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Wave Interaction with Caisson Defenced by an Offshore Low-Crested Breakwater

M.G.Muni-Reddy† **and S.Neelamani**‡

†Department of Civil Engineering
College of Engineering, Andhra University
Visakhaptnam 530003,
Indiamunireddy99@yahoo.co.in

‡Coastal & Air Pollution Department
Kuwait Institute for Scientific Research
13109 Safat,
KUWAITnsubram@kisr.edu.kw

ABSTRACT

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Low-crested offshore breakwaters are gaining more popularity as a potential protection structure where a moderate transmission is allowed with significant energy dissipation. Wave force reduction on a caisson type breakwater due to the presence of an offshore breakwater is experimentally investigated. Although there have been numerical and experimental investigations on the performance of the submerged rubble mound breakwaters, there are only a few experimental works done on the performance of low-crested structures as defence structure in reducing the wave forces on the caisson breakwaters. The height of the offshore low-crested breakwater was kept constant and the water depth was changed to simulate the different states of a tidal variation. The influence of crest width on wave force was also studied and observed significant reduction in wave force. Formula for the force on the caisson in the presence of offshore breakwater is provided for 2% probability of exceedence.

ADITIONAL INDEX WORDS: *Submerged breakwater, wave force, force reduction.*

INTRODUCTION

Vertical structures such as seawalls and vertical breakwaters have been used as coastal protection structures for many decades. A number of these structures are being damaged and failed by storms and the failures can be catastrophic (HOU, 1990, OUMERACI, 1994). Such failures are mainly caused by extreme wave actions, through displacement of the entire structure, or progressive failure starting from locally weak point, or through overall foundation failures, or through overtopping and toe erosion. The need for force reduction on structures like caisson breakwaters to increase the life span has resulted in different force reduction techniques like introduction of porosity at the front face of the caisson, construction of horizontally composite caissons, construction of low crested caissons etc. Introduction of porosity introduces weakness in the strength of the structure. Construction of horizontally composite structure in a dynamic environment is risky. Low-crested caisson breakwater attracts lesser forces but the overtopping waves create significant disturbance on the lee side. These drawbacks have motivated the authors to investigate the effect of offshore breakwaters in front of caisson breakwaters in reducing the forces on the caisson. The offshore breakwater can be constructed after installation of caisson without much risk for floating vessels and caisson.

In the present study an offshore low-crested rubble mound breakwater is considered as a defense structure to reduce the wave energy levels that reach the vertical impervious caisson. This type of protection can also be used, in situations wherein it is required to reduce the wave forces, to enhance the functional life of structures (caissons) that are damaged by extreme wave forces, as a rehabilitation measure. In-situ rectification of these damaged structures is difficult and dumping of rubble stones in front of these structures is simple and easy.

In the regions of large tidal range reflection, transmission, and dissipation characteristics may change considerably during tidal cycle. Offshore breakwaters need not be emergent to be effective. Submerged, or reef breakwaters are designed on the concept that the shallow depth over the structure will induce wave reflection, breaking, and turbulent energy dissipation within the structure, leading to a reduction in wave height shoreward of it. Many investigators (POWELL and ALLSOP, 1985, AHRENS, 1987, VAN DER MEER and PILARCZYK, 1990, VAN DER MEER and DEAMEN, 1994, LOSADA *et al*., 1997) have studied transmission and reflection characteristics of the low-crested and submerged breakwaters.

Low-crested rubble mound breakwaters may also become submerged after being damaged or matured. Results of the monochromatic waves on the low-crested and submerged breakwater shows considerable reduction in the wave forces on the caisson. The permeability of rubble-mound breakwater and the stability of armor units are not discussed herein. Due to the complexity of the physical processes at submerged breakwaters, physical modeling is necessary to define the site-specific interactions between the structure and the local wave climate. The defense structure may be submerged or emerged during a tidal variation. Keeping the breakwater height constant, water depth was varied to achieve five different relative breakwater heights to simulate the different state of tidal variation

EXPERIMENTAL INVESTIGATION

Experimental investigation was carried out in a 30m long, 2m wide and 1.50m deep wave flume in Department of Ocean Engineering at IIT Madras, Chennai, India. A Six-component force balance (GmbH R67) is used for force measurement, which is capable of measuring forces (200kgf in x and y directions and 800kgf in z direction) in three directions (inline, transverse and uplift) and the corresponding moments. The sensitivity of the force balance transducers at the rated loading is about 2mV/V. Wave amplitudes are measured with capacitance type wave gauges. Data was acquired at 40Hz frequency and recorded through a dedicated computer for further analysis.

Experimental Set-up

As shown in Figure.1 box caisson model of size 870 mm X 1980 mm X 1200 mm is fabricated by using different steel sections and foam plastic sheets. The model was fixed over the six-component force balance. The top elevation of the model of the caisson was selected based on the maximum run up over the caisson to ensure non-overtopping during wave action. Two different crest widths of the breakwater B (B=0.4m and 1.20m) and two pool lengths, L_p (L_p = 0.5m and 1.0 m where L_p is the distance between the lee side toe of offshore breakwater and caisson) were used. Rubble mound breakwater cross-section consisting of a core section and primary amour section was subjected with a wide range of regular waves. The stable amour weight was estimated by using VAN DER MEER (1987) formulae. Weight of the amour stone is 1.50 to 2.0 kg, which was estimated for the inputs H_s = 0.29 m, T_z = 3 s, S = 2, N = 3000

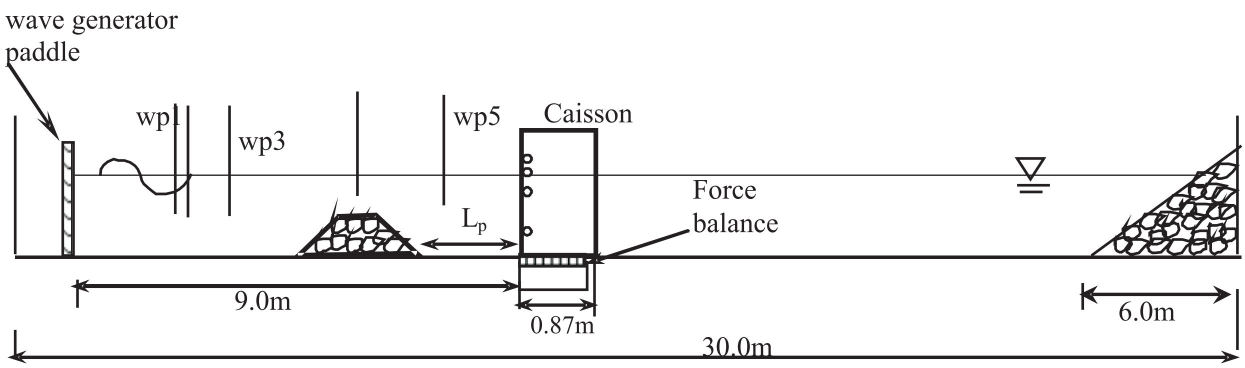

Fig.1. Schematic diagram of experimental set-up for the present study.

and γ_r = 2.65 t / m^3 for plunging breaking, where H_s is the significant wave height, T_z is the zero crossing period, γ_r is the specific weight of the stone used, N is the number of waves, S is the damage level as defined by VAN DER MEER (1987). A stable slope of 2H: 1V was adopted as the effects of breakwater slope and amour diameter on the wave transformation were found to be relatively unimportant the wave transmission were found to be relatively unimportant (SEABROOK and HALL, 1998). Keeping the breakwater height 'h' constant at 0.60m, water depth 'd' was varied from 0.50m to 0.70m with an increment of 0.05m.

The ranges of various normalized hydrodynamic input parameters employed are:

Relative water depth d/L	: 0.050-0.450
Relative wave height H_i/d	: 0.068-0.538
Incident wave steepness H_i/L	: 0.006-0.111
Relative break water height, h/d	: 0.86-1.20

Where, L is the deepwater wavelength.

ANALYSIS

The wave synthesizer (WS4) software was used for the measurement and analysis. The software is capable of controlling the wave paddle and at the same time acquires data from sensors used in the tests. Regular waves of different pre-determined wave period and wave amplitude combinations are generated for the tests. The regular time series of force was then subjected to threshold-crossing analysis to get the mean amplitude of wave force.

The mean of all the amplitudes above the reference level in a time series is taken as a positive or shoreward force. Similarly mean of the all the amplitudes below the reference level in a time series is taken as negative or seaward force. The mean amplitudes of measured hydrodynamic forces were obtained by using the above procedure for each test run. $[F_{xwob}]_{shore}$ is defined as the positive or shoreward force in the direction of wave propagation in the absence of offshore breakwater and $[F_{xwb}]_{shore}$ is defined as the positive or shoreward force in the direction of wave propagation in the presence of offshore breakwater. $[F_{xwob}]_{sea}$ and $[F_{xwb}]_{sea}$ carries the same meaning but for seaward force. Similarly $[F_{xwob}]_{Uplift}$ and $[F_{xwb}]_{Uplift}$ are the vertical upward forces acting on the caisson in the absence and in the presence of the offshore breakwater respectively. The forces are non-dimensionalized such as

Shoreward force ratio

$$[F_x]_{shore} = \left[[F_{xwb}]_{shore} \big/ [F_{xwob}]_{shore} \right]$$

Seaward force ratio

$$[F_x]_{sea} = \left[[F_{xwb}]_{sea} \big/ [F_{xwob}]_{sea} \right]$$

Uplift force ratio

$$[F_z]_{Uplift} = \left[[F_{zwb}]_{Uplift} \big/ [F_{zwob}]_{Uplift} \right]$$

Statistical Analysis of various dimensionless output variables was carried out to propose a design formula for the estimation of the wave force on the caisson defended by an offshore breakwater

RESULTS

Experiments were conducted for five different h/d ratios (0.86-1.20), which consists of two emerged, two submerged

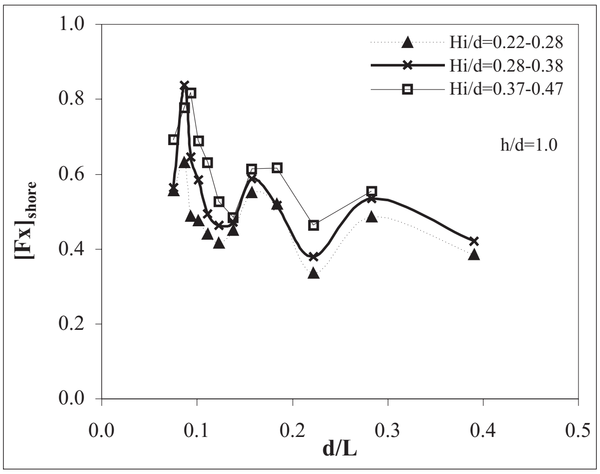

Fig.2.Variation of shoreward force ratio $[F_x]_{shore}$ versus relative water depth d/L for different relative wave heights [h/d=1.0 and L_p/L= 0.06-0.32.

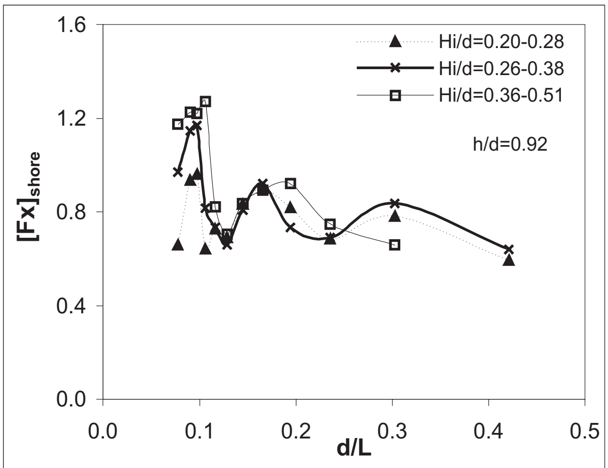

Fig.3. Variation of shoreward force ratio $[F_x]_{shore}$ versus relative water depth d/L for different relative wave heights.[h/d=0.92 and L_p/L=0.06-0.32].

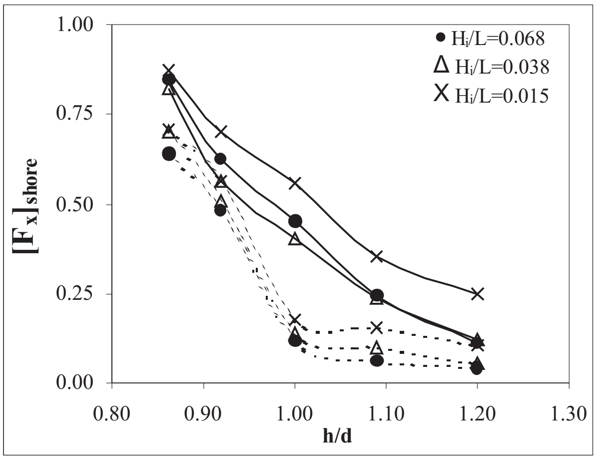

Fig.4. Variation of Shoreward force ratio with relative breakwater heights, h/d [B=0.40m (solid lines), B=1.20m (broken lines) and L_p/L=0.095-0.0.44].

and one with the crest of the offshore breakwater at SWL.

Figure.2 shows the variation of shoreward force ratio with relative water depth for h/d=1.0 and L_p/L=0.06-0.32. This figure shows the oscillatory response with decreasing amplitude as the relative water depth is increased. It shows that short period waves dissipate more energy compared to the long period waves. Similar response can also be seen in Figure.3 for h/d=0.92 (small submergence) but the shoreward force ratio is more. The maximum shoreward force ratio is more than one. Qualitative analysis of wave set-up (Drei and Lamberti, 2000) and pumping effect of the submerged and low-crested breakwaters (Diskin et al., 1970) are not carried out in analyzing the wave forces. Possibly this may effect in shoreward force ratio more than one in Figure.3.

Effect of Water Depth on the Normalized Wave Forces

Figure.4 is provided to understand the h/d and wave steepness on the normalized inline shoreward force. The other normalized force ratios are presented in table1.

For offshore breakwater with h/d = 0.86 (i.e. submerged), the waves transmit freely and gets reflected from the caisson. This phenomenon contributes significantly for the wave forces on the caisson. For offshore breakwater with smaller submergence (say h/d=0.92), prominent wave breaking on the offshore breakwater was observed. This results in significant loss of wave energy and the weak transmitted wave results in reduced forces on the caisson. The reduction in average horizontal force ratio is about 52% (with standard deviation is 0.08, Table.1) for h/d =1.0 with B=0.40m, where 'B' is the crest width of the offshore breakwater. The percentage decrease in the magnitude of peaks of force ratios was found to increase with an increase in h/d. The time series of wave force shows that the wave breaking on the breakwater generates high frequency waves on the lee side of the breakwater, which results in irregular force time series consisting of superposition of the fundamental wave frequencies and the higher wave frequencies.

Effect of Crest Width on the Normalized Wave Forces

Though the depth of submergence or emergence of the offshore breakwater is the primary parameter for the present study, the effect of top width of the breakwater is also investigated. The crest width can be easily controlled during construction. It was reported that increase in crest width reduces the wave energy transmission. From Fig.4, for B=0.40m and h/d=1.0, 52% reduction in force ratio is achieved. For the same h/d values, and for B=1.20m, reduction in average force ratio is 64%. This shows the benefit of increasing the crest width of breakwater.

Probability Analysis

The cumulative probability or probability of non-exceedence of force ratios for the measured wave forces [for all wave heights and periods and for different relative heights of the offshore breakwater] are given in table 2. The value corresponding to 98% non-exceedence (i.e. 2% exceedence) values are plotted in Fig.5. This plot can be used for the purpose of preliminary design. The following equation (with regression coefficient of 0.94) is obtained for 2% probability of exceedence of force ratio:

$$([F_x]_{shore})_{2\%} = 0.75\,(h/d)^{-3.2} \qquad (1)$$

This equation is valid for 0.85 < h/d < 1.20. Incorporation of other dependent normalized variables are found to contribute insignificantly and hence omitted.

DISCUSSIONS

The main focus of many investigators on submerged and low-crested breakwaters is on wave transmission and reflection characteristics and the corresponding shoreline response, including study of damping action of deeply submerged breakwaters by (SHENG *et al*., 2000). For most coastal seawalls and for many breakwaters in shallow water, wave under larger storms may be significantly reduced by depth limited breaking before they reach the seawall or breakwater. Reduction in wave energy and overtopping is also achieved by construction of an offshore low-crested rubble mound breakwater seaward of the primary structure, i.e. vertical breakwater (GONZELEG *et al*., 1990). When the tidal range is high, these shallow water low-crested and submerged breakwaters have to perform differently like intermediate and some times as deep water submerged structures. Present study was done in the intermediate range (d/L=0.062-0.452).

Oscillating nature of force ratio $[F_x]_{shore}$ is observed when d/L is varied. This oscillating nature of the force ratio is due to the interaction of reflected and re-reflected waves between the caisson and the offshore breakwater. The force spectra resulting from the various testing configurations showed the high frequency components in force time series. This observation is further supported by transmitted spectra resulting from the testing configurations with decomposition of the fundamental wave frequencies in to harmonic frequency components, which is a typical phenomenon of submerged obstacles. At low h/d, the process seems to be governed by depth limited or wave breaking effects, while at larger relative submergence, processes related to crest width (B) appear to be predominant. This is contrary to experimental observation of YAMASHIRO *et al*. (2000), where the authors explains that the total power of transmitted wave is not so much dependent on the crown width of the submerged breakwater, but the shape of the transmitted spectrum changes considerably depending on the crown width.

As the depth is varying it was observed that the interaction of waves with the offshore breakwater is entirely different. Wave interaction process on and over the low-crested breakwater evolves from overtopping (at low tide level) to intense wave breaking (crest level is at or very close to tide level) and finally

Table.2. *2% non-exceedence probability of force ratios.*

	B/h=0.67 L_p/L=0.071-0.64			B/h=2.0 L_p/L=0.071-0.64		
h/d	shore ward	sea ward	uplift	shore ward	Sea ward	uplift
0.86	1.06	1.10	1.00	0.90	0.76	0.81
0.92	1.16	1.07	0.66	0.78	0.64	0.45
1.00	0.73	0.58	0.40	0.37	0.34	0.42
1.09	0.53	0.55	0.43	0.24	0.23	0.28
1.20	0.38	0.47	0.28	0.14	0.16	0.15

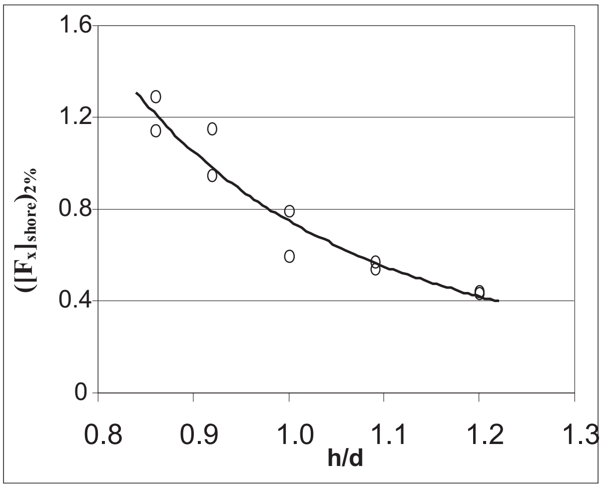

Fig.5. Variation of 98% exceedence shoreward force ratio with relative breakwater heights, h/d for all wave heights and wave periods, pool length L_p/L=0.071-0.64, B=0.40m and B=1.20m.

to transmitted wave or partially transmitted wave (tide level is well above the crest level).

Effective damping of waves was observed for h/d > 1.0, but it should be noted that higher the crest free board, the cost of the structure will be also higher. On the other hand, if the crest elevation is very low (under storms and high tides) it will result in reduced wave damping and increased forces on the caisson. Hence, an optimization between the total cost and life of the system must be established.

CONCLUSIONS

Wave forces on the vertical breakwater defenced by low-crested and submerged breakwater are studied. Results of tests conducted in a 2D wave flume are presented for monochromatic waves. Wave interaction with the low-crested offshore breakwater is significantly different with varying water depth (tide cycle). Significant reduction in wave force is obtained when the crest level of the breakwater is very close to still water level. When the crest level of low-crested breakwater is at still water level, the reduction in the average force ratio is about 52% for B = 0.40m and is about 62% for B=1.20m. A formula based on the investigation to estimate the 2% probability of exceedence force ratio is given, which can be used for the preliminary design of caissons defenced by offshore breakwaters.

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