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Influence of Relative Water Depth on Wave Run-up over Coastal Structures: Rough Slopes

D. A. Peiris and J. J. Wijetunge

Abstract: This paper is concerned with 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 rough sloping structure. The run-up measurements were carried out over a bed of gravel of median diameter 20 mm for practically important ranges of the wave steepness, the relative water depth and the structure slope. The results indicate a maximum increase in the wave run-up of about 20% at shallow depths compared to deep water conditions. The measurements also suggest that the range of relative depths that cause an increase in the wave run-up compared to deep water conditions fall between 0.8 and 2 with the maximum effect occurring at a relative depth of about 1.2.

Keywords: Wave Run-up, Breaker Parameter, Water Depth, Rough Slope

1. Introduction

Determination of the crest level of coastal structures such as revetments and breakwaters with provision for no or little overtopping requires an accurate estimation of the run-up height due to the design wave. The run-up level on a coastal structure depends on the incident wave conditions 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 both smooth and rough slopes has been investigated in detail, for example, [1-6], among several others. Further, Wijetunge and Sarma [7] have examined the effect of the surface roughness of the structure on the wave run-up and 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 of Van der Meer & Stam [9] and De Waal & Van der Meer [10] with irregular waves, and more recently, the study of Peiris & Wijetunge [11] with regular waves.

The studies reported in [9] and [10] 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, thus making specific observations and conclusions on the effect of water depth not possible.

The measurements of Peiris & Wijetunge indicated that shallow water effects are important for values of relative depth (i.e., the ratio between the water depth and the wave height) falling between 0.8 and 2 with the maximum effect occurring at a relative depth of about 1.2. They also found that the maximum percentage increase of relative run-up (i.e., the run-up normalized with the wave height) at shallow water depths with respect to the mean

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value in deep water is about 20% for plunging breakers and about 65% for surging breakers. However, their study was limited to a smooth, impermeable slope, so it is not entirely clear whether or not the results are valid for rough slopes of coastal structures as well.

Accordingly, there is a need to shed further light on the way in which depth-limited wave conditions influence the wave run-up over rough slopes, particularly because most rubble-mound breakwaters in Sri Lanka and in many other parts of the world 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 rough slopes 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). 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. The rough beds consisted of a single layer of angular granite chippings of median diameter 20 mm set on a thin cement paste.

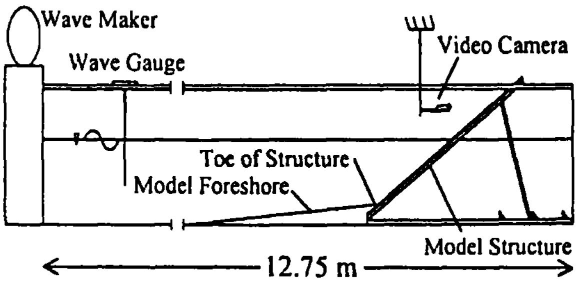

Figure 1 - Experimental set-up.

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.

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 single layer of stones laid on an impermeable slope under the present experimental conditions depends on ds, 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; k, the roughness height of the stones; α, the slope angle of the structure; and β, the slope angle of the foreshore.

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

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

where, the roughness height (k) of the slope is taken as equal to the median diameter (D) of the stones. So, we see that, in non-dimensional form, R/H_0 is dependent upon the wave steepness (H_0/gT^2), the relative depth (d_s/H_0), the relative roughness (D/H_0) as well as the slope angles of both the structure and the foreshore, under the present experimental conditions.

We now define a breaker parameter for wave action slopes [12]:

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

Following many previous investigations of wave run-up on slopes (e.g., [1, 3-12]), 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 α 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.

Table 1 - Test conditions.

Parameter	Study Range	
	Data Set *A*	Data Set *B*
H_0	4 - 13 cm	4.5 - 14.6 cm
T	0.7 - 1.2 s	0.7 - 1.1 s
d_s	34.2 cm	0 - 27 cm
α	17.5, 24.8, 32.7 deg.	24.8, 32.7 deg.
β	0	3.7 deg.
d_s/H_0	2.7 - 12.2	0 - 6
H_0/gT^2	0.003 - 0.021	0.005 - 0.023
ζ_0	0.8 - 4.0	1.5 - 3.55
D/H_0	0.15 - 0.50	0.14 - 0.45

The measurements in Data Set *A* were made with a horizontal foreshore, i.e., β=0 and at comparatively higher values of d_s/H_0 to obtain the general variation of R/H_0 with ζ_0 to enable further verification of the reliability of the results from the present experimental set-up with rough slopes.

The measurements in Data Set B are available over a range of from 1.5 to 3.55 covering both the plunging and the surging breaker types. In these tests, the water depth at the toe of the structure was lowered from 27 cm to 0 in steps of 1 cm, for each value of ζ_0. The run-up measurements have been made for two different values of the structure slope: α = 24.8 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.

5. Results and Discussion

Let us first examine the reliability of the present experimental set-up for wave run-up measurements over rough slopes. Accordingly, Fig. 2 shows the way in which the non-dimensional run-up R/H_0 varies with the breaker parameter ζ_0; for these measurements β = 0 and $2.7 < d_s/H_0 < 12.2$.

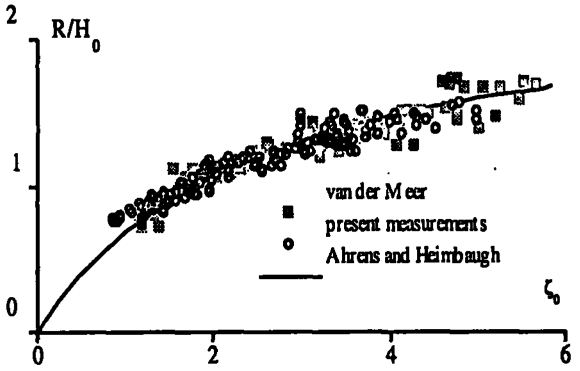

Figure 2 - Variation of R/H0 with ζ_0: Data Set A. Measurements of van der Meer [9] and the formula of Ahrens and Heimbaugh [13] are also shown for comparison.

The present measurements show a gradual increase of R/H_0 with ζ_0. The measurements of van der Meer [9] and the formula of Ahrens & Heimbaugh [13] for rip-rap slopes are also shown in this figure for comparison. It must be added that van der Meer has used irregular waves whereas the present measurements are for regular waves. Nevertheless, it was possible to obtain the mean values of run-up required for the above comparison from the measurements of van der Meer as the wave heights and the subsequent run-up are approximately Rayleigh distributed [9].

Clearly, the present measurements show good agreement with those of van der Meer and also with the curve of Ahrens & Heimbaugh.

Now, it is interesting to compare the measurements in Fig. 2 at comparatively high values of d_s/H_0 ($d_s/H_0 > 2.7$) with those from Data Set B over a range of d_s/H_0 ($0 < d_s/H_0 < 6$; i.e., inclusive of low values of d_s/H_0) and at several values of ζ_0. This is shown in Fig. 3, which clearly indicates that some data points from Data Set *B* fall significantly above and below the general scatter shown by the data points from Data Set *A*. Note that the ζ values indicated on Fig. 3 are applicable only for waves that break due to the structure. The results in Fig. 3 appear to suggest that the relative depth in particular does have an influence on the wave run-up over rough slopes too. So, we need to examine in detail the way in which R/H_0 varies with d_s/H_0 over a range of ζ_0.

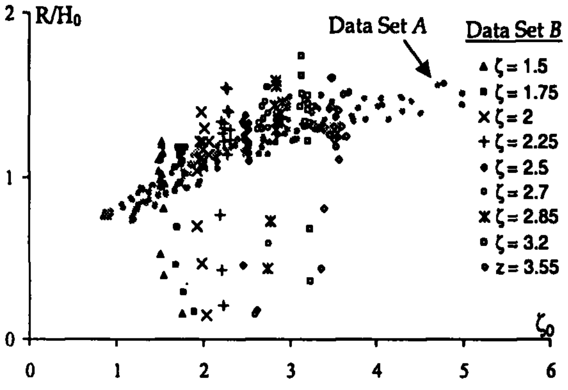

Figure 3 - Comparison of run-up measurements from Data Sets A and B.

Accordingly, Fig. 4 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) and the relative roughness (D/H_0) 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. 4 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). Also, there appears to be a slight dip in the curves just to the right of point C. The results in Fig. 4 suggest 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. This means that the way in which R/H_0 varies with d_s/H_0 over a rough slope is qualitatively similar to that over a smooth slope reported in [11].

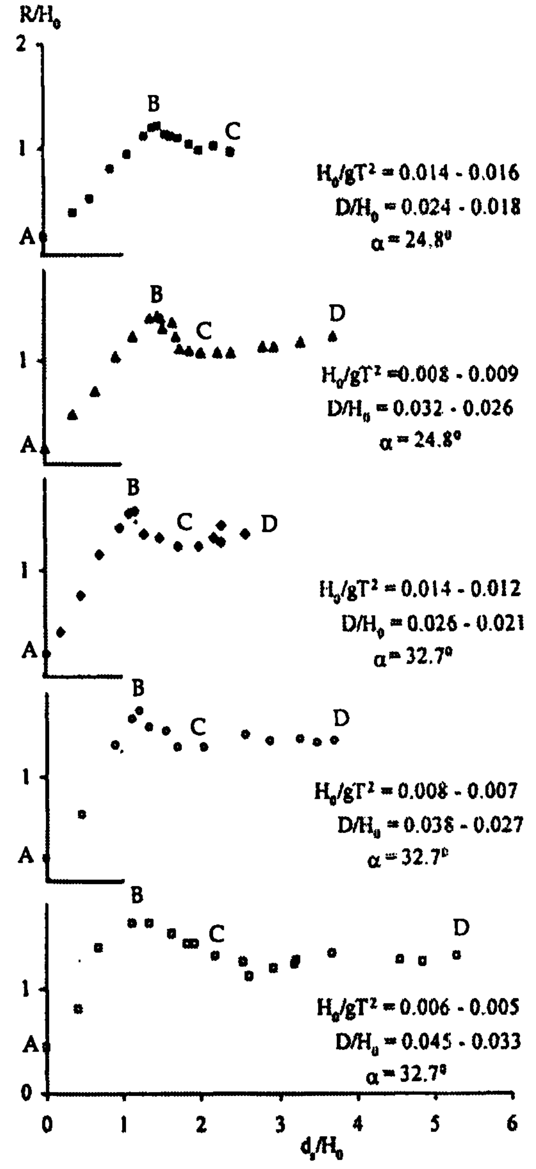

Figure 4 - Examples of the way in which R/H_0 varies with d_s/H_0

Let us first consider the run-up records in segment AB of the curves. As would be expected, 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. 5 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: α=24.8 deg. and 32.7 deg.. It must, however, be added that D/H_0 is not kept constant for the data points in Fig. 5, viz., D/H_0 = 0.14 - 0.45. The corresponding smooth bed curve reported in [11] is also shown in Fig. 3 for comparison. Although the data points in Fig. 5 for two values of α, taken together or separately, do not show a clear consistent trend, it appears that the value of R/H_0 at $d/H_0 = 0$ increases with decreasing H_0/gT^2 for values of H_0/gT^2 larger than about 0.006. The corresponding smooth bed curve reported in [11] is also shown in Fig. 5 for comparison.

On the other hand, wave breaking was primarily due to the structure slope at values of d/H_0 in segments BC and CD of the curves in Fig. 4. Now, an interesting question is what causes significantly higher values of R/H_0 at low values of d/H_0 around the peak at B compared to higher values of d/H_0, say at C. So, to find a clue to the processes that are responsible for this behaviour we follow the same procedure as for the study reported in [11] for a smooth slope: a close examination of the event that leads to wave 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.

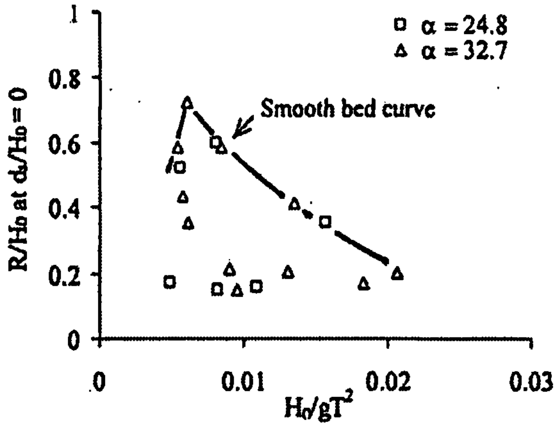

Figure 5 - Variation of H_0/gT^2 with R/H_0 at $d/H_0 = 0$. (Values of α in degrees to the horizontal.)

The height of the wave above the SWL at the point of breaking was obtained from these still images 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 ±5 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. 4) whilst curve (C) is for those near point (C).

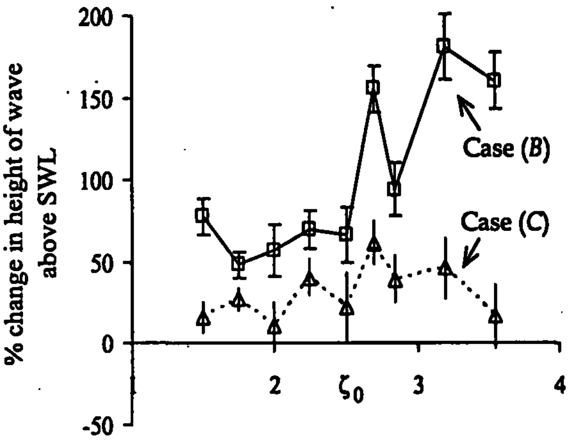

Figure 6 - Variation with ζ_0 of the change in the height of the wave above SWL.

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 25% - 50% higher at B than at C. On the other hand, most of the data points that represent surging breakers (i.e., ζ_0 = 2.7, 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. This was done for the smooth bed results in [11] and it was found that the shoaling of waves over the foreshore slope alone could 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.

We have already seen from the curves of wave run-up variation with d/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/H_0 values in which R/H_0 is higher than the mean R/H_0 for segment CD. This is shown in Fig. 7 for all measurements over a range of values of ζ_0. The inset in Fig. 7 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/H_0 within which shallow water depths could cause an increase in the run-up, together with the d/H_0 value corresponding to the peak (P) in R/H_0.

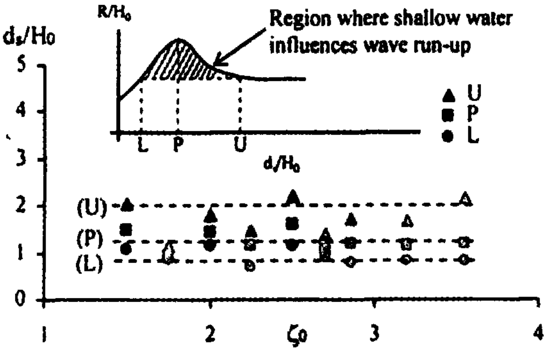

Figure 7 - Range of d/H_0 in which shallow water causes an increase in R/H_0

In Fig. 7, the symbols in black are those for α =24.8 deg. whilst the symbols in grey are for α =32.7 deg.. 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/H_0 within which shallow water effects could be important. Accordingly, we see that the peak value of R/H_0 mostly occurs at $d/H_0 \approx 1.2$ whilst, on the whole, it appears that shallow water could cause an increase in the run-up for values of d/H_0 falling between 0.8 and 2. The smooth bed results of [11] too suggested a similar range of values of d/H_0.

Fig. 8 shows the variation with ζ_0 of the peak value of R/H_0 (peak of run-up with d/H_0, at B in Fig. 4) 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 $ds/H_0 > 2$) follow the usual pattern of most previous measurements in relatively deep water conditions, i.e., a gradual increase of R/H_0 with ζ_0. The peak value of R/H_0 (with d/H_0) that occurs at $d/H_0 \approx 1.2$ too shows a qualitatively similar variation to that of the mean R/H_0. There are two outliers in the 'peak' curve at ζ_0=1.75 and 2.5, however, any underlying cause for this could not be found. One other thing to note in Fig. 8 is that the peak values of R/H_0 scale reasonably well with ζ_0 showing no significant dependence on the slope angle of the structure (α).

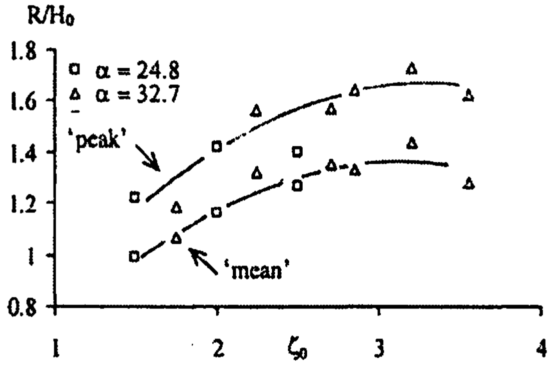

Figure 8 - Variation with of the "peak" and "mean" values of R/H_0 with d/H_0. (Values of α in degrees to the horizontal.)

We now examine in Fig. 9 the maximum percentage increase of R/H_0 at low values of d/H_0 with respect to the mean value. The smooth bed results [11] are also shown in this Fig. for comparison. We see that, for the rough slopes, the maximum increase in R/H_0 at shallow depths compared to that in deep water is about 10% - 25% (mostly about 20%) irrespective of the wave breaking type. On the other hand, for the smooth slope, the increase in R/H_0 for plunging breakers ($\zeta_0 < 2.5$) is about 20%, i.e., the same as for rough slopes, but then rising sharply through the collapsing breakers ($2.5 < \zeta_0 < 3$) to a value of about 65% for surging breakers ($\zeta_0 > 3$).

Finally, it must be added that the wave run-up measurements reported in the present paper have been made over a single layer of stones placed on an impermeable slope. Thus the applicability of the present results for wave run-up over rough, permeable structures must be tested, in addition to any possible model and scale effects.

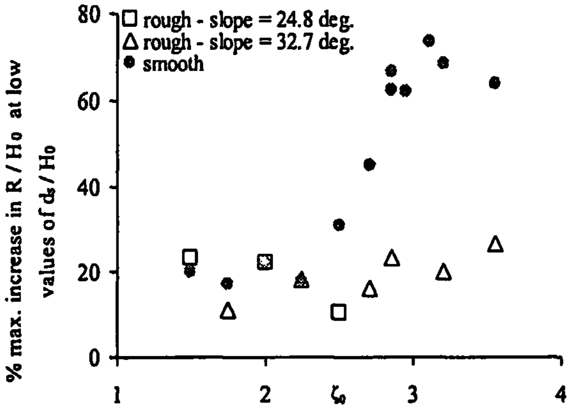

Figure 9 - Variation with ζ_0 of the maximum increase in R/H_0 at low values of d_s/H_0. Smooth bed results from [11] are also shown for comparison.

6. Conclusions

The following conclusions are made for the range of conditions covered in the present experiments of wave run-up over a rough sloping structure consisting of a single layer of stones placed on an impermeable surface:

1. The present measurements of wave run-up over a 20 mm bed roughness show good agreement with the measurements of Van der Meer [9] on rock slopes and with the run-up formula of Ahrens & Heimbaugh [13] for rip-rap slopes.
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% irrespective of the breaker type.

Acknowledgment

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