ABSTRACT: The shoreline erosion is a major problem that persist world wide and seawall still remain as one of the most widely adopted coastal protection structure. The design of an efficient seawall should be such that overtopping is minimized even during coastal flooding and extreme events by maintaining its crest elevation as low as possible. This can be obtained with curved front face sea walls. Three such curved configurations have been chosen for the study. The experimental investigation on dynamic pressure variation along the surface and run-up over the seawall models placed over a bed slope of 1 in 30 and subjected to the action of random waves following the PM spectrum were conducted. The results on the variations of dynamic pressures and the run-up on the curved seawall models compared with for a vertical wall are analysed and discussed in detail.

INTRODUCTION

The dissipation of the incident energy in a coastal structure is mostly due to that lost in the waves running over the front slope of the structure and due to partial reflection. In the case of vertical face seawall the reflection will be more which although results in lesser run-up requiring lower crest elevation, but the magnitude of the waves near the vertical seawall magnifies to a maximum extent of twice the incident wave height, during the ingress of storms and extreme waves the crest elevation has to be higher in order to avoid overtopping. In order to dissipate the incident wave energy gradually through shoaling, sloping walls were introduced. Although, the present study does not cover overtopping of walls, a literature survey on this aspect was carried out which is discussed below in brief. The results from a comprehensive experimental program on overtopping and wave loading on vertical walls with and without parapet, [1] reported that the parapet is effective in reducing overtopping only under conditions for relative crest freeboard $R_c/H_s > 1.5$, where, $H_s$ is significant wave height and $R_c$ is the free board. This formed the basic study that lead to the group, VOWS (Violent Overtopping by Waves at Seawalls). The preliminary results were reported by [2]. A collection of articles on overtopping and wave impact pressures on sloping and vertical walls has been edited by [3]. Although more stable, [4] and [5] reported that the impact pressures and the resulting forces on sloping walls are greater than those on vertical walls. [6] Reported that for a given incident wave height the maximum run-up occurred for a slope angle of 30° and that if there was any variation from that slope in either direction, the wave run-up would decrease. The sloping walls are not desirable, since it experiences high pressures and run-up and thus requiring higher crest elevation and further it occupies more space compared to that of a vertical seawall. Hence, it is evident that a seawall having the characteristics of lesser reflection, run-up or overtopping of waves with less utilization of coastal space and maintenance costs would be an ideal one. Hence, the shape of the wall front is the one for which investigations are warranted. For the present study, three different curved front face walls are considered. The smooth curvature of the curved front sea wall is expected to guide the wave over its curvature so as to allow it to return back into the sea by the process of which
significant amount of energy get dissipated. [7] Has given a conceptual design of curved seawall with a combination of a parabolic and a circular arc that brings a smooth change in the direction of propagation from horizontal to vertical and vice versa to reduce the wave induced pressures. [8] Has proposed a new type of circular arc non-over topping seawall and measured the pressures and forces due to regular waves. It was concluded that the critical crest elevation is much less compared to that for a vertical seawall. The maximum pressures occurred near the still water surface changing with relative water depth (water depth/ deep water wave height) and inducing large vertical force. [9] investigated the characteristics of the curved seawall and the fluid flow near the seawall was reproduced through numerical simulation using finite volume method. The results obtained were almost similar to that of [8]. Similar study was reported by [10] along with the investigation on the spray when the waves strike the wall. [11] Reported the efficiency of a curved seawall under increased water level due to global warming. The literature review reveals that, the concept of using curved front seawalls with different curvatures instead of vertically faced seawall to reduce the overtopping, has been adopted at several locations, however, the literature on the hydrodynamic characteristics of curved front seawall is scanty and hence the present study was taken up.

DESCRIPTION OF THE MODEL AND EXPERIMENTAL SET-UP

The models considered for the study are, vertical wall (model–VW). The seaside front face of curved front seawall (model–GS) is a combination of two radii of curvature as suggested in [12] by US Army Corps of Engineers that was adopted at Galveston, Texas, USA, during 1905. The model (model–FSS) is a modified version of the model proposed by [9]. The cross section of the seawall model proposed by him was formed with the deepest point from its base and from the vertical joining its toe and the crest of the wall are around 40% and 50% of its height respectively. The pressure experienced by such a wall is reported as some 3 to 4 times more than that on a vertical wall, and hence for the present study a modified section with the deepest point from the vertical joining its toe and the crest of the wall as 40% of its height was considered. The curved front seawall was thus formed by adopting nine varying radii increasing from bottom towards top. The other model (model–CPS) considered is a curved front seawall from the concepts of [7], which consists of a parabolic curve, at the bottom, with a quarter circle, at the re-curved portion which was connected smoothly at the intersection. All the four models are fabricated with Fibre Reinforced Plastic (FRP) and the geometries of all the curved front seawall models considered under the present study are presented in Fig. 1.

The experimental study was carried out in a wave flume of 72.5 m long, 2.0 m wide and 2.7 m deep, in the Department of Ocean Engineering, Indian Institute of Technology Madras, India, by adopting a model scale of 1:5. A computer controlled wave maker is installed at one end of the flume capable of generating regular and Cnoidal waves of different heights and frequencies, as well as the random waves of predefined spectral characteristics. The other end of the flume is provided with a rubble mound wave absorber the reflection from the rear end of the flume. The water depth in the flume can be varied from 0.5 m to 2.0 m. In the present study, the models were exposed to the action of random waves following the PM spectrum (as it describes a fully developed sea state), with the peak periods between 1 and 3 sec at an interval of 0.4sec, each of which was associated with wave heights of 0.05m, 0.1m and 0.15m. Two water depths of 0.8m and 1.0m near the wave maker corresponding to 0.34m and 0.46m at the toe of the model were employed for the tests( However, the results from 1.0m water depth near the wave maker is presented in this, in consideration with page limitation). The data acquisition is done using WS4 (wave synthesise 4- a DHI product) and the frequency
of 40Hz is used to acquire all the data. The experiments have been conducted by placing the model over a rigid bed of slope 1:30 made up of steel frames and marine plywood, which is also having a rigid partition at the centre of flume along the entire length of slope provided to facilitate the testing of two models at the same time. The toe of the model was placed at a rear end of the adopted bed slope over a steel frame at a distance of 40m from the wave maker. The pressure transducers were rigidly fixed to the models along its depth on the central line of the model, such that the depth of submergence of the pressure port, \( z/d \) (\( z \) is depth below or above still water and \( d \) is water depth) is the same. The cross section of models (VW, GS, FSS and CPS) along with the locations of the pressure ports are presented in Fig 2. The wave gauges are placed at a distance of one wave length from the toe of the model (distance change with the wave period) to capture the time history of the composite water surface elevation. The run-up probe consists of two parallel stainless steel wires of 1 mm diameter spaced 10 mm apart that are fixed along the surface of the seawalls. The plan and sectional view of the models positioned in the wave flume are shown in Fig 3.
RESULTS AND DISCUSSIONS

Dynamic Pressure

Typical time histories sensed by the wave probe and pressure transducers at four different measuring locations \((z/d = 0.0, -0.26, -0.52\) and \(-0.78\)) along with their respective spectra for all the model (VW) for \(d/L_p=0.133\) \((L_p – \text{wave length with respect to the peak period})\) and \(H_s/d = 0.217\), are shown in Fig. 4. The peak period, \(T_p\) and significant wave height, \(H_s\) are obtained by subjecting the random time histories to frequency domain analysis. From this analysis, significant values of wave elevation and pressure exerted on the structures were obtained.

![Fig.4 Typical time histories and spectral densities of water surface elevation and pressures along the depth of model (VW) for \((d/L_p = 0.133, H_s/d = 0.217)\)](image)

The variations of dimensionless pressure, \(P_s/H_s\), (where \(H_s\) – Significant wave height) along the depth, \(z/d\) for \(H_s/d\) ratios of 0.108 to 0.411 and \(d/L_p\) of 0.064 to 0.307, for vertical wall model (VW), for tests with \(d\) of 0.46m are projected in Figs. 7. Similarly variations in the results for GS, FSS and CPS are projected in Figs. 8, 9 and 10 respectively. The pressure decay along the depth below SWL is clearly seen for all \(d/L_p\) for all the models considered. It is observed to be more for models (GS) and (CPS) than for models (VW) and (FSS). This is due to the nature of the curvature of models (GS) and (CPS), being more flat near the bottom,
in which case, the bottom port of the seawall acts nearly as a horizontal bottom where the exerted dynamic pressure is less. The pressure at the still water level is found to be less than that on the pressure port below it. Since the pressure port near the still water level will have successive exposure to both atmosphere and the water due to fluctuations in the wave surface elevation. Hence, the pressure time record shows zero pressure for the time when that pressure port is exposed to the atmosphere. As reported by [13], the absence of seaward pressures in pressure time history is known as the intermittence effect. This effect can be seen in pressure variation plot, depth at the pressure port location, \( z/d = 0.0 \) for all the models, and hence the comparison in pressure difference with the vertical wall is made with the pressure port just below the SWL.

Fig. 7 Wave pressure distribution on model (VW) for various \( H_s/d \) and \( d/L_p \) ratios with their toe in a water depth of 0.46m under random waves

Fig. 8 Wave pressure distribution on model (GS) for various \( H_s/d \) and \( d/L_p \) ratios with their toe in a water depth of 0.46m under random waves

Fig. 9 Wave pressure distribution on model (FSS) for various \( H_s/d \) and \( d/L_p \) ratios with their toe in a water depth of 0.46m under random waves
The intensity of pressures on the different shaped walls, with that exerted on a vertical wall under random waves is compared; this is done by obtaining the percentage difference in pressures, with vertical seawall to other three models GS, FSS and CPS for a particular $z/d$, $d/L_p$ and $H_s/d$ as

$$p_s^* = \left[ \frac{p_s(GS/FSS/CPS) - p_s(VW)}{p_s(VW)} \right] \times 100$$

\[(1)\]

**Model (GS)**

The variation of $p_s^*$ for GS model as a function of $d/L_p$ for $H_s/d$ ratio of 0.108 to 0.304 and $z/d$ values of 0.0, -0.26, -0.52 and -0.78, with its toe in a water depth of 0.46m are shown in Fig.11. The pressure on the GS model is found to be higher than that on VW model near the free surface. For locations closer to the bed (absolute of $z/d > 0.25$) a reverse trend is seen, that is the pressure on VW model is higher than on GS model. At $z/d = -0.26$, the maximum percentage increase in the pressures on GS models compared to for model VW, occurs at lower $d/L_p$ for all the $H_s/d$ ratios, to a maximum extent of about 30%, for a water depth of 0.46m water depth at the toe of the model.

**Model (FSS)**

The variation of $p_s^*$ for FSS model as a function of $d/L_p$ for $H_s/d$ ratio of 0.108 to 0.304 and $z/d$ values of 0.0, -0.26, -0.52 and -0.78, with its toe in a water depth of 0.46m are shown in Fig.12. The pressure on the FSS model is found to be higher than that on VW model for all $H_s/d$ tested. At $z/d = -0.26$, the maximum increase in $p_s^*$ for FSS model, compared to model VW at lower $d/L_p$ of 0.184 for a $H_s/d$ of 0.108, is observed to be about 35 % for a water depth of 0.46m water depth at the toe of the model.

**Model (CPS)**

The variation of $p_s^*$ for CPS model as a function of $d/L_p$ for $H_s/d$ ratio of 0.108 to 0.304 and $z/d$ values of 0.0, -0.26, -0.52 and -0.78, with its toe in a water depth of 0.46m are shown in Fig.13. The trend in the pressure variation on CPS model is found to be almost similar to that on GS model. At locations below $z/d = -0.52$, the pressure on CPS model is found to be less than for VW model and at $z/d > -0.52$, the pressure found to be higher for CPS model.

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**Fig. 10 Wave pressure distribution on model (CPS) for various $H_s/d$ and $d/L_p$ ratios with their toe in a water depth of 0.46m under random waves**
-0.26, the maximum increase in \( p_s^* \) for CPS model, compared to model VW at lower \( d/L_p \) of 0.075 for an \( H_s/d \) of 0.304, is observed to be about 60\%, for a water depth of 0.46m water depth at the toe of the model.

Fig. 11 The \( p_s^* \) distribution of model (GS) for various \( d/L_p \) and \( H_s/d \) ratios, with their toe in a water depth of 0.46m under random waves

Fig. 12 The \( p_s^* \) distribution of model (FSS) for various \( d/L_p \) and \( H_s/d \) ratios, with their toe in a water depth of 0.46m under random waves
Run-up analysis

The variations of relative run-up ($R_u/H_s$) (where, $R_u$ – significant run-up) as a function of $d/L_p$ for models (VW) and (GS) with their toe in a water depth of 0.46m are plotted in Fig. 14, for $H_s/d$ values of 0.108, 0.217 and 0.304. The $R_u/H_s$ in general is found to decrease with an increase in $d/L_p$. The results show that model (GS) experiences higher run-up with a decrease in the water depth. This is due to the shoaling of waves while progressing over the toe of the model and becomes steeper. A closer examination of results shows that model (GS) experiences a run-up of about 55% higher compared to model (VW).

When the waves propagate over a curvature of the seawall, whole or part of its surface is wetted, so the run-up is not significant for re-curved seawall models (FSS) and (CPS), for fixing the crest elevation. The curvature of the seawall guides the wave towards the sea and hence the overtopping is avoided.
SUMMARY AND CONCLUSIONS

A detailed experimental study to investigate the hydrodynamic characteristics of three different curved seawall models along with a vertical seawall was carried out. Most of the energy is spent in wave running over their relatively flat horizontal portion for models (GS) and (CPS); hence the reflections are comparatively less. However, the shape of the curvature of model (GS) is not adequate in directing the water more towards the ocean by dissipation, leading to an increase in the run-up and subsequently requiring a higher crest elevation to avoid overtopping. Even though, the dynamic pressure on the re-curved seawall models (FSS) and (CPS) are higher than on a vertical seawall, it can be considered as a solution for coastal protection. Since the curvature of the curved front seawall guides the wave along its surface and enables it to return back into the sea, by the process of which, significant amount of energy is dissipated, and also overtopping is avoided even with a minimum free board. The advancement in the construction field enables the designing and construction of complex curved walls. Hence re-curved walls are found to have a few advantages over the vertical wall in particular, the reduced crest level.

• At \( z/d = -0.26 \), the maximum percentage increase in the pressures on model (GS) compared to that on (VW), under random waves occurring at lower \( d/L_p \) for all \( H_s/d \) is about 30%.
• At \( z/d = -0.26 \), the maximum percentage increase in the pressures on model (FSS) compared to that on (VW), under random waves occurring at lower \( d/L_p \) of 0.184 and \( H_s/d \) of 0.108 is about 35%.
• At \( z/d = -0.26 \), the maximum percentage increase in the pressures on model (CPS) compared to that on (VW), under random waves occurring at lower \( d/L_p \) of 0.075 and \( H_s/d \) of 0.304 is about 60%.
• The maximum percentage increase in the run-up on model (GS) compared to that on model (VW), under random waves is about 55%.
• The results on the models (FSS and CPS) have yielded favorable results towards the reduction in the crest elevation, because of its re-curved nature.
• Both the models (FSS) and (CPS) can be effectively used even in the places where there is a considerable tidal variation. However, model (CPS) is less preferred due to higher velocities near the toe that might induce high scour.

REFERENCE