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Wave shoaling over steep slopes-An experimental investigation

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ABSTRACT

Shoaling characteristics of waves on steep slopes are unique due to significant reflections. Wave heights on steep slopes are altered in a way that is different from wave interaction with mild slopes. Studies on detailed characterization of such phenomenon on steep slopes are scanty. In this study, an attempt has been made to quantify the wave shoaling coefficient (K_s) on steep slopes. Wave shoaling and reflection characteristics are studied on steep sloped (1/2.8, 1/3.8, 1/5.6), smooth and impermeable beaches a physical wave tank facility. The thorough analysis of experimentally measured wave heights along the steep slopes revealed that K_s is influenced by relative depth which is the ratio of shoaling depth (d_{sh}) and shoaling wave length (L_{sh}) as well as surf similarity parameter (ξ) and this led to an empirical formula between K_s and other important parameters related to initial wave and beach slope conditions. Through this study, application of linear wave theory (LWT) has been extended for the estimation of shoaling coefficients on steep slopes, which otherwise reported to be not applicable. The derived empirical relations were also tested for the results obtained from experiments performed on a gentle slope (1/100) for similar test conditions. The details of experimental program, analyzing methodology and results are discussed in this paper.

1. Introduction

Understanding of wave shoaling, transformation of wave heights, over beach slopes is essential for many coastal engineering applications. Combined reflection, shoaling and breaking lead to complex variation in wave heights, when the wave travels on steep slopes, which cannot be represented by the linear wave theory as it is reportedly suitable for gentle slopes (slope < 1/10; CEM, 2002). In the past experimental and field studies were carried out to understand the shoaling mechanism in a variety of situations, however majority of the past studies are pertaining to gentle slopes (Wiegel, 1950, Iverson (1953), Eagelson (1956), Iwagaki, 1968, Iwagaki and Sakai, 1972, Yamaguchi and Tsuchiya (1976), Svendson and Hansen, 1976, Thompson and Vincent (1984), Black and Rosenberg, 1992). Though the wave interaction with steep slopes were studied, in the past, by few investigators (Iyyer, 1970 and Tsai et al. (2005)), the influence of initial wave and slope conditions on the wave shoaling coefficients were not reported. It is also evident that there are attempts to estimate the transformation characteristics of wave heights on gentle beaches, through numerical model studies (Watanbe and Dibjania, 1988; Madsen and Sorenson, 1992; Nwogu, 1993; Grilli, 1996; Madsen et al., 2002; Jabbari, 2013).

Through an experimental investigation, Tsai et al. (2005) studied shoaling and breaking of waves on steep as well as gentle slopes (1/3, 1/5 and 1/10). The experimental results for wave shoaling were found to deviate when compared to the existing empirical formula given by Shuto (1974). However, no attempt has been made to characterize wave shoaling over steep slopes, as function of ξ.

It is clear from the review of past literatures that most of the experimental studies conducted to understand wave shoaling are pertaining to gentle slopes. To the best of authors' knowledge, the studies for the combined shoaling and reflection of regular waves on steep slopes are scanty and there is no formula existing for determination of shoaling coefficient for regular wave shoaling over steep slopes and this has motivated the present experimental study. Based on experimental results, an empirical formula to estimate the value of K_s on any location on the slope for given initial wave conditions as well as slope of beach is found out. The experimental results from the steep slopes are also compared with the experiments performed on one gentle slope for similar test conditions.

2. Experiments

2.1. Experimental conditions

The experimental investigations were carried out in a two dimensional wave flume; 50 m long, 1 m wide and 1 m deep at ocean engineering laboratory of IIT Bombay, India. One end of the wave

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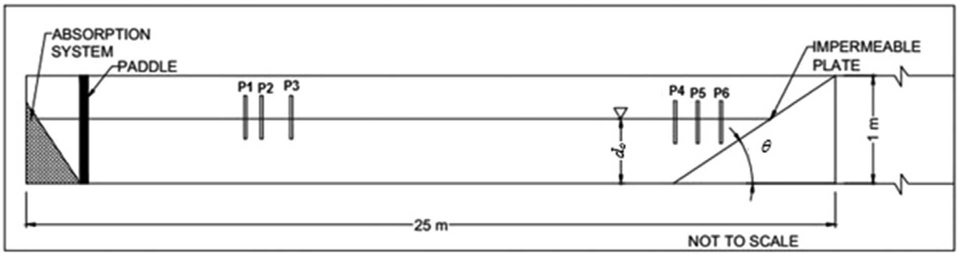

Fig. 1. Longitudinal section of wave flume with experimental set-up of steep slope.

Table 1
Range of experimental data for first set of experiments.

Parameter	Tested range	
	Min	Max
d_o/L_o	0.06	0.63
H_o/L_o	0.005	0.079
H_o/d_o	0.0625	0.166
ξ	0.63	5.14

flume is installed with a piston type wave maker, which is capable of producing regular waves of a wide range of amplitudes and frequencies. Experiments were divided into two distinct sets. The first set of experiments was performed with three steep slopes and second set of experiments was carried out with one gentle slope. The sloping bed was made of steel plates supported on an adjustable frame to arrive at various slopes by changing the bottom angle of the plate.

For the first set of experiments, three different bottom angles (θ) 10°, 15° and 20° were considered to get the steep slopes, 1/5.6, 1/3.8 and 1/2.8 respectively. A series of capacitance type probes were used to measure the wave elevations, which were acquired at a sampling frequency of 40 Hz. Three wave probes (P1, P2 and P3), as shown in Fig. 1, were used to measure composite reflection and incident wave elevations, the distance between these probes were obtained as per Mansard and Funke (1980). Three more wave probes (P4, P5 and P6) were deployed to measure wave elevations on the slope and thus get the values of shoaling wave heights (H_{sh}). The wave probe P4 is kept at the beginning of the slope and other probes are kept on the slope at an equal distance of 0.3 m such that all three probes were away from the breaking zone.

For the experiments, regular waves of five different periods (T_o) varying from 0.9 to 2.5 s at an interval of 0.4 s were considered. Two different wave heights (H_o) of 0.05 m and 0.1 m were considered, for each wave period. Tests were conducted in two different water depths (d_o = 0.6 m and 0.8 m) measured at the toe of the slope. Thus, ratio of depth (d_o) to deep water wavelength (L_o) varied from 0.06 to 0.63 indicating that wave conditions considered in the first set of experiments corresponded to intermediate water depths to deep water waves. The range variations of parameters adopted in this study are given in Table 1.

For the second set of experiments, a gentle slope of 1/100 is used which is sloping for a distance of 18 m followed by a flat portion. Seven capacitance type gauges (P1, P2, P3, P4, P5, P6 and P7) were deployed on the slope to measure wave elevations. Probe P1 is placed at the starting of slope. Probe P7 was placed on the flat portion of the slope. While probes P2, P3, P4, P5 and P6 were placed along the varying depth of the slope. Spacing between the probes is shown in the Fig. 2. For these experiments, regular waves of five different periods (T_o) varying from 2 s to 2.8 s at an interval of 0.2 s were considered. For each of the wave period, five different wave heights (H_o) of 0.112 m, 0.113 m, 0.119 m, 0.120 m and 0.117 m were considered. Tests were conducted in water depth (d_o = 0.7 m) measured at the toe of the slope, whereas water depth above the flat portion of the slope is (d = 0.52 m). Ratio of depth (d_o) to wavelength (L_o) varied from 0.06 to 0.11 indicating the wave conditions considered in the second set of experiments confined to intermediate water depths.The range of variation of parameters adopted in the second set of experiments is shown in the Table 2. Test conditions of both sets of experiments lie in Stokes' second order theory regime, as shown in Fig. 3. Typical measured wave elevation (η) time series, obtained for H_o = 0.05 m, T_o = 0.9 s, deep water wavelength (L_o) = 1.26 m, slope = 1/2.8 and d_o = 0.6 m are shown in Fig. 4.

3. Results and discussions

3.1. Wave reflection

For the first set of experiments, the average reflection coefficients (K_r) were estimated from the wave elevation time series obtained from three probes (P1, P2 and P3) as per the method proposed by Mansard and Funke (1980). The variation of reflection coefficients with surf similarity parameter ($\xi = \tan\theta/\sqrt{(H_o/L_o)}$) is shown in Fig. 5, along with empirical variation of earlier studies (Krishnendu and Balaji, 2014; Battjes and Seelig and Ahrens, 1974, 1981). It is clear from the figure that present experimental results closely follow the trend of

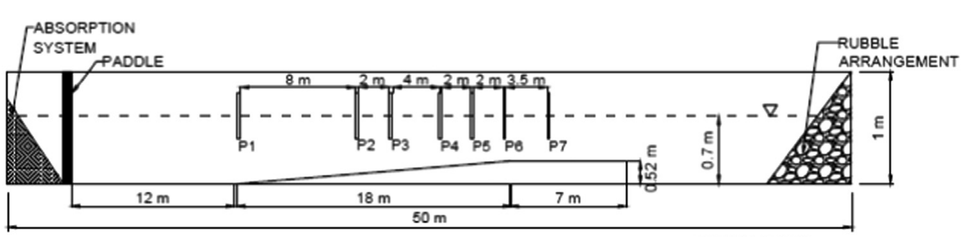

Fig. 2. Longitudinal section of wave flume with experimental set-up of a gentle slope.

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