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RESEARCH PAPER

An Experimental Study on Interaction of Regular Waves with Steep Inclined Perforated Plates

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Abstract
The hydrodynamic efficiencies of perforated plates arranged at different inclinations are assessed through experimental investigations. Wave absorption capability of the perforated plates is governed by the optimum porosity and the slope of the structure. The reflection and transmission characteristics of waves influenced by the perforated plate exposed to different incident wave conditions are analysed for different porosities and slopes. The modified predictive equation for estimating wave reflection for impermeable plate is derived through experiments. Better wave absorption is observed for a plate with 10 % porosity and 15° slope. The details of the effects of slope and porosity of the inclined perforated plate on the wave reflection and transmission are discussed in this paper.

Keywords Perforated inclined plates · Porosity · Slope · Reflection coefficient · Transmission coefficient

Introduction

The impact of wave forces on an open coast can be minimised by the construction of sloped coastal structures like seawalls and revetments. The efficiency of these structures is determined by the amount of wave energy dissipated, which is governed by the porosity and the slope of the structures which in turn is governed by reflection and transmission characteristics of waves past the structure. The reflection characteristics of waves from the coastal structures will influence the navigation of the vessels, vessel lifetime, the stability of the toe of the structure and overall functioning of the protective barrier. Apart from this, sloped structures can also be used in the wave tank testing facilities as wave absorbers at the far end of the facility. These wave absorbers in wave tanks are required to be effective in absorbing the incident wave energies, without occupying much of testing space. Though there are active wave absorbers available, the most popular are passive wave absorbers such as constant plane slope or beach constructed of gravels, and they are widely adopted in wave tanks. The sloped perforated structures can also be used in areas where the conventional coastal protective structures may not be feasible for wave energy dissipation.

In an early stage of understanding of wave characteristics over sloping bed, investigations on impermeable plates were carried out [1] and reported that for a constant wave steepness [ratio of wave height (H) to wavelength (L), H/L], the reflection decreases when relative depth [ratio of water depth (d) to L), d/L] increases. Battjes [2] found that the reflection coefficient (K_r) defined as the ratio of reflected wave height (H_r) to incident wave height (H) was related to surf similarity parameter [$\xi_0 = \tan\theta/\sqrt{\mathrm{H}/\mathrm{L}_0}$] by an equation; $K_r = 0.1\ (\xi_o)^2$. The investigation was carried for varied slopes of 1/3.3, 1/5, 1/6.7 and 1/10 at a d of 0.35 m. The four types of breaking waves was clearly demarcated using the surf similarity parameter (ξ) defined by Battjes [2] as spilling if $\xi < 0.5$, plunging if $0.5 < \xi < 2.5$, collapsing if $2.5 < \xi < 3.7$ and surging if $3.7 < \xi$ [3]. Seelig and Ahrens [4] investigated the reflection measurements on two of slopes of 1/15 and 1/2.5 range, at a d of 0.215 m and 0.53 m and wave period (T) ranging from 1.25 s to 3.5 s and proposed an equation to determine K_r. The effect of the different wave breaker type on wave reflection characteristics of smooth, impermeable, uniform laboratory beaches was investigated [5] for the same range of slopes as [2]. The performance characteristic of different type of structures was discussed [6] and has identified the ξ as a single

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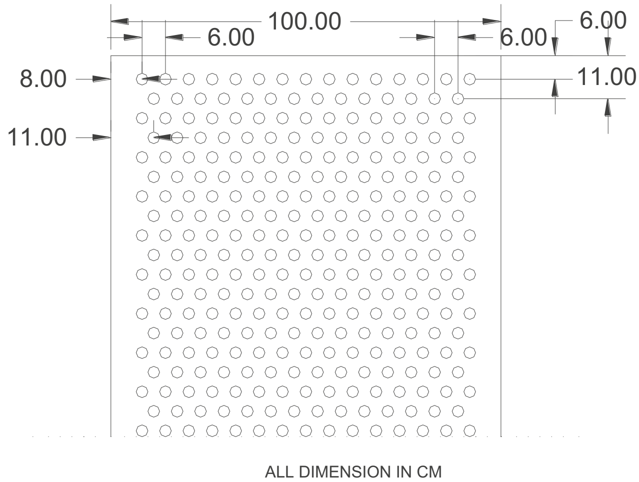


Fig. 1 Schematic sketch of 10 % perforated plate

parameter influencing the wave action. A new formula for calculation of K_r applicable for different slopes ranging from 1/1.5 to 1/4 was developed after analysing wave reflections from various structures [7]. Neelamani and Sandhya [8] studied the hydrodynamic performances of the vertical and sloped plane, dented and serrated seawalls and reported that introducing serrations helped in decreasing wave reflection from seawall due to higher wave energy dissipation. They also studied the surface roughness effect of vertical and sloped walls under random wave conditions [9]. Cho and Kim [10] investigated the wave energy absorption efficiency of the submerged horizontal and inclined porous plate using analytic and boundary element method solutions. The hydrodynamic performance of the inclined thin plate was studied [11]. The use of single and multiple vertical porous plates to function as a wave energy absorber were experimentally and theoretically investigated [12–14]. Alsaydalani et al. [15] investigated the performance of triple vertical slotted wall breakwater in terms of reflection, transmission and loss coefficient. However, vertical porous plate wave absorbers demand larger space to attain desirable efficiency. In view of this, the present study focuses on analysing the wave absorption performance of perforated plates arranged at different slope conditions. From the past literature, it is found that the efficiency of a perforated plate structure to dissipate the incident wave energy can be examined by understanding the reflection, transmission and loss characteristics.

The objective of the present study is to investigate the performance of perforated plates over the impermeable structure by considering various parameters for the effective use of such structures to attenuate wave energy, both in practice and in the laboratory wave flume facility. The present experimental study also addresses the wave energy absorption capability of a perforated plate at different slopes to effectively absorb the waves generated in a specific wave flume facility. Optimum design of an inclined perforated plate will reduce the reflected and transmitted waves and thereby being an alternative to a temporary arrangement of rubbles or any other structures. This paper discusses the performance of perforated plates arranged at different slopes and porosities exposed to a range of wave conditions.

Materials and Methods

Test Facility

The experimental investigations were carried out in a 50 m long, 1 m wide and 1 m deep wave flume facility in the Ocean Engineering Laboratory, Indian Institute of Technology Bombay, India. The flume is equipped with a computer controlled piston-type wave generator, capable of simulating regular waves of a wide range of amplitudes and periods with an absorption beach consisting of an open-cell foam material fitted behind the paddle system to prevent water splashing. At the other end of the wave flume, a temporary arrangement of rubbles is provided to restrict the re-reflected waves to enter the study area.

Physical Model Details

The physical model used in the present study is an aluminium plate with a thickness of 0.003 m, covering the width of the wave flume of 1 m. These plate models were supported with

Fig. 2 View of single inclined plate model arranged inside the wave flume

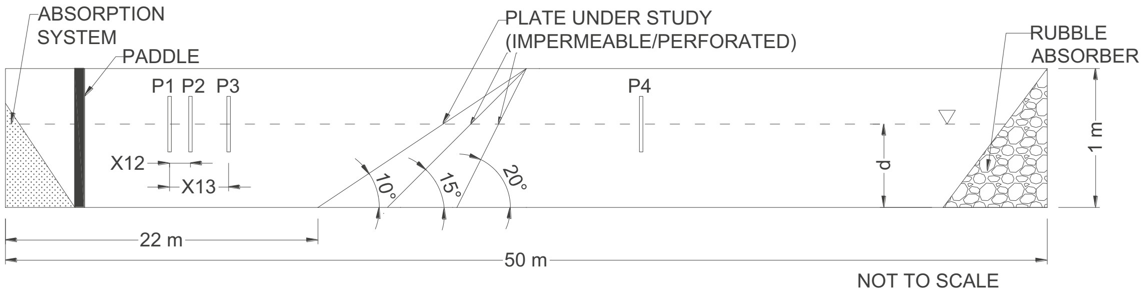


Fig. 3 Schematic sketch of the arrangement of plates at different inclinations inside the wave flume

steel member frame arrangement and the plate was held tightly from the top to minimise the vibrations. Holes with a constant diameter of 0.03 m were made on the aluminum plates to represent the porosity of the plate for carrying out the present study. By varying the spacing between the two adjacent holes by 0.07 m and 0.06 m, different porosities were obtained, as shown in Fig. 1. Photograph of impermeable and perforated plates placed inside the wave flume is shown in Fig. 2 and the schematic sketch of the arrangement of plates at different inclinations inside the wave flume is illustrated in Fig. 3.

Position of Instruments

One wave probe was positioned at a distance of 4 m from the wave paddle to measure the incident wave elevations. The reflection characteristics of the inclined perforated and impermeable plates are measured using three wave probes positioned on the seaward side of the model at a distance of 18 m away from the structure to measure the composite incident and reflected wave elevations as shown in Fig. 3. The distance between the wave probes is determined as per the method proposed by Mansard and Funke [16]. To measure the transmitted wave elevation after passing through the perforated plate, one wave probe was positioned at a distance of 4 m on the leeward side of the model. A data acquisition system was used to graphically display and store wave elevation time histories.

Table 1 Range of parameters adopted in the study

Water depth (d)	0.6 m and 0.8 m
Wave height (H)	0.05 m and 0.10 m
Wave periods (T)	0.9 s, 1.3 s, 1.7 s, 2.1 s, 2.5 s
Porosity (P)	0%, 10% and 20%
Slopes (θ)	20° (1/2.8), 15° (1/3.8), and 10° (1/5.6)
Wave steepness (H/L)	0.008–0.08
Surf similarity parameter (ξ)	0.625–4.117
Relative water depth (d/L)	0.63–0.11

Range of Parameters

The experiments were carried out with regular waves of periods (T) ranging from 0.9 s to 2.5 s at an interval of 0.4 s in two different water depths (d), 0.6 m and 0.8 m. Two wave heights (H), 0.05 m and 0.10 m were tested for each T. The different parameters adopted in the experiments are given in Table 1. As initial calibration of the experimental set-up, different incident wave elevations are measured using wave probes without any structure inside the wave flume. The wave probes were calibrated before every set of experiments by lowering and raising the wave probes by a known amount of still water and measuring the corresponding voltage. A calibration constant was derived using regression analysis and wave elevations obtained was minimised for possible errors. The error in the measurement of the maximum H of 0.10 m was estimated to be 0.48 %. Typical wave elevations obtained for H of 0.05 m and a T of 2.1 s in a d of 0.6 m over a 20 % perforated plate at 15° slope are shown in Fig. 4.

Results and Analysis

Impermeable Plate

The composite wave elevations measured on the seaward side of the inclined impermeable plate were subjected to the three-probe method of analysis [16] to get the average K_r. The variations of K_r and loss coefficient, K_l [where$K_l = sqrt(1 - {K_r}^2)$] are shown in Fig. 5. The plots are also marked with zones of different breaking types as per the classification of Sunamura and Okazaki [3] for ease of understanding the physical process. It is observed from the figures that K_r increases with an increase in ξ_o, due to the fact that waves of low steepness surge on the slope without much energy dissipation through breaking. Combining the results of the three different slopes, the minimum and maximum K_r of about 0.04 and 0.58 are observed respectively. The K_l is found to decrease with the increase in ξ_o. The results of all the impermeable plate

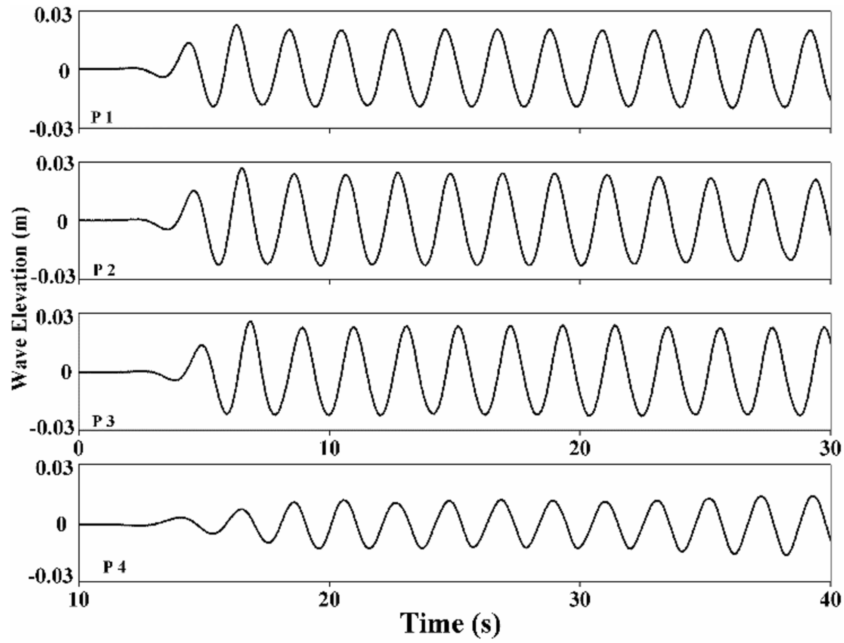


Fig. 4 Typical time series of the measured wave elevations for 20 % perforated plate (T = 2.1 s, H = 0.05 m, d = 0.6 m)

tests were compared with the past studies as shown in Fig. 6. It is clear from the figure that though the K_r coefficients follow a similar trend as reported in past investigations, the magnitude of the K_r values is found to be less. This may be due to the effect of wave energy dissipation over steep slopes and the range of adopted experimental scale parameters. The best fit curve is obtained for the present experimental data and a modified Zanuttigh and Van der Meer [7] equation is arrived with a root mean square value of 0.89. The modified predictive equation is given below which is also mentioned by Gupta and Balaji [17];

$$K_r = 0.571\left[\tanh\left(0.11(\xi_0)^2\right)\right] \quad (1)$$

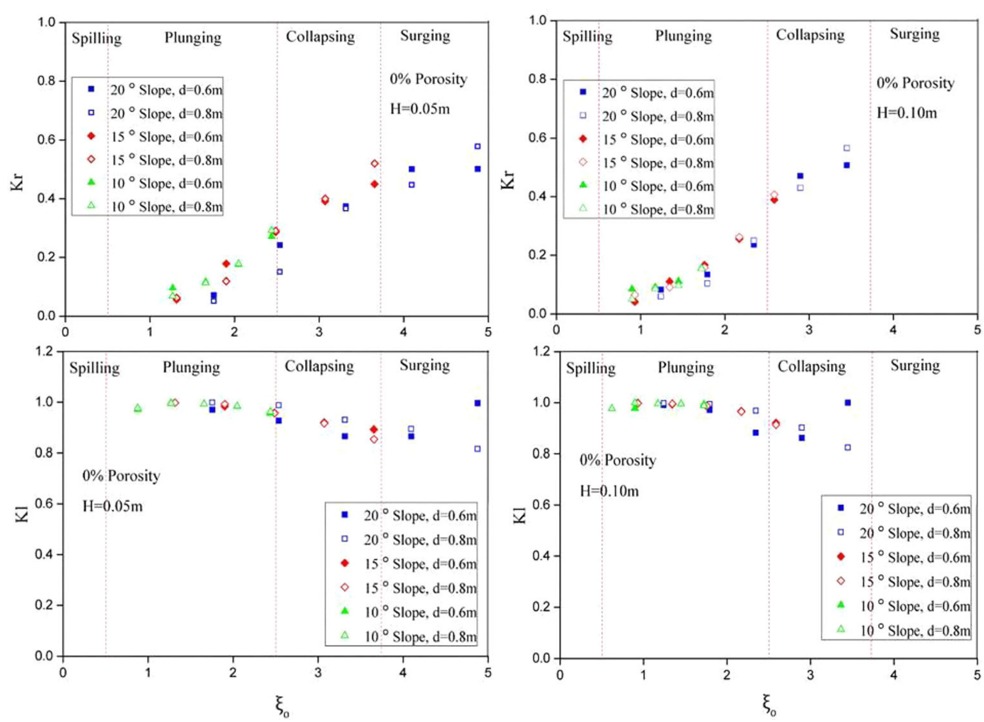


Fig. 5 Effect of slope on K_r and K_l

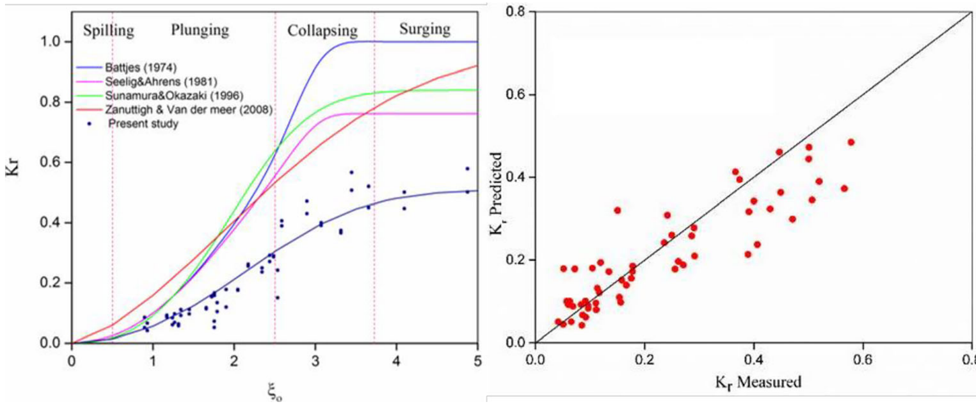


Fig. 6 Comparison of theoretical and experimental K_r of impermeable plate

Perforated Plates

Reflection coefficient

In order to assess the effect of the slope of plates on reflection characteristics, the variations of K_r with respect to ξ_o for different slopes are illustrated in Fig. 7. For a given porosity of the plate, K_r is found to increase with the increase in the incident H. A maximum K_r value of 0.22 and 0.12 are observed in 10 % and 20 % perforated plates respectively. Wave reflections from the perforated plates are observed to be more for wave conditions that fall in collapsing and surging breaker zones, as the wave energy incident is not effectively dissipated. The effects of porosity on the variations of K_r for the three different tested slopes are illustrated in Fig. 8. It is observed from the figure that with an increase in the porosity of plate, K_r is found to decrease. The plates of larger porosity allow more waves to pass through it. In general, the reflection of incident waves is found to be less in the plunging region, due to the energy dissipation caused by breaking. Interestingly, the plate with an inclination of 10° is observed to exhibit similar wave reflection characteristics of that of impermeable inclined plates, for all the tested porosities, specifically in the plunging region.

Transmission coefficient

The transmission coefficients, K_t for perforated plates are observed to increase with the increase in ξ_o as shown in Fig. 9 for the tested two different porosities and three different slopes.

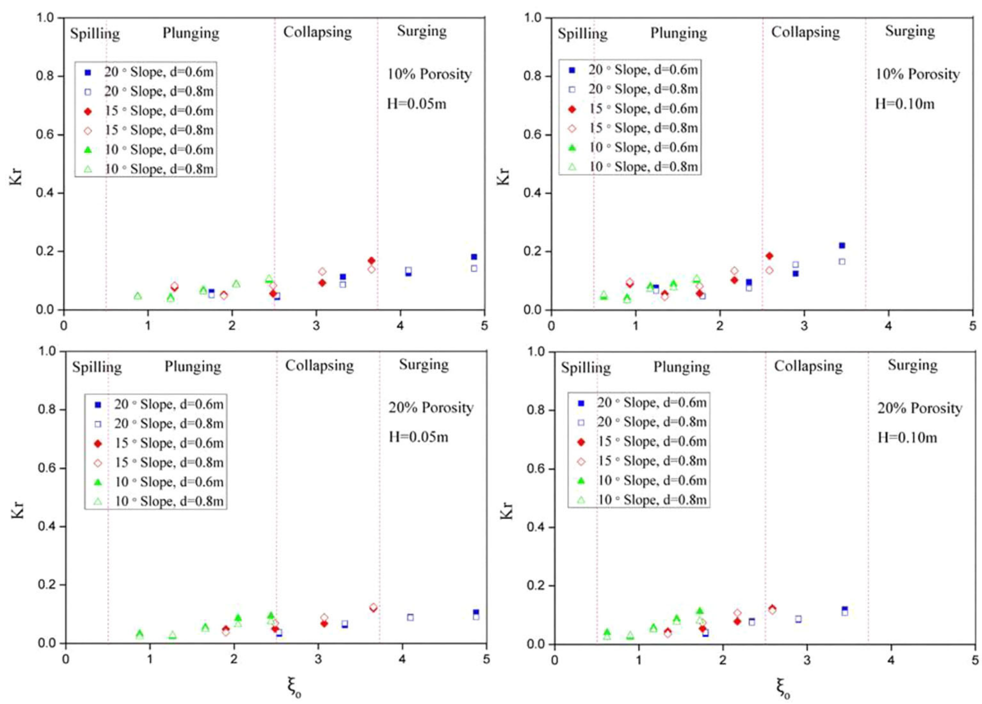


Fig. 7 Effect of slope on K_r for perforated plates

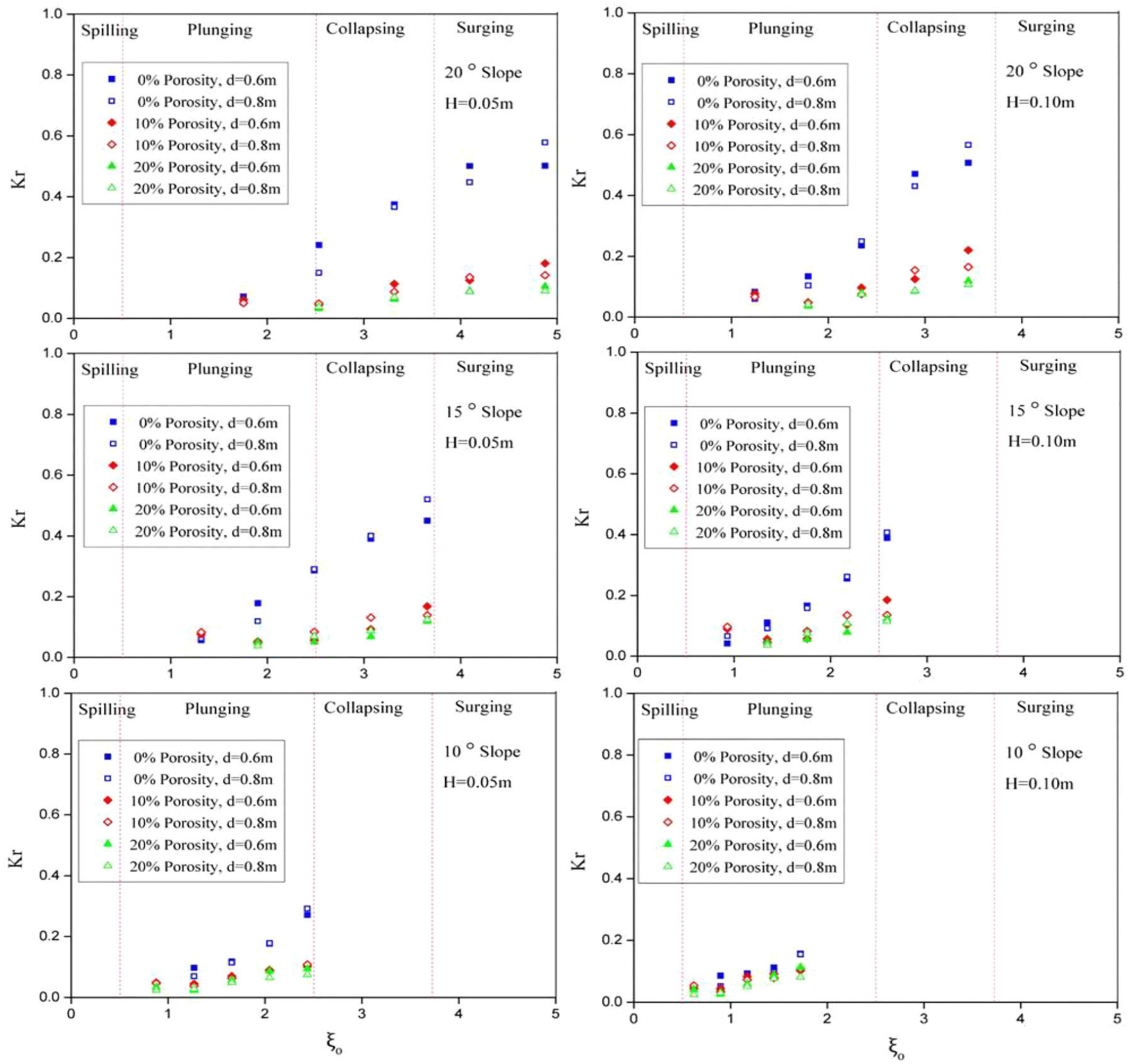


Fig. 8 Effect of porosity on K_r for perforated plates

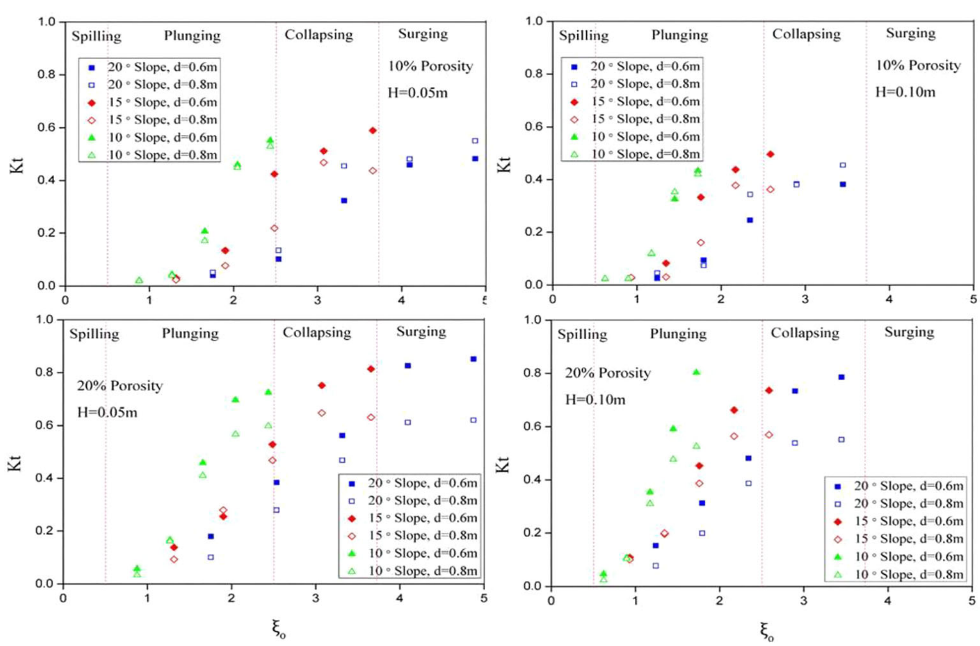


Fig. 9 Effect of slope on K_t for perforated plates

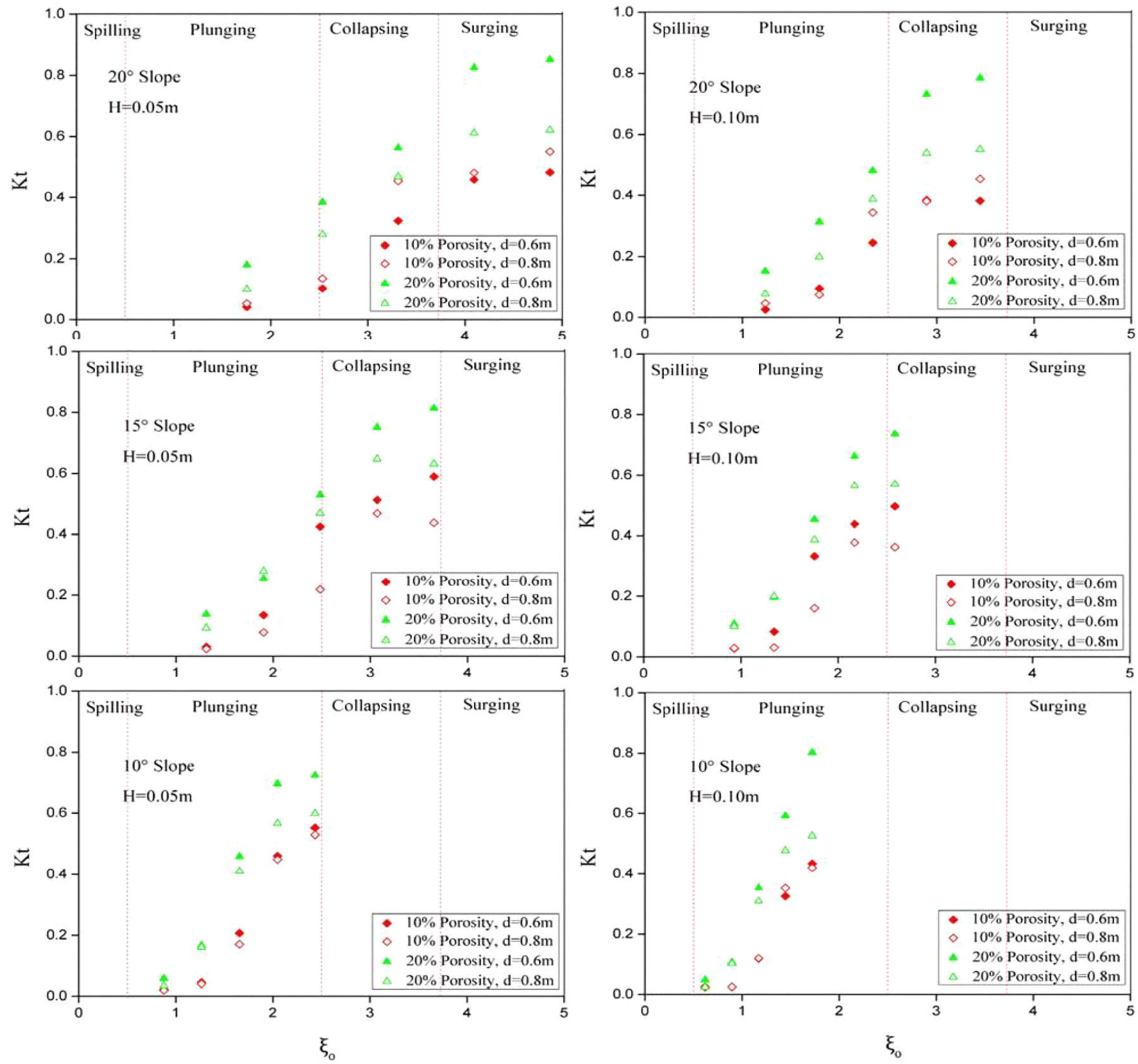


Fig. 10 Effect of porosity on K_t for perforated plates

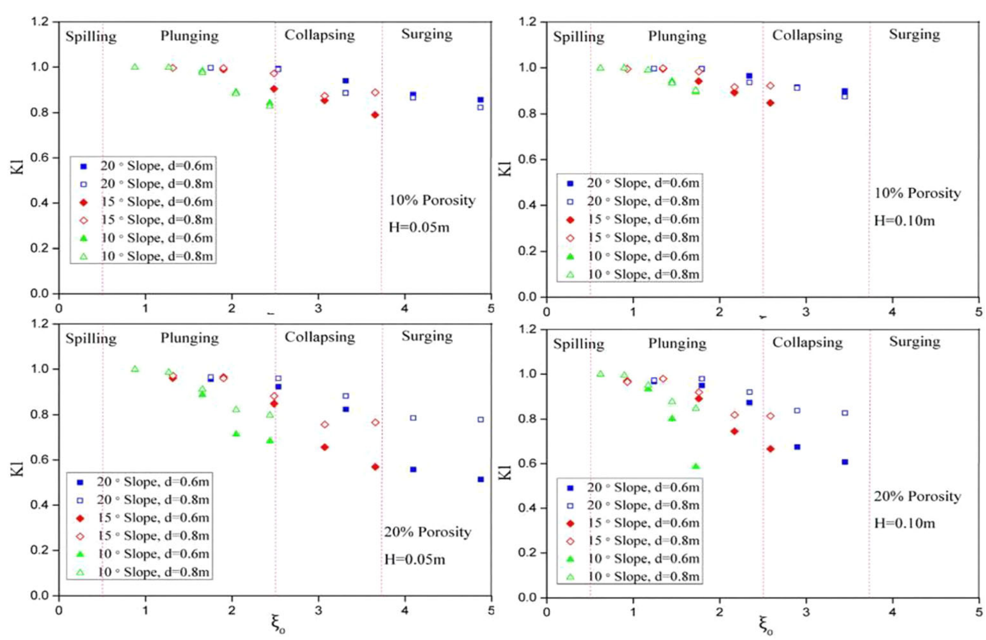


Fig. 11 Effect of slope on K_l for perforated plates

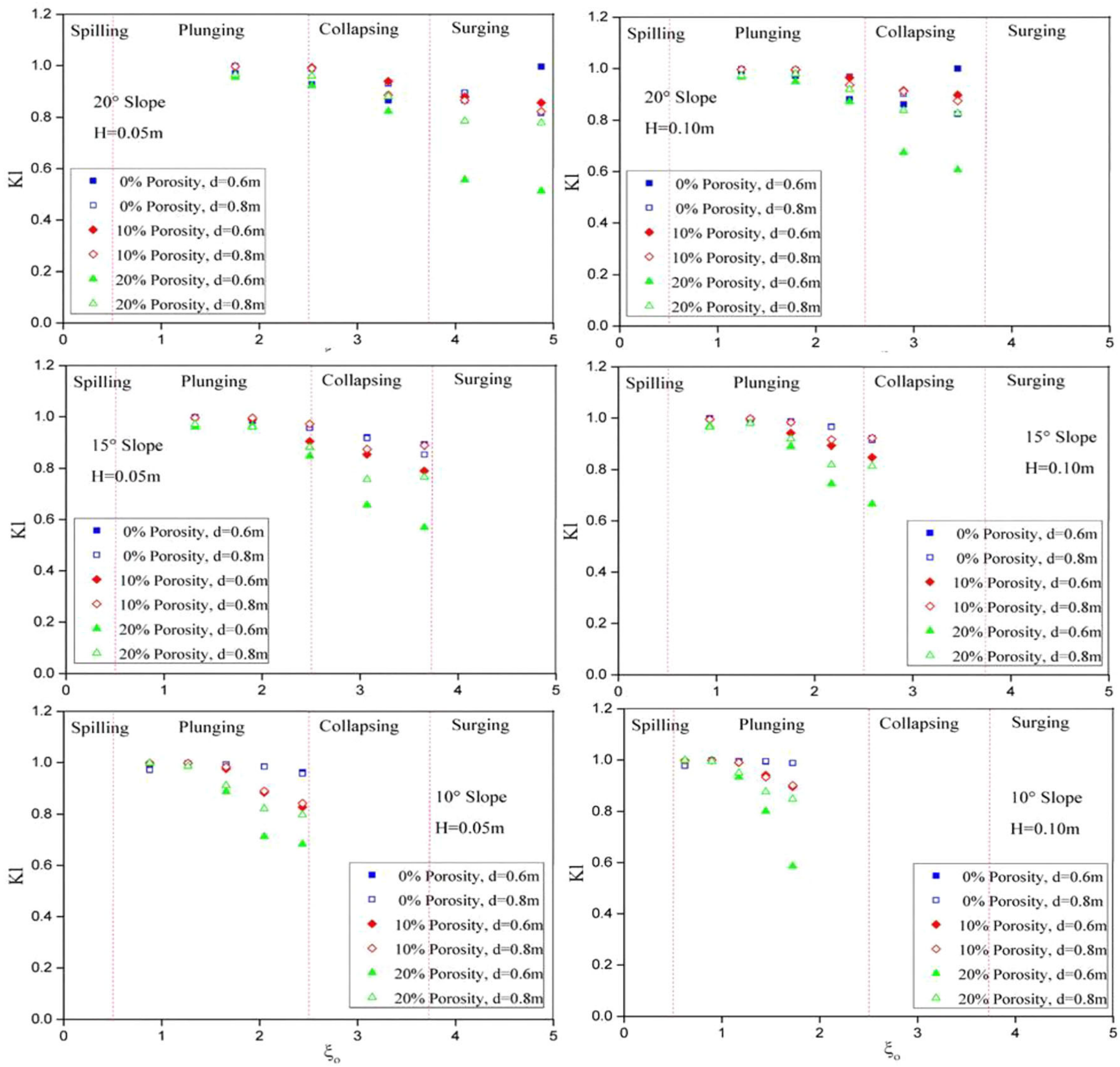
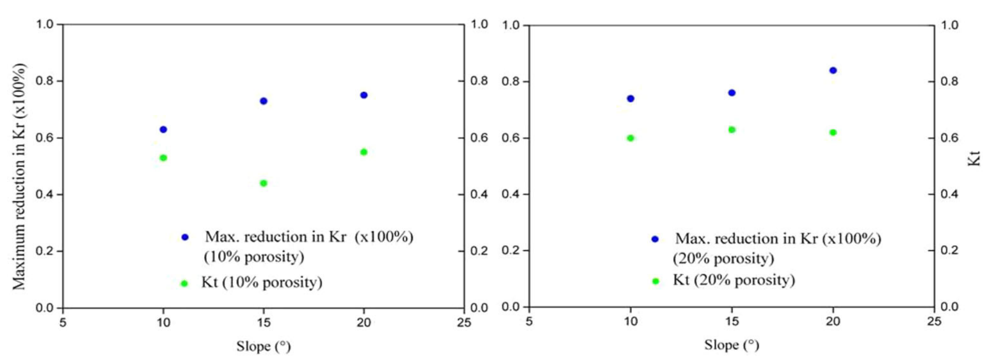


Fig. 12 Effect of porosity on K_t for perforated plates

For a given porosity and ξ_o, K_t is found to increase with the decrease in slope angles, as more waves propagate through the perforated plate with less energy dissipation. It is observed from Fig. 10 that the inclined plate of 20 % porosity transmits more wave energy than that of 10 % perforated plates for all the tested slope angles. Interestingly, the perforated plates of milder slopes exhibit higher wave transmission compared to that of steep slopes, specifically in the region of plunging breakers. It is to be noted here that the increase in d led to a reduction in the wave transmission for a plate of given porosity and slope, due to increase in the area of the perforated plate and thereby higher energy loss during wave interactions with

Fig. 13 Maximum reduction in K_r and corresponding K_t



perforations. From the figures, it is observed that K_t varies from a range of 0.04–0.58 for 10 % perforated plates to a range of 0.06–0.85 for 20 % perforated plate.

Loss coefficient

The energy loss at the structures of the present study are two-fold; one due to the wave breaking on the steep slope and another due to the turbulence at the perforations of the plates. The K_l calculated using the below equation, are shown in Fig. 11 for two different porosities and three different slopes.

$$K_l = sqrt\left(1 - k_r^2 + k_t^2\right) \tag{2}$$

In general, it is observed that higher the water depth more is the wave energy loss. This has been predominantly seen in the plate with 20 % porosity, which may be due to the larger area of perforations. In addition, the wave energy loss is higher in the plunging region than collapsing and surging regions of wave breaking. Within the region of a particular type of wave breaking, the K_l increases with an increase in the slope angles. When compared to the impermeable slope, the K_l values for the perforated slopes are less, which may be due to the wave transmission through the perforations. And as expected, lesser values of K_l were obtained for the sloped plate of 20 % porosity, as can be seen in Fig. 12. Within a particular wave breaking region, the K_l decreases with a decrease in the slope angles. For a given slope and breaking region, an increase in wave height resulted in a decrease in K_l due to the higher reflection and transmission of waves.

Hydrodynamic efficiency

In order to compare the hydrodynamic efficiencies of the different models tested in the present study, the percentage reduction in K_r of the plates of two different porosities with respect to the K_r of the impermeable sloped plates was estimated. The maximum percentage reduction in K_r, obtained for the plates with 10 % and 20 % porosities for all the three slopes are given in Fig. 13. The K_t values corresponding to the maximum reduction in K_r are also presented in the figure for ready reference. It is clear from the figure that the reduction in K_r increases with an increase in slope angles for both tested porosities. Interestingly, a lower K_t is obtained for the plate of 10 % porosity placed at 15^0 slope angle, which shall be considered as the optimum slope and porosity, within the tested range of model and wave parameters.

Conclusions

An experimental investigation has been performed on plates of different porosity and slopes to assess their reflection and transmission wave characteristics. Impermeable plates of similar slopes were also tested under same wave conditions, in order to compare the hydrodynamic characteristics. A modified Zanuttigh and Van Der Meer [7] equation, as a function of ξ, to estimate the K_r for steep impermeable slopes is derived from the experimental results. It is observed from the experiments that the inclined perforated plate benefits from the energy loss due to breaking of waves on the slope and turbulent characteristics of waves while passing through the perforations. Though the K_r values are observed to be less for the inclined perforated plates with respect to the inclined impermeable plates, K_t are found to be high. Criteria for the optimum wave absorption system are governed by the optimum slope/inclination of the structure and porosity. For the present study, the perforated plate with 10 % porosity arranged at an inclination of 15° is arrived as the optimal parameters of the structure to dissipate wave energy with minimum reflection and transmission characteristics within the tested range of model and wave conditions. The wave energy dissipation characteristics of the perforated plates with different diameter and shape of the holes defining the porosity of the perforated plate is recommended for further research.

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