

Influence of Relative Water Depth on Wave Run-up Over Costal Structures; Smooth Slopes

D. A. Peiris and J. J. Wijetunga

Abstract: This paper describes an experimental study carried out in a laboratory wave flume to quantify the influence of the relative water depth on the wave run-up over a smooth sloping structure. The run-up measurements were carried out over practically important ranges of the wave steepness, the relative water depth and the structure slope. The results indicate an increase in the wave run-up at shallow depths compared to deep water conditions. This increase is up to about 20% for plunging breakers and is as much as 65% for surging breakers.

Keywords: Wave Run-up, Breaker Parameter, Water Depth, Smooth Slope, Plunging Waves, Surging Waves

1. Introduction

Wave run-up is one main parameter required to determine the crest level of coastal structures that are designed for no or only marginal overtopping, such as revetments, dikes, and breakwaters for small-craft harbours. The wave run-up on a coastal structure depends on the incident wave properties as well as on the structure characteristics such as the slope angle, the surface roughness, the water depth at the toe of the structure and the slope angle of the foreshore.

The combined effect of the incident waves and the slope angle of the structure on the wave run-up over slopes has been investigated in detail, for example, [1-6], among others. Further, Wijetunge and Sarma [7] have examined the effect of the surface roughness of the structure on the wave run-up, and more recently, Peiris and Wijetunge [8] have studied the influence of the slope angle of the foreshore on the wave run-up over smooth slopes. However, very little detailed information is available on the effect of the water depth at the toe of the structure on the wave run-up. The paucity of data on the effect of water depth on the wave run-up is partly owing to the fact that most laboratory experiments on wave run-up over coastal structures have been conducted in relatively deep water. Consequently, little is known about the effect of wave transformation at shallow depths including possible breaking of waves due to the foreshore on the subsequent run-up over coastal structures. The limited number of experimental studies of wave run-up under depth-limited conditions include those reported in [9] and [10] with irregular waves breaking on foreshores inclined at 1:30 and 1:100, respectively. They found that breaking of irregular waves on a

shallow foreshore results in lower maximum run-up heights, although higher mean run-up heights could sometimes occur. However, an explanation as to what caused the higher mean run-up heights in some of the tests is not provided. Moreover, both these studies examined only the influence of the foreshore induced breaking of higher wave heights in an irregular wave train on the subsequent wave run-up, so their measurements have not been analysed in terms of the effect of the water depth.

Accordingly, there is a need to further examine the way in which depth-limited wave conditions influence the wave run-up, particularly because most coastal structures in Sri Lanka are located in shallow waters. Thus, the primary objective of the present paper is to quantify the effect of the relative water depth at the toe of the structure on the wave run-up over a smooth slope for a range of the relevant dimensionless parameters.

2 Experimental Set-up and Procedure

The experiments were carried out in a wave flume in The Fluids Laboratory of University of Peradeniya. This flume consists of a regular wave generator and a 12.75 m long, 0.52 m wide and 0.70 m deep Perspex walled channel (see Fig. 1).

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A wooden model of a sloping structure together with a 2 m long foreshore was placed at the far end of the channel. The inclination of both the structure and the foreshore could be changed according to the requirement.

A Perspex sheet was also placed on the face of the model structure to obtain a smooth surface.

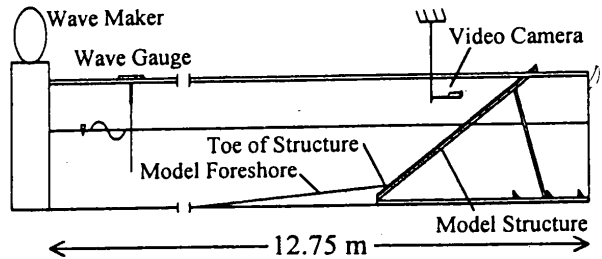


Figure 1: Experimental set-up.

The wave parameters were recorded using an Armfield H40, resistant type, twin-wire probe. The use of a single probe meant that the wave parameters could not be obtained at the toe of the structure as the incident waves at a location so close to the structure get distorted by the waves reflected from the structure itself in no time. Therefore, the wave probe ought to be positioned some distance away from the structure to enable the recording of wave parameters before the waves reflected from the structure have had time to reach the probe. Accordingly, after several trial runs over a range of wave periods, the wave probe was placed at a location 4 m in front of the toe of the structure. The wave records at this location indicated that the reflected waves reach there only after about 5 – 7 incident waves have passed the probe. Accordingly, the wave parameters and the corresponding run-up were always recorded for an incident wave that had not been affected by the reflections from the structure (i.e., usually for the 5th or the 6th wave). The wave parameters obtained in this way may be considered as 'deep water' conditions as the waves are yet to transform over the sloping foreshore ahead of the structure.

A video camera was employed to obtain the wave run-up on the slope. The video clips obtained in this way were played on a Personal Computer (PC) at 25 frames per second to obtain run-up levels, averaged at 5 cm intervals across the slope. Moreover, the run-up measurement for a given wave setting was repeated twice and the average was taken. Preliminary tests of the repeatability

of the measurements indicated that the wave as well as run-up records for a given wave setting could be repeated with less than 5% deviation.

About 150 tests were performed in this way over a range of practically useful values of the wave steepness as well as the water depth at the toe of the structure.

3. Dimensional Analysis

We first identify the dimensionless groups relevant to the present problem to facilitate the interpretation of the experimental results. The wave run-up (R) over a smooth, impermeable slope under the present experimental conditions depends on d_s , the depth of water at the toe of the structure; g , the acceleration due to gravity; H_0 , the deep water wave height; T , the wave period; α , the slope angle of the structure; and β , the slope angle of the foreshore.

Thus, the non-dimensional run-up (R/H_0) may be expressed as a function of the following dimensionless groups:

$$\frac{R}{H_0} = \phi \left(\frac{R_0}{gT^2}, \frac{d_s}{H_0}, \tan \alpha, \tan \beta \right) \quad (1)$$

We now define a breaker parameter for wave action slopes [11]:

$$\zeta_0 = \frac{\tan \alpha}{\sqrt{s_0}}, \text{ where } s_0 = \frac{2\pi H_0}{gT^2}$$

Following many previous investigations of wave run-up on slopes (e.g., [1, 3-11]), the present study employs the breaker parameter ζ_0 to represent the dual dependence of the non-dimensional wave run-up on H_0/gT^2 and $\tan \alpha$ for waves that break on the structure.

4. Test Conditions

The test ranges of the main parameters relevant to the present study are summarized in Table 1. The measurements are available over a range of ζ_0 from 1.5 to 3.55 covering both the plunging and the surging breaker types. The water depth at the toe of the structure was lowered from 27 cm to 0 (corresponding range of water depths in the horizontal part of the tank was 48 cm to 21 cm) in steps of 1 cm, for each value of ζ_0 . All tests were carried out with the foreshore in place, and tests without a sloping foreshore (i.e., $\beta = 0$) were not possible owing to the limitations of the wave



flume. The run-up measurements have been made for three different values of the structure slope: $\alpha = 24.8$ deg., 28.7 deg., and 32.7 deg. to the horizontal. The slope angle of the foreshore was kept at 3.7 deg. to the horizontal whilst its length was about 1-2 times the wave length for the range of waves tested. The foreshore slope employed is representative of field conditions in Sri Lanka though its length is constrained by the comparatively shorter length of the flume.

Table 1: Test conditions.

Parameter	Study range
H_0	4.2 – 14.5 cm
T	0.7 – 1.1 s
d_s	0 – 27 cm
α	24.8 – 32.7 deg.
β	3.7 deg.
d_s/H_0	0 – 6
H_0/gT^2	0.005 – 0.023
ζ_0	1.5 – 3.55

5. Results and Discussion

Fig. 2 shows several examples of the way in which the relative run-up (R/H_0) varies with the relative water depth at the toe of the structure (d_s/H_0). Note that the values of the wave steepness H_0/gT^2 have been confined to a narrow range whilst keeping the slope angle of the foreshore as well as the slope angle of the structure constant for each set of measurements.

We see in Fig. 2 that R/H_0 initially increases with d_s/H_0 and reaches a peak value (segment AB of the curves), then declines with further increase of d_s/H_0 (segment BC) before reaching a nearly constant value for relative depths larger than about 2 (segment CD). Accordingly, we see that, although R/H_0 is affected little or perhaps not at all by the relative water depth at values of d_s/H_0 larger than about 2, the water depth does have a significant influence on R/H_0 at low values of d_s/H_0 i.e., segments AB and BC.

We shall first consider the run-up records in segment AB of the curves. As one would expect, the run-up records in segment AB were due to waves that were breaking on the foreshore. Consequently, it is not surprising that R/H_0 in the foreshore induced breaking region reduces gradually with decreasing d_s/H_0 because waves break progressively away from the toe of the

structure as d_s/H_0 is reduced. It is also interesting to examine the way in which the values of R/H_0 at $d_s/H_0 = 0$ vary with H_0/gT^2 . Accordingly, Fig. 3 shows R/H_0 at $d_s/H_0 = 0$ over a range of H_0/gT^2 for two different values of the slope of the structure: $= 24.8$ deg. and 32.7 deg..

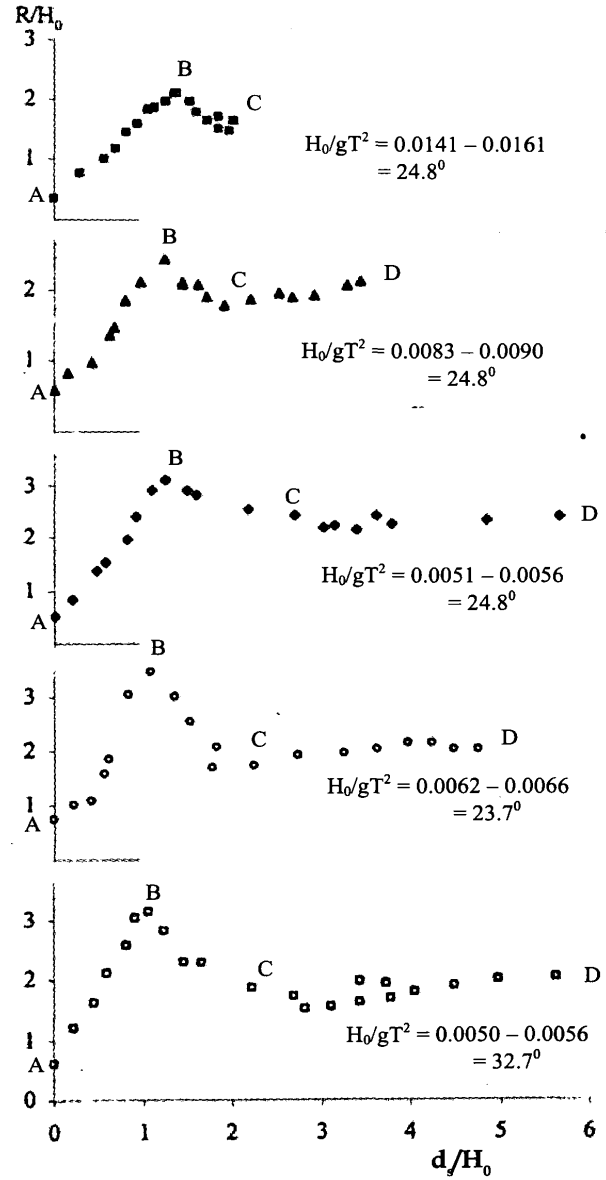


Figure 2: Examples of the way in which R/H_0 varies with d_s/H_0 .

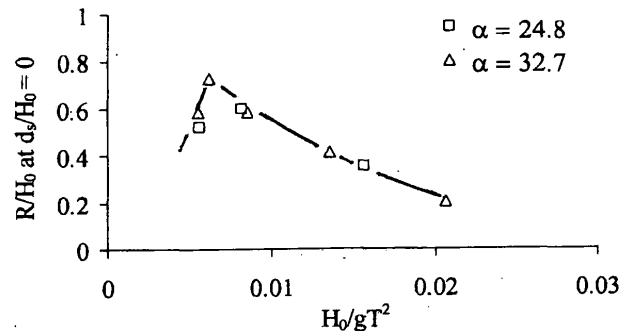
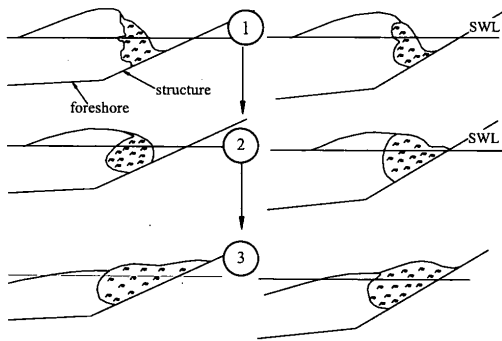


Figure 3: Variation with of H_0/gT^2 of R/H_0 at $d_s/H_0 = 0$ (Values of α in degrees to the horizontal.)



Fig. 3 appears to suggest that, as the wave steepness is reduced, R/H_0 at $d_s/H_0 = 0$ increases and reaches a peak value of $R/H_0 \approx 0.75$ at $H_0/gT^2 \approx 0.007$, before beginning to decline towards zero. The curve in Fig. 3 is drawn by eye through the data points merely to indicate the trend.

On the other hand, wave breaking was primarily due to the structure slope at values of d_s/H_0 in segments BC and CD of the curves in Fig. 2. Now, an interesting question is what causes significantly higher values of R/H_0 at low values of d_s/H_0 around the peak at B compared to higher values of d_s/H_0 , say at C. So, to find a clue to the processes that are responsible for this behaviour, let us have a closer look at the event immediately preceding the run-up, i.e., wave breaking. Accordingly, video records of the wave breaking and the subsequent run-up corresponding to data points B and C were made through the side panels of the wave channel, and still images of the time frames immediately preceding the run-up were obtained at 1/25 s intervals. Two such examples of the time sequence of wave breaking leading to run-up on the slope are shown in Fig. 4 and Fig. 5 for plunging and surging breaker types, respectively. The time sequence of wave motion shown on the left side of each Figure (Case B) corresponds to a data point at B (i.e., the peak in run-up) whilst that on the right side (Case C) is for a data point in the vicinity of C.



Case (B) : $d_s/H_0 \sim 1.2$ Case (C) : $d_s/H_0 > 2$

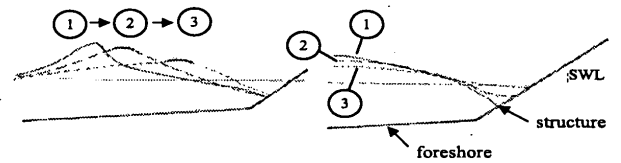


Bubbles of air in water that form in the highly violent leading part of the breaking wave.

Figure 4: Examples of the time sequence of wave breaking (plunging breakers) on the slope corresponding to data points B and C (see Fig. 2.).

Now, for plunging breakers shown in Fig. 4, the wave forms during the breaking process for case

(B) and case (C) appear to be qualitatively similar. However, a closer look reveals that, at the point of breaking (i.e., image no. 1 in time sequence for Case B), the height of the wave above the still water level (SWL) is, in this instance, about 20% more than that in case (C), indicating a notable increase in the height of wave above the SWL at shallow depths. On the other hand, for surging breakers shown in Fig. 5, we immediately see that the wave forms between the two cases are not similar. The video clip of case (B) for shallow depth clearly shows that, as the waves approach the toe of the structure, the wave steepness increases significantly and the waves pretend to curl over and plunge on to the structure (time sequence no. 1 for case B), but eventually just surging forward (2 & 3). If waves were to break in a more violent plunging action, there would have been less energy left for the wave to run up over the slope. But, as that does not happen and the waves just surge over the slope, one would expect case (B) in Fig. 5 with a larger breaker height to be associated with a comparatively larger run-up.



Case (B) : $d_s/H_0 \sim 1.2$

Case (C) : $d_s/H_0 > 2$

Figure 5: Examples of the time sequence of wave breaking (surging breakers) on the slope corresponding to data points B and C (see Fig. 2.).

However, in comparatively deep water (i.e., case C in Fig. 5), there is no marked increase in the wave steepness, and the waves gently surge over the slope of the structure.

The run-up measurements at each of the other values of the wave steepness and the structure slope covered in the present study too showed a behaviour qualitatively similar to those described above for plunging and surging breakers.

The height of the wave above the SWL at the point of breaking was obtained from the still images mentioned earlier, for all values of ζ_0 . Thus, the change in the height of wave above SWL at the point of breaking with respect to the height of wave above SWL measured at the middle of the channel (i.e., 4 m ahead of the toe of the structure)

was determined and the results are shown in Fig. 6. However, it must be mentioned that the wave heights closer to the structure at the point of breaking obtained from the still images are much less accurate than the wave heights obtained from using the wave gauge placed in the middle of the channel. The error of taking the wave heights from the video images is estimated to be $\pm 5\text{mm}$, which is indicated in Fig. 6 in the form of error bars. Note that curve (B) is for run-up records at the peak (point B in Fig. 2) whilst curve (C) is for those near point (C). The negative values of some of the data points suggest a reduction in wave height.

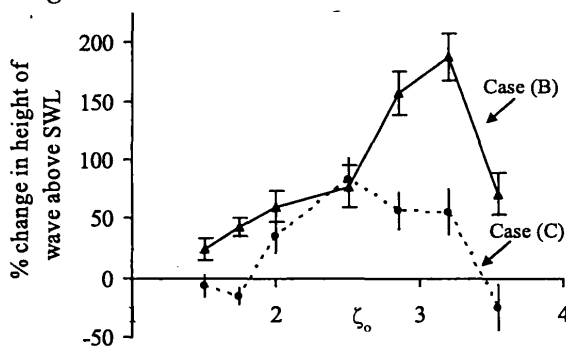


Figure 6: Variation with ζ_0 of the change in the height of the wave above SWL.

We see in Fig. 6 that, for plunging breakers (i.e., ζ_0 less than about 2.5), the wave height in front of the structure just before breaking is about 20% – 30% higher at B than at C. More importantly, the data points that represent surging breakers (i.e., $\zeta_0 = 2.5, 3.2$ and 3.55) indicate that the increase in the wave height just before breaking at B is quite substantial, over 100%, compared to that at C. At first sight, this increase in the height of the wave above the SWL and the consequent increase in R/H_0 for both plunging and surging breakers is, perhaps, not entirely surprising as one would expect the waves to shoal over shallow foreshores thus increasing the wave steepness, and then the higher breaker heights to give higher run-up levels. However, waves reflected by the structure interact with incident waves, and consequently, wave transformation on the foreshore could also be influenced by the hydraulic processes at the structure. So, we need to estimate the contribution from shoaling alone over the foreshore slope without the structure in order to quantify the effect, at least the order of magnitude, of the presence of the structure on the wave field in front of it.

Accordingly, the shoaling coefficient K_s at the toe of the structure was determined using the small amplitude wave theory for each value of ζ_0 and for wave conditions represented by curves (B) and (C) in Fig. 6, and the results are shown in Fig. 7. It should be added that Shuto's [11] non-linear theory for wave shoaling, which includes the finite amplitude effect as well, also gives the same value for K_s as the small amplitude theory, for the range of values of d_s/L considered here. Now, Fig. 7 clearly shows that the shoaling of waves over the foreshore slope alone can account for only less than 10% of the increase in wave height at the point of breaking. Consequently, it appears that the influence of the hydraulic responses owing to the presence of the structure, further aided by the shallow depths, is largely responsible for the significant increase in the height of the wave above the SWL closer to the structure.

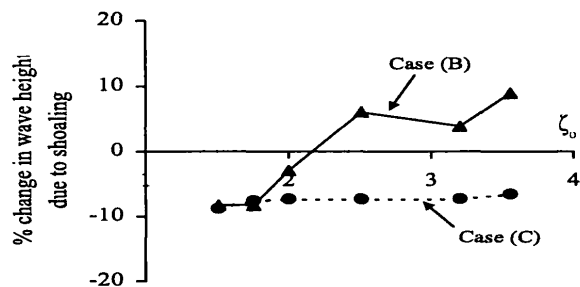


Figure 7: Variation with ζ_0 of the % change in wave height due to shoaling.

We have already seen from the curves of wave run-up variation with d_s/H_0 that the run-up is higher in segment BC and in part of AB than the mean run-up for segment CD. It is interesting to examine the range of d_s/H_0 values in which R/H_0 is higher than the mean R/H_0 for segment CD. This is shown in Fig. 3 for all measurements over a range of values of ζ_0 . The inset in Fig. 8 indicates the region where shallow water effects could be important in the design of coastal structures. The inset also identifies the lower bound (L) and the upper bound (U) of d_s/H_0 within which shallow water depths could cause an increase in the run-up, together with the d_s/H_0 value corresponding to the peak (P) in R/H_0 .

In Fig. 8, the symbols in black are those for $\alpha = 24.8^\circ$ whilst the symbols in grey are for $\alpha = 32.7^\circ$. The curves that are drawn through the data points for the peak, the lower bound and the upper bound of R/H_0 despite the scatter of



data are approximate lines to merely indicate the range of values of d_s/H_0 within which the shallow water effects could be important. Accordingly, we see that the peak value of R/H_0 mostly occurs at $d_s/H_0 \approx 1.2$ whilst, on the whole, it appears that shallow water could cause an increase in the run-up for values of d_s/H_0 falling between 0.8 and 2.

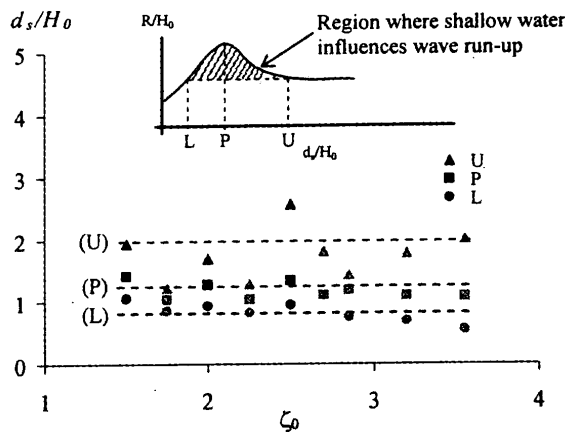


Figure 8: Range of d_s/H_0 in which shallow water causes an increase in R/H_0 .

Fig. 9 shows the variation with ζ_0 of the peak value of R/H_0 (peak of run-up with d_s/H_0 at B in Fig. 2) as well as the mean value of R/H_0 for segment CD. Apparently, the mean R/H_0 for segment CD (i.e., for $d_s/H_0 > 2$) follow the usual pattern of most previous measurements in relatively deep water conditions, with an initial increase of R/H_0 with ζ_0 reaching a peak at about $\zeta_0 = 2.5$ before beginning to decline with further increase of ζ_0 . The peak value of R/H_0 (with d_s/H_0) that occurs at $d_s/H_0 \approx 1.2$ too show a qualitatively similar variation to that of the mean R/H_0 . However, the maximum value of the peak R/H_0 variation is shifted to around $\zeta_0 = 3$. We also see that the peak R/H_0 is considerably larger than the mean R/H_0 for $\zeta_0 > 2.5$, i.e., at values of ζ_0 for which wave breaking type is surging. One other thing to note is that the peak values of R/H_0 scale well with ζ_0 showing no significant dependency on the slope angle of the structure (α).

We now examine in Fig. 10 the maximum percentage increase of R/H_0 at low values of d_s/H_0 with respect to the mean value. Also indicated on this figure are the types of wave breaking obtained from the examination of video records as well as from visual observations of wave breaking on the structure.

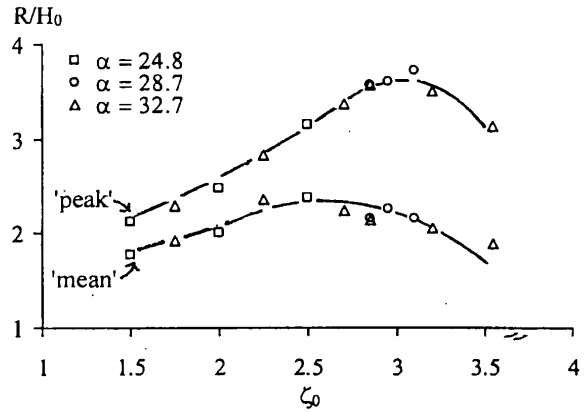


Figure 9: Variation of ζ_0 with the "peak" and "mean" values of R/H_0 with d_s/H_0 . (Values of α in degrees to the horizontal.)

Accordingly, $\zeta_0 < 2.5$ belongs approximately to the plunging breaker; $2.5 < \zeta_0 < 3$, to the collapsing breaker; and $\zeta_0 > 3$, to the surging breaker. However, it must be added that the change from one type of breaker to another does not happen suddenly, but over a transition region.

The broken line shown in Fig. 10 is drawn to merely guide the eye through the data points. We see that the increase in R/H_0 for plunging breakers at low values of ζ_0 is about 20%. However, this figure increases sharply through the collapsing breaker region up to as much as about 65% for surging breakers.

Finally, a word of caution. The wave run-up measurements reported in the present paper have been made over a smooth, impermeable slope. The results are therefore applicable, barring any scale effects, to smooth concrete slopes of revetments and dikes employed in coast protection. However, it is not entirely clear whether or not the present measurements are valid for rough slopes of coastal structures such as rubble-mound breakwaters and revetments as well. Therefore, further research is in progress to quantify the effect of the water depth on the wave run-up over rough slopes too.



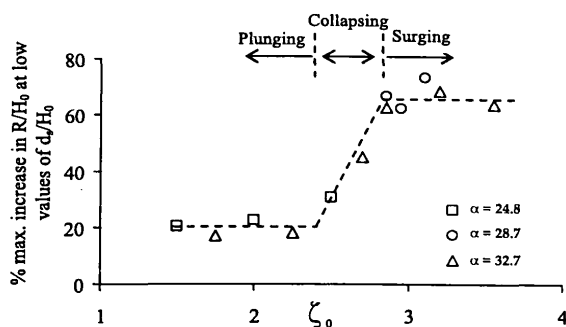


Figure 10: Variation with ζ_0 of the maximum increase in R/H_0 at low values of d_s/H_0 . (Values of α in degrees to the horizontal.)

5. Conclusions

The following conclusions are drawn for the range of conditions covered in the present experiments of wave run-up over a smooth sloping structure.

1) The relative wave run-up (R/H_0) initially increases with the relative water depth at the toe of the structure (d_s/H_0), reaches a peak value at $d_s/H_0 \approx 1.2$, before beginning to fall and approach a nearly constant value for d_s/H_0 larger than about 2.

2) The measurements also indicate that shallow water effects are important for values of d_s/H_0 falling between 0.8 and 2 with the maximum effect occurring at $d_s/H_0 \approx 1.2$.

3) The maximum percentage increase of R/H_0 at shallow water depths with respect to the mean value in deep water ($d_s/H_0 > 2$) is about 20% for plunging breakers and about 65% for surging breakers.

Acknowledgment

The first author wishes to gratefully acknowledge the financial support from the Science & Technology Personnel Development Project of the Ministry of Science & Technology, Sri Lanka, which enabled him to carry out the experimental work described in the present paper.

The authors also wish to thank the reviewers for their valuable comments.

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