1. A mooring frame was fabricated and fixed to the bottom of the flume bed in order to anchor the model using the mooring chains. Facilities for varying the damping of air column in the OWC were arranged by providing ten holes of 12.5 mm diameter on the top of the OWC chamber. The damping was achieved by plugging the holes using rubber corks. When all the holes were unplugged, the a/A ratio was found to be 1.13% where a = area of orifice open and A = plan area of OWC chamber. a/A ratios of 0.9, 0.67 and 0.45 was used. Two caisson models are used to cover the flume width. This principle can be extended to many numbers of caissons in array to form a part of or a full portion of floating breakwater.

Experimental Set-up, Instrumentation, Model Tests and Analysis

The model was tested in the new 2m wide wave flume in the Department of Ocean Engineering, IIT Madras at a constant water depth of 1m. Mooring arrangement of Scope 4 (length of the mooring line/water depth) has been used for testing the Floating Wave Energy Device. This is found to be the better option among scope 4, 5 and 6. The details of instrumentation, data acquisition and analysis can be found in Prasanna (2003).

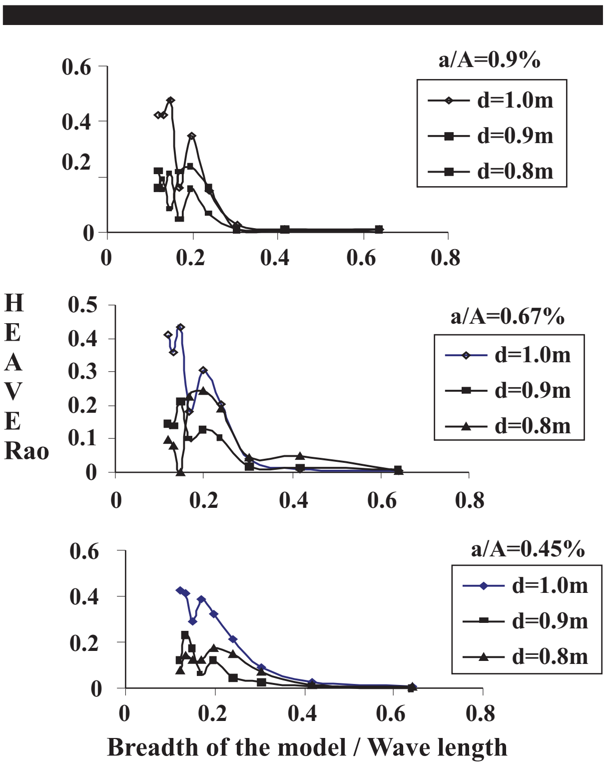

Figure 3. Roll RAO (H = 10 cm).

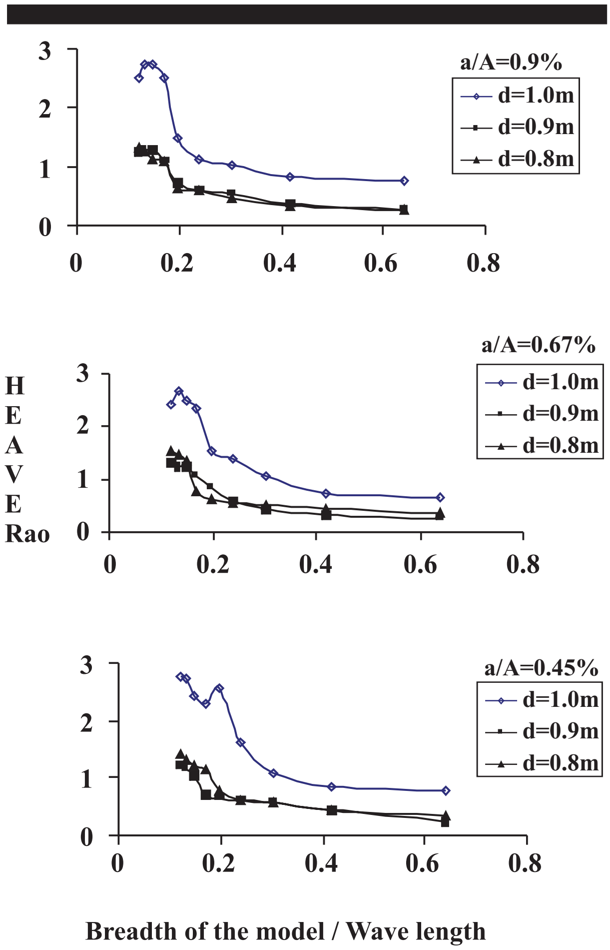

Figure 4. Sway RAO (H=0.10 m).

The experiments were carried out on the floating model for Scope 4, three damping conditions, which corresponds to a/A = 0.9, 0.68, 0.45 under regular waves for wave heights of 0.05, 0.75 and 0.10 m and wave periods ranging from 1 to 3 s in steps 0.25 sec. During the model tests the following data were collected

a. Air pressure and water surface fluctuations inside the OWC of the Model

b. Transmitted and reflected wave heights along with incident wave height.

c. Heave, sway and roll

d. Mooring forces

After the arrival of the waves at the test section, the data were collected for 30s with a sampling time interval of 0.025s. The details of the proposed prototype and the model details are given in table 1.

RESULTS AND DISCUSSIONS

General

The present investigation is carried out for three different incident wave heights (0.05 m, 0.1 m and 0.15 m). The change in wave height has insignificant change in the normalized output. Hence all presentations are provided for $H_i = 0.10$ m.

The wave period has very significant influence on all the normalized output. Hence the presentation is made in terms of B/L, where 'B' is the width of the caisson and 'L' is the local wave length.

Heave RAO

The effect of B/L, damping of OWC chamber in terms of a/A and variation of water depth on heave RAO is presented in Figure 2. In general, the heave RAO reduces with increased B/L, which is anticipated. The maximum value of heave RAO is about 2.0, which occurs for d=1.0, which is the high tide level.

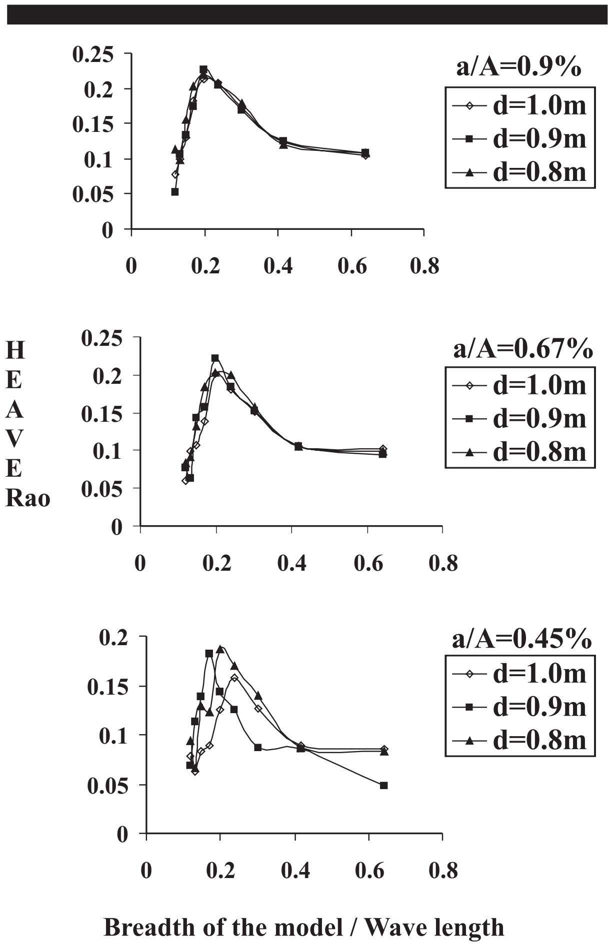

Figure 5. Normalised mooring line tension.

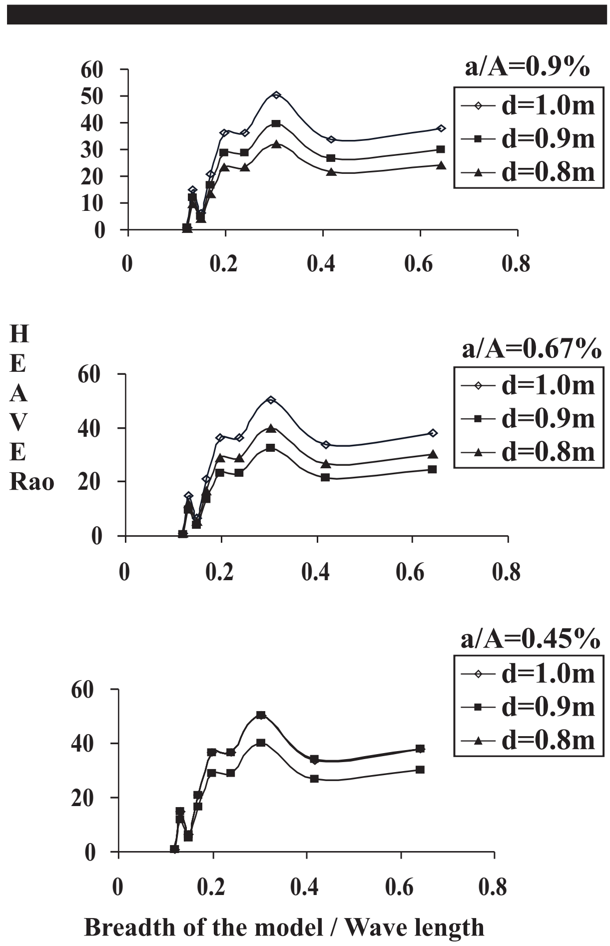

Figure 6. Pneumatic efficiency (H = 0.10 m).

The change in a/A from 0.9% to 0.45% does not have significant change in RAO. Hence a/A is an insensible parameter as far as heave is concerned.

Roll RAO

Figure 3 is a similar plot like Fig.2 but for roll RAO. The maximum value of roll RAO is about 0.7, which occurs for the lowest value of B/L studied (i.e. 0.12). The variation in B/L has significant influence on the variation of roll RAO. The change of water depth also has some noticeable change in roll RAO. Again variation in damping of OWC chamber (a/A from 0.9% to 0.45%) does not have significant change in roll RAO.

Sway RAO

Figure 4 shows the effect of B/L on sway RAO. The trend and magnitude of sway RAO is similar to that of heave RAO.

Normalized Mooring Line Tension (Seaward Side)

Figure 5 provides the effect of B/L on normalized mooring line tension in the seaward side for different a/A values and different water depth. The maximum normalized mooring line tension occurs at B/L of about 0.25. The maximum normalized tension for incident wave height of 0.1 m (which corresponds to 2.0 m in the scale of 1:20) is about 0.22.

Pneumatic Efficiency

The pneumatic efficiency is one of the important aspects of the present investigation. It is because the results of the present investigation are not only used for the design of floating breakwaters but also for the wave energy conversion plants. The effect of B/L on pneumatic efficiency for three different a/A values and for three different water depths for each a/A value is provided in Fig.6. It is seen that the pneumatic efficiency is less than 10% for B/L < 0.2. With increased B/L, the pneumatic efficiency is increasing. The peak value is reached for B/L = 0.3. For a/A = 0.67% and 0.45%, the maximum pneumatic efficiency obtained is about 0.5 for d = 1.0 m. At any B/L, the pneumatic efficiency is smaller for smaller water depth. From these values, it is found that the pneumatic efficiency is more during high water levels. It is to be recorded that the mooring lines has set with zero pretension when d = 0.9 m. Hence at d = 1.0 m, it has pretension corresponds to 0.1 m increase in water depth and was in slacked condition when d = 0.8 m. The pretension causes better pneumatic efficiency when d = 1.0 m.

Wave Transmission and Reflection

Wave transmission is a measure of the efficiency of the floating breakwater. A floating breakwater, which gives a smaller value of transmission coefficient is considered to be the best one. The effect of B/L on transmission Coefficient, K_t for three different damping and for three different water depths was studied. The value of K_t is found decreasing with increased B/L. The value of K_t is greater than 0.5 for B/L < 0.2, which is not desirable. It is also noted that the pneumatic efficiency is also less than 10% when B/L < 0.2. Hence from both wave transmission and pneumatic efficiency point of view, the floating wave energy caisson should be designed for B/L > 0.2. For example, if the most predominant wave length is 100.0 m, then the width of the floating wave energy device must be greater than 20.0 m. The effect of B/L on reflection coefficient for the three different a/A and water depths are also studied. It is found that change in B/L has oscillating characteristics in the reflection coefficient. The average reflection coefficient is about 0.6 and the maximum is about 0.8. Neither the change in water depth nor the change in a/A has any significant change in the trend of reflection coefficient. Hence a system like this has to be designed for reflection coefficient of about 0.7.

CONCLUSION

The following important conclusions are arrived:

The maximum heave RAO of the floating wave energy caisson is about 2.8, which occurs when B/L = 0.1. The heave RAO is negligible, when B/L > 0.4. The heave RAO is also the maximum when the water depth is maximum.

The roll RAO is also more for the higher water depth and the maximum value is about 0.50. Roll RAO is negligible, when B/L > 0.3.

Sway RAO is also maximum when the water depth is high (High tide condition). The maximum value of sway RAO is about 3.0.

Maximum normalized seaward side line tension occurs when B/L is about 0.25. The seaward side normalized line tension is almost independent of change of water depth from d = 0.8 m to 1.0 m in the model.

The pneumatic efficiency of the floating OWC caisson is maximum for taut mooring case (d = 1.0 m). The maximum pneumatic efficiency is about 50%, which occurs when B/L = 0.25. For slack mooring case (d = 0.8 m) the pneumatic efficiency falls down by more than 50%.

The transmission coefficient is almost closer to 1.0, when B/L is about 0.1 and it reduces to 0.1, when B/L is above 0.6. The transmission coefficient is independent of change in water depth from d=0.8 to 1.0 m and change in a/A from 0.45% to 0.9%.

The average wave reflection coefficient from the present floating wave energy device is about 0.6. Reflection coefficient oscillates significantly, when B/L is increased from 0.1 to 0.65.

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