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

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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 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).
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.

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; \( H_o \), the deep water wave height; \( T \), the wave period; \( a \), the slope angle of the structure; and \( \beta \), the slope angle of the foreshore.

Thus, the non-dimensional run-up \( \frac{R}{H_o} \) may be expressed as a function of the following dimensionless groups:

\[
\frac{R}{H_o} = \phi \left( \frac{R}{H_o}, \frac{d_s}{H_o}, \frac{c}{H_o}, \tan a, \tan \beta \right) \tag{1}
\]

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

\[
\zeta = \frac{\tan \alpha}{\sqrt[4]{\text{S}_0}}, \text{ where } \text{S}_0 = \frac{2\pi H_o}{gT^2}
\]

Following many previous investigations of wave run-up on slopes (e.g., [1, 3-11]), the present study employs the breaker parameter \( \zeta \) to represent the dual dependence of the non-dimensional wave run-up on \( H_o/gT^2 \) and \( \tan a \) 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 \( \zeta \) 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 \( \zeta \). 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: $a = 24.8\,\text{deg.}, 28.7\,\text{deg.},$ and $32.7\,\text{deg.}$ to the horizontal. The slope angle of the foreshore was kept at $3.7\,\text{deg.}$ to the horizontal whilst its length was about 1-2 times the wavelength 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     |
| $T$                      | $0.7 - 1.1\,\text{s}$ |
| $d_i$                    | 0 - 27 cm         |
| $a$                      | 24.8 - 32.7 deg.  |
| $\beta$                  | 3.7 deg.          |
| $d_i/H_0$                | 0 - 6             |
| $HJgT$                   | 0.005 - 0.023     |
| $c_0$                    | 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 $(d_i/H_0)$. Note that the values of the wave steepness $HJgT$ 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 $d_i/H_0$ and reaches a peak value (segment AB of the curves), then declines with further increase of $d_i/H_0$ (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 $d_i/H_0$ larger than about 2, the water depth does have a significant influence on $R/H_0$ at low values of $d_i/H_0$, 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 $R/H_0$ increases progressively away from the toe of the structure as $d_i/H_0$ is reduced. It is also interesting to examine the way in which the values of $R/H_0$ at $d_i/H_0 = 0$ vary with $HJgT$. Accordingly, Fig. 3 shows $R/H_0$ at $d_i/H_0 = 0$ over a range of $HJgT$ for two different values of the slope of the structure: $a = 24.8\,\text{deg.}$ and $32.7\,\text{deg.}$.

![Figure 2: Examples of the way in which $R/H_0$ varies with $d_i/H_0$.](image)

![Figure 3: Variation with of $HJgT$ of $R/H_0$ at $d_i/H_0 = 0$. (Values of $a$ in degrees to the horizontal.)](image)
Fig. 3 appears to suggest that, as the wave steepness is reduced, \( \frac{R}{H} \) increases and reaches a peak value of \( \frac{R}{H} = 0.75 \) at \( H = 0.007 \), 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 \( \frac{d}{H} \) in segments BC and CD of the curves in Fig. 2. Now, an interesting question is what causes significantly higher values of \( \frac{R}{H} \) at low values of \( \frac{d}{H} \) around the peak at B compared to higher values of \( \frac{d}{H} \) 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.

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.

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 \( \zeta \). 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 ±5mm, 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 $\zeta_o$ of the change in the height of the wave above SWL.](image)

Accordingly, the shoaling coefficient $K$ at the toe of the structure was determined using the small amplitude wave theory for each value of $\zeta_o$ 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 $K$ as the small amplitude theory, for the range of values of $d/L$ 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 $\zeta_o$ of the % change in wave height due to shoaling.](image)

We have already seen from the curves of wave run-up variation with $d_jH_0$ 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 $d_jH_0$ 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 $\zeta_o$. 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 $d_jH_0$ within which shallow water depths could cause an increase in the run-up, together with the $d_jH_0$ value corresponding to the peak (P) in $R/H_0$.

In Fig. 8, the symbols in black are those for $\alpha = 24.8$ deg. whilst the symbols in grey are for $\alpha = 32.7$ 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 $d_j/H_0$ within which the shallow water effects could be important. Accordingly, we see that the peak value of $R/H_0$ mostly occurs at $d_j/H_0 \approx 1.2$ whilst, on the whole, it appears that shallow water could cause an increase in the run-up for values of $d_j/H_0$ falling between 0.8 and 2.

![Figure 8: Range of $d_j/H_0$ in which shallow water causes an increase in $R/H_0$.](image)

Fig. 8 shows the variation with $\zeta$ of the peak value of $R/H_0$ (peak of run-up with $d_j/H_0$ 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 $d_j/H_0 > 2$) follow the usual pattern of most previous measurements in relatively deep water conditions, with an initial increase of $R/H_0$ with $\zeta$ reaching a peak at about $\zeta = 2.5$ before beginning to decline with further increase of $\zeta$. The peak value of $R/H_0$ (with $d_j/H_0$) that occurs at $d_j/H_0 = 1.2$ 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 $\zeta = 3$. We also see that the peak $R/H_0$ is considerably larger than the mean $R/H_0$ for $\zeta > 2.5$, i.e., at values of $\zeta$ for which wave breaking type is surging. One other thing to note is that the peak values of $R/H_0$ scale well with $\zeta$, showing no significant dependency on the slope angle of the structure ($\alpha$).

We now examine in Fig. 10 the maximum percentage increase of $R/H_0$ at low values of $d_j/H_0$ 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 $\zeta$ with the "peak" and "mean" values of $R/H_0$ with $d_j/H_0$. (Values of $\alpha$ in degrees to the horizontal.)](image)

Accordingly, $\zeta < 2.5$ belongs approximately to the plunging breaker; $2.5 < \zeta < 3$, to the collapsing breaker; and $\zeta > 3$, 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 $\zeta$ 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.
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 \( \frac{R}{H_0} \) initially increases with the relative water depth at the toe of the structure \( \frac{d_s}{H_0} \), reaches a peak value at \( \frac{d_s}{H_0} = 1.2 \), before beginning to fall and approach a nearly constant value for \( \frac{d_s}{H_0} \) larger than about 2.

2) The measurements also indicate that shallow water effects are important for values of \( \frac{d_s}{H_0} \) falling between 0.8 and 2 with the maximum effect occurring at \( \frac{d_s}{H_0} = 1.2 \).

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

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