Rundown Velocity Along the Slope of a Breakwater with Accropode Cover Layer

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ABSTRACT ■

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Rundown velocity along the slope of a breakwater is quite an important parameter in breakwater design. Literature review on rundown velocity measurements indicates that a few small scale studies have been attempted in the past, mostly along beach slopes. This paper details the experimental investigations conducted at large wave flume (GWK), Franzius Institute, Hannover, Germany, in regard to rundown velocity along the slope of a rubble mound breakwater with an accropode armour layer. As the wave flume facilitates generation of wave heights in the range of 0.20 to 2.0 m with wave period ranging between 3.0 and 12.0 seconds, measurements on rundown velocity for the near prototype conditions were possible. Two methods were adopted to determine rundown velocity *viz.*, (i) with a float and (ii) with a wave gauge. The results on the variation of rundown velocity with Iribarren Number and wave steepness are presented in the form of non-dimensional graphs and discussed.

The studies indicated that for identical wave input parameters float method predicts a higher value of rundown velocity compared to wave gauge method. For instance, with a wave height of 0.6 m and wave period of 5.8 seconds, float method predicts a rundown velocity of 1.7 m/sec as against 1.24 m/sec predicted by wave gauge. The experimental results strongly predict the dependency of rundown velocity on wave period, in addition to wave steepness and Iribarren Number The trend curves of rundown velocity show the existence of an upper boundary below which all trend curves lie regardless of the wave period. Present experimental investigations provided valuable information about the magnitude of rundown velocity along breakwater slope which hitherto was not available to the engineers dealing with breakwaters.

ADDITIONAL INDEX WORDS: *Rundown velocity, breakwater, accropode, rubble mound, runup, float, wave steepness.*

INTRODUCTION

Rubble mound breakwaters are constructed for protection of harbour basins, entrance channels, *etc.* These breakwaters are built with quarry stones of a certain weight which are placed in a specific fashion to form a mound. All over the world, necessity for construction of breakwaters in larger water depths was felt when very large crude carriers (VLCC) came into existence demanding sheltered berthing facilities in deep waters. This factor necessitated a critical analysis for design of breakwaters considering all disturbing forces that would challenge its stability.

Various parameters that would destabilize the breakwater have been investigated by scientists and engineers in the past. However, very few attempts were made to determine the magnitude of wave rundown velocity along breakwater slopes which carry importance from the point of view of stability of stones and toe protection. A general

formula for determination of rundown velocity has been proposed by BRUNN (1977) and refined by JENSEN (1983) which is applicable for a certain range of the Iribarren Number, thereby limiting the applicability of the formula. A few small scale model studies have also been reported (KOBAYASHI *et al.*, 1987; BATTJES and SAKAI, 1980; STIVE, 1980; NADAOKA and KONDOH, 1982; IWAGAKI *et al.*, 1971; IWAGAKI *et al.*, 1972; IWAGAKI *et al.*, 1974) wherein measurements related to vertical velocity variations either in the surf zone or along a beach slope were made. A brief literature review suggested that large scale measurements on rundown velocity along breakwater slopes have not been attempted so far. As rundown velocity is an important parameter in the design of breakwaters, large-scale tests were conducted in the wave flume at Hannover, Germany.

The aim of the study was to determine rundown velocity along a breakwater armoured with a layer of accropode blocks. Two methods were adopted to determine rundown velocity *viz.*, (i) with a float and (ii) with a wave gauge. As the waves were
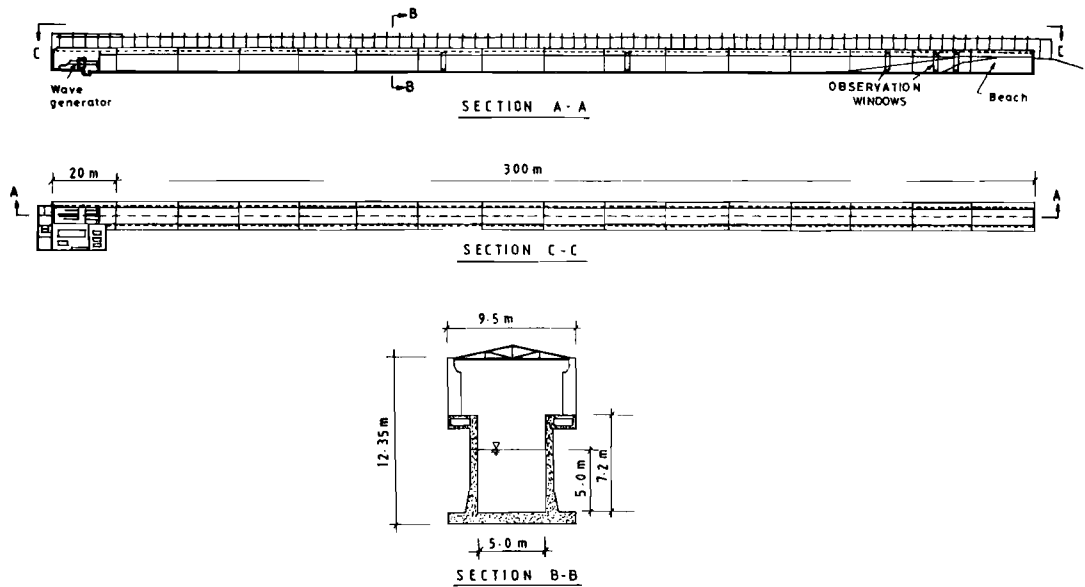
Figure 1.   Details of large wave flume (GWK) at Hannover, Germany.

nearly similar to prototype conditions (wave heights varied from 0.2 to 2.0 m and wave periods from 3.0 to 12.0 sec), it was possible to make a critical evaluation of rundown velocity. Variation of rundown velocity parameters with wave steepness, wave period and the Iribarren Number were studied and the results presented in the form of

non-dimensional graphs. Use of a new experimental technique has led to the determination of vital information about rundown velocity along the slope of a breakwater.

In addition, wave runups obtained with the present breakwater system were compared with those reported in the SHORE PROTECTION MANUAL
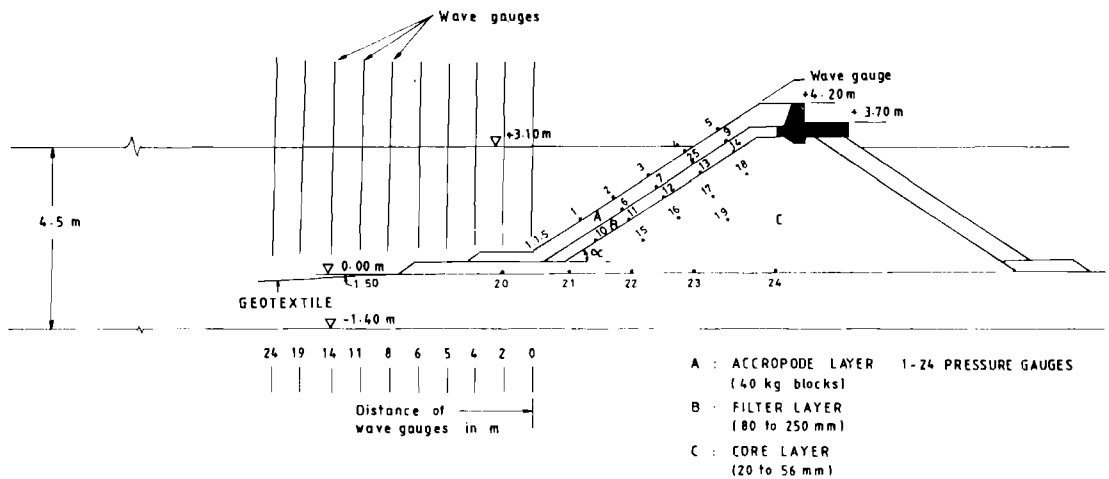

Figure 2.   Schematic diagram of the breakwater and wave gauge positions.

Table 1. *Characteristics of the wave flume.*

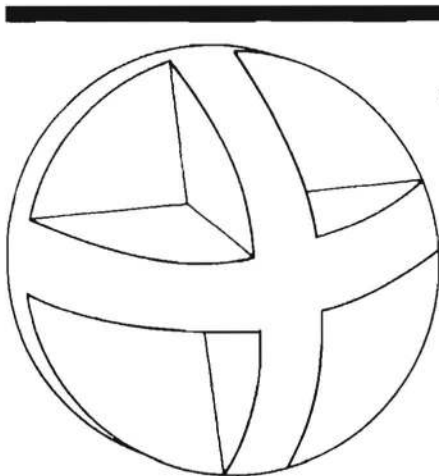| Sl. No.	Parameter	Range
1.	Length of channel	320 m
2.	Width	5 m
3.	Depth	7.2 m
4.	Water depth (max)	5 m
5.	Wave height	0.20–2.00 m
6.	Wave period	3.0–12.0 sec
7.	Wave length $L_{4.5}$	12.7–69.0 m
8.	Wave length $L_{3.1}$	12.0–63.00 m
9.	Wave steepness H/L	0.004–0.077 m
10.	Iribarren No. (ϵ)	2.47–10.12 m

(1977) for a rubble mound breakwater. This exercise was carried out to check the feasibility of application of rundown velocity results for a conventionally adopted rubble mount breakwater.

EXPERIMENTAL SETUP AND FLUME CHARACTERISTICS

Experiments related to rundown velocity measurements were carried out in the large wave flume (measuring 320 m long, 5.0 m wide and 7.2 m deep) at Hannover, Germany. Figure 1 shows the details of the wave flume. The flume is provided with a piston type wave generator capable of sensing reflected wave amplitude and correcting its stroke for the next incident wave so as to avoid multiple reflections in the flume. Details of wave charac-

Photo 1: A typical wave generated in the flume (wave height (Hia): 2.0 m, wave period (T): 10 sec.

teristics and wave parameters that can be reproduced with the wave generator are given in Table 1. Details of the breakwater for which the studies were conducted are shown in Figure 2. The break-
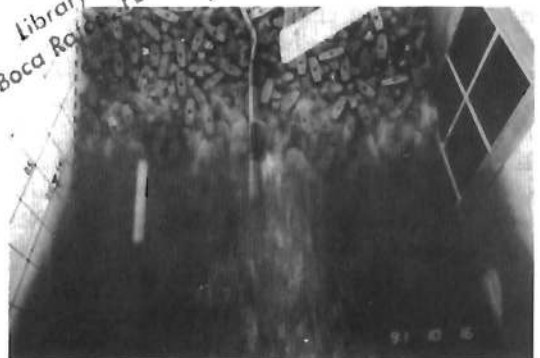

Photo 2: A sample flow path tracked by the float along the breakwater slope (Hia: 0.6 m, T: 5 sec, Ruf: 2.08 m/sec.

DIAMETER = 16 cm

WALL THICKNESS = 3 cm
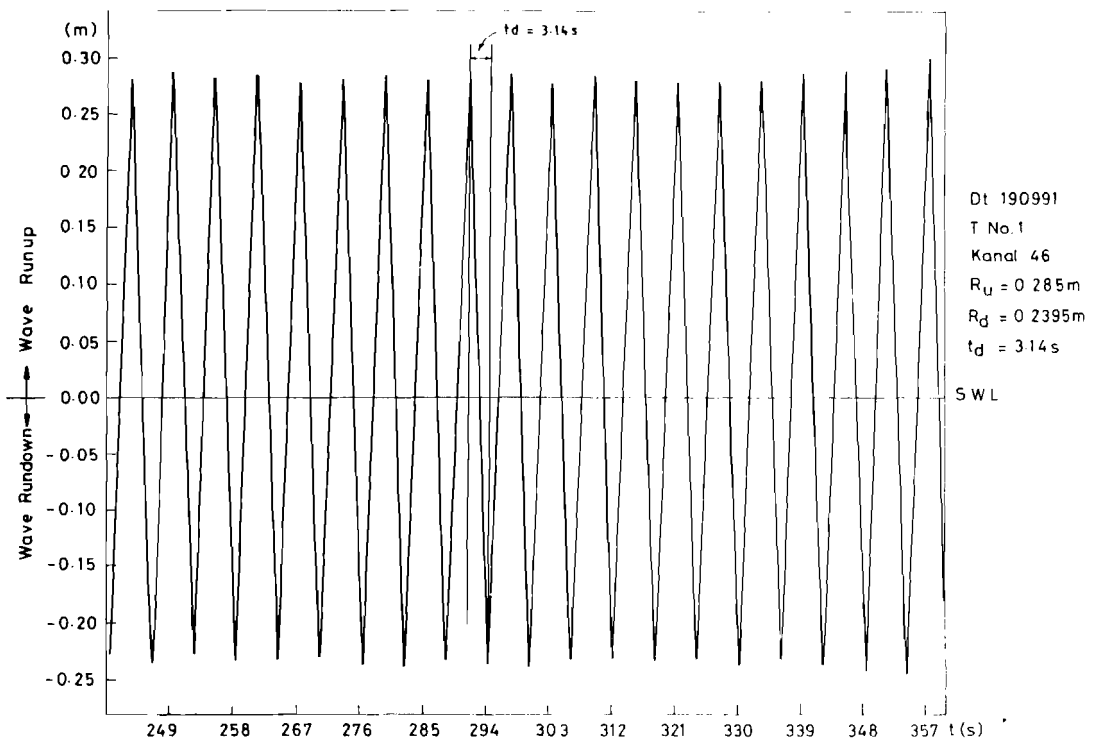
Figure 3. A view of the float.

Figure 4. Time history of wave runup and rundown.

water was constructed out of rubble with its sea-ward side protected by accropode blocks placed over a slope of 1:1.5. Water depth at the toe of the breakwater was 3.10 m, whereas the water depth in the flume was 4.50 m. A gentle slope of 1:50 was maintained fronting the toe of the break-water. Wave gauges were mounted in front and along the breakwater slopes for measurement of incident, reflected, and transmitted wave heights, wave uprush and backwash (Figure 2). In order to measure rundown velocity, two methods were adopted, the details of which are given below.

VELOCITY MEASUREMENT BY FLOAT

To measure velocity, a light spherical float, 16 cm in diameter (made out of thermocole) with eight compartments was fabricated to suit the breakwater. Details of the float are shown in Fig-ure 3. The following steps were involved in the measurement of velocity:

(1) Release of float along the seaward slope of the breakwater at the instant when wave run-down was at its peak.

(2) Tracking of float path with the help of a cam-era mounted onto a rigid platform fronting the breakwater.

Photo 1 shows a typical wave generated in the wave flume and Photo 2 shows the path tracked by the float during a wave rundown.

Calibration of Camera Speed

In order to measure peak rundown velocity, the shutter speed for the camera was set to one half of a second. To check the speed of the camera, photographs of a line marked on a strip chart paper were taken. The strip chart recorder was set to run at a speed of 60 cm/min. The line marked on the strip chart produced a black band, 5 mm long on the photograph indicating the correctness of camera speed.

Calibration of Travel Distance by Float

As already indicated, wave gauges were mount-ed on the seaward slope of the breakwater for measuring wave uprush and backwash. One such wave gauge was housed in a cage (mesh size = 1
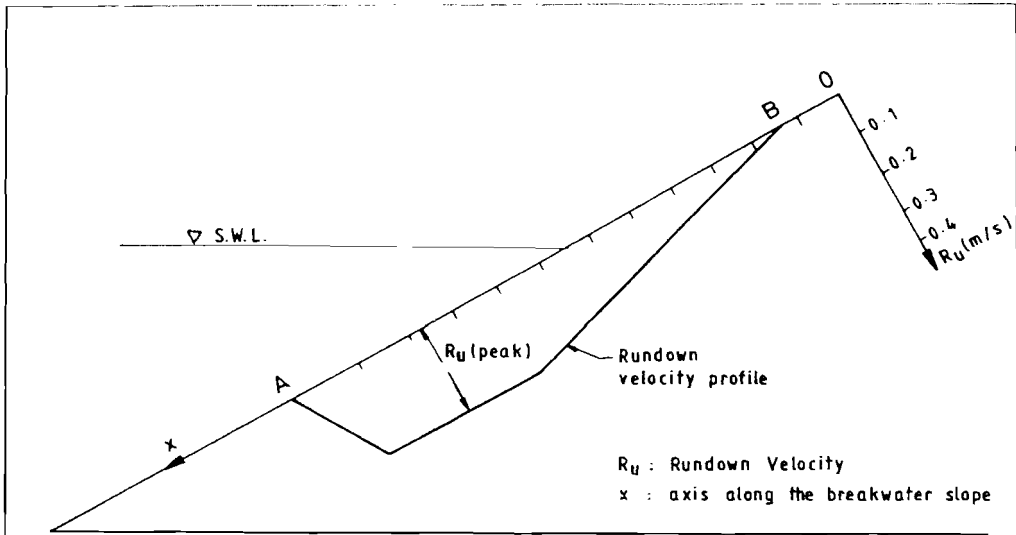
Fig. 5a. Horizontal Velocity variation along the breakwater slope during a rundown
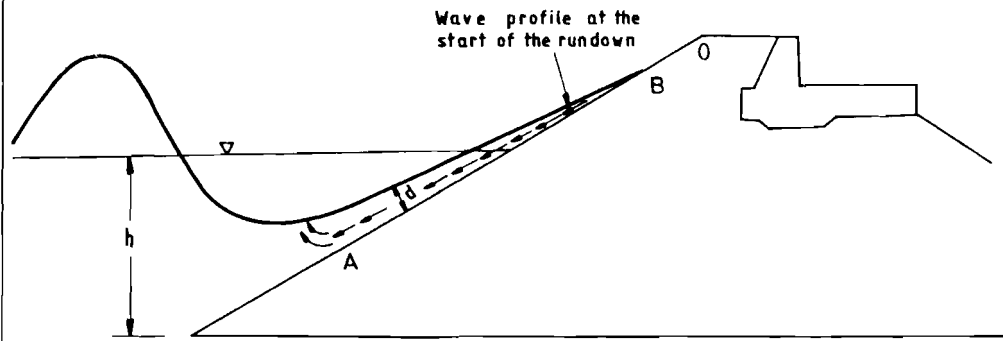

Fig. 5b. Velocity Vectors during a rundown

Figure 5. Typical rundown velocity profile. a. Horizontal velocity variation along the breakwater slope during a rundown. b. Velocity vectors during a rundown.
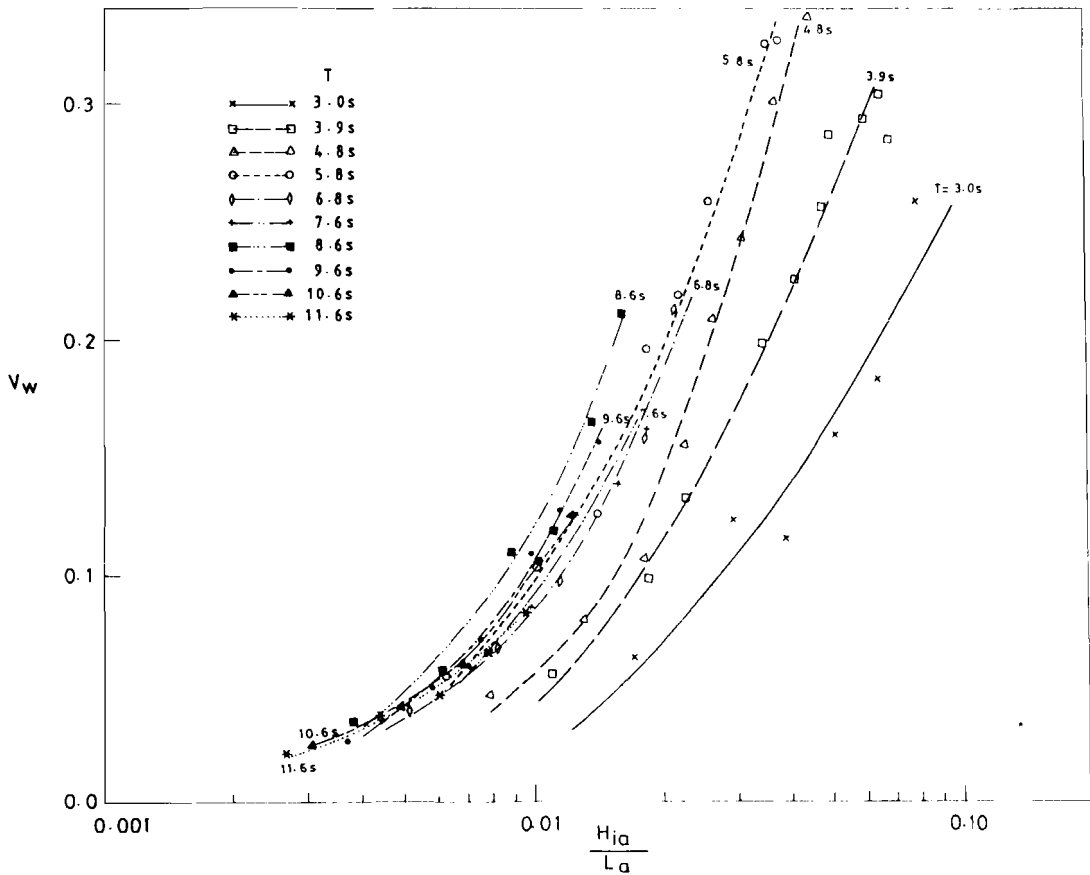
Figure 6.   Variation of rundown velocity with wave steepness (wave gauge measurements).

square inch) with every 50 cm length of the cage painted alternately with yellow and blue colours. The camera mounted on the rigid platform was tilted so that the camera frame was parallel to the seaward face of the breakwater and photographs of the cage were taken. The photo prints indicated that the 50 cm length of yellow strip of the cage measured 9.07 mm on the print. This gave a correspondence of 1:55.1 between the photo and the breakwater.

To determine velocity, the distance recorded by the float on the photograph was converted (using the conversion factor) and then divided by the shutter speed of the camera. Thus:

Rundown velocity in cm/sec = $((Df \times con) - D)/0.5$

Where

Df = Distance tracked by the float on the photo (in cm)

con = Conversion factor to determine actual distance (1:55.1)

D = Diameter of float

VELOCITY MEASUREMENT BY WAVE GAUGE

Velocity measurements were made using a wave gauge mounted along the seaward slope of the breakwater. From the time histories (Figure 4) of wave uprush and backwash, rundown distance along the slope of the breakwater was first determined. Time difference (td) between crest and following trough of the wave profile which had produced the uprush and backwash was then determined to obtain velocity of rundown. Thus:
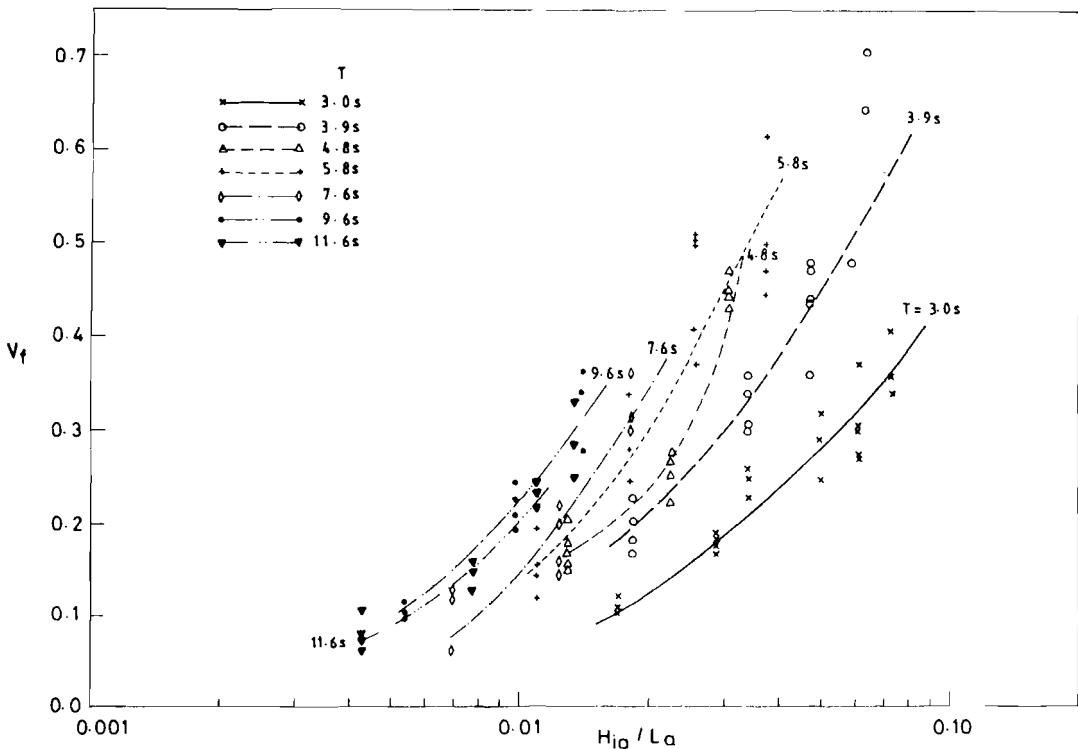
Figure 7. .Variation of rundown velocity with wave steepness (float measurements).

Rundown velocity in cm/sec
= [(Ru + Rd)/sin(α)]/td

Where Ru and Rd are wave runup and rundown height measured from still water level (Figure 4), α is the slope angle (Figure 2), and td is the actual time taken by the water level to reach from its maximum to minimum (Figure 4).

ASSUMPTIONS

The following assumptions are made under the present studies:

(1) The flow during rundown remains steady for a few seconds, though the flow is unsteady for the total duration of rundown. A trapezoidal rundown velocity–time history has been considered (Figure 5a).
(2) During rundown, the depth of flow along the breakwater slope remains constant, meaning that the water surface is parallel to the slope of the breakwater. (Figure 5b).
(3) Velocity distribution over the depth of flow is constant as the water depth along the

breakwater slope is quite small compared to water depth; *i.e.*, d ≪ h (Figure 5b).

DATA COLLECTION

Regular waves were generated with the help of a piston type wave generator installed at one end of the flume. A minimum of 150 cycles of given wave characteristics were generated for test purposes. Wave heights sensed by a series of wave gauges (Figure 2) and wave gauges along the seaward slope of the breakwater were recorded on magnetic tapes using a HP-2250 computer. Calibration factors for all wave gauges were stored separately in an information file for analysis. As wave characteristics were identical for every wave generated under each test series, rundown velocity measurements using float and camera were repeated for eight wave cycles so as to check the consistency of the results.

EXPERIMENTAL RESULTS

As the present experimental studies stress the importance of rundown velocity, a non-dimen-

Table 2. *Run down velocities with float and wave gauge for different wave steepnesses.*

Hia/La	T (sec)	V_w	V_f	Ruw (m/sec)	Ruf (m/sec)	% Increase
0.005	3.9	0.009	0.060	0.049	0.331	575
	4.8	0.020	0.095	0.110	0.524	376
	5.8	0.036	0.055	0.198	0.303	53
	7.6	0.030	0.045	0.165	0.248	50
	9.6	0.042	0.100	0.232	0.551	58
	11.6	0.041	0.090	0.226	0.496	119
0.01	3.0	0.022	0.065	0.121	0.358	196
	3.9	0.044	0.130	0.243	0.717	195
	4.8	0.058	0.150	0.319	0.827	159
	5.8	0.100	0.140	0.551	0.772	40
	7.6	0.092	0.150	0.507	0.827	63
	9.6	0.106	0.225	0.584	1.241	112
	11.6	0.085	0.205	0.468	1.130	141
0.025	3.0	0.093	0.160	0.513	0.882	72
	3.9	0.145	0.260	0.799	1.434	79
	4.8	0.197	0.310	1.086	1.710	57
	5.8	0.245	0.380	1.351	2.096	55
	7.6	0.233	0.450	1.285	2.48	93
	9.6	0.271	0.505	1.494	2.78	86
	11.6	0.163	0.440	0.899	2.43	170
0.050	3.0	0.169	0.285	0.932	1.572	69
	3.9	0.267	0.455	1.472	2.510	70
	4.8	0.396	>1.000	2.184	>5.0	—
	5.8	0.435	0.650	2.399	3.58	49
	7.6	0.338	0.690	1.864	3.80	104
	9.6	0.470	0.730	2.592	4.03	55
	11.6	0.206	0.720	1.136	3.97	·248

Notations

Con	Conversion factor
D	Diameter of the float
Df	Distance traced by the float in photograph
d	Depth of flow
d,	Water depth at the structure
g	Acceleration due to gravity
H	Wave height
Hia	Actual incident wave height in front of the breakwater
H_o'	Unrefracted wave height
h	Water depth
h_t	Water depth at the toe of the structure
La	Actual wave length in front of the breakwater
R	Wave runup
Rd	Wave rundown
Ru (or) R	Wave runup
Ruf	Wave rundown velocity with float
Ruw	Wave rundown velocity with wave gauge
T	Wave period
V_f	Relative rundown velocity obtained with float $\left(= \dfrac{Ruf}{\sqrt{gh_t}}\right)$
V_w	Relative rundown velocity obtained with wave gauge $\left(= \dfrac{Ruw}{\sqrt{gh_t}}\right)$
ζ	Iribarren No. $= \tan \alpha / \sqrt{Hia/La}$
$\tan \alpha$	Breakwater slope

sional parameter termed as "relative rundown velocity" has been adopted in this paper. This parameter is defined as follows.

$$V_f = \frac{Ruf}{\sqrt{gh_t}} \quad \text{and} \quad V_w = \frac{Ruw}{\sqrt{gh_t}}$$

where

V_f = Relative rundown velocity obtained with float

Ruf = Actual velocity determined by float

V_w = Relative rundown velocity obtained with wave gauge

Ruw = Actual velocity determined by wave gauge

g = Acceleration due to gravity

h_t = Water depth at the toe of the structure

Variation of Relative Rundown Velocity with Wave Steepness

Figures 6 and 7 show the variation of V_w and V_f with wave steepness (Hia/La), respectively. Based on data points, trend curves were drawn for different wave periods ranging between 3 and 11.6 seconds. Non-dimensionalising of the wave period was not done intentionally as wave periods
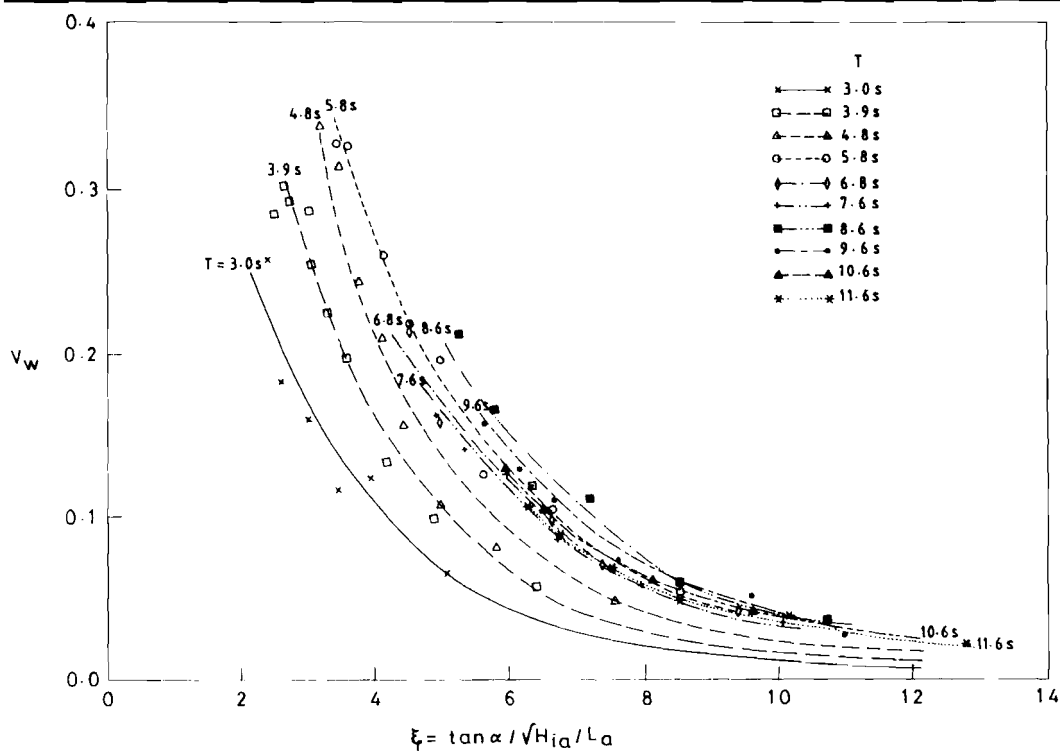
Figure 8. ˙Variation of rundown velocity with ξ (wave gauge measurements).

generated in the flume match with wave periods observed in nature. This led to a better interpretation of results. Table 2 shows a comparison of the magnitudes of relative rundown velocities obtained with float and wave gauge measurements. The results indicate that:

(1) Relative rundown velocity increases exponentially with an increase in wave steepness. For the range of wave steepness (0.004–0.077), the increase in relative rundown velocity is a function of wave period. For small wave periods (less than 5 sec), a steady rise in relative rundown velocity is predicted; whereas for large wave periods (greater than 5 sec), a steep rise is observed (Figures 6 and 7).

(2) Relative rundown velocity obtained with the float consistently indicates a higher magnitude compared to those with the wave gauge. The float predicts velocities which are 50 to 400 percent higher than the velocities with the wave gauge (Table 2). This percentage increase is a function of wave steepness. For wave steepness less than 0.01 and T less than 5 sec, the increase is of the

order of 400 percent. For wave steepness greater than 0.01 and T greater than 3 sec the percentage increase varies between 50 and 200 percent.

Variation of Relative Rundown Velocity with Iribarren Number

Figures 8 and 9 show the variation of rundown velocity with the Iribarren Number (ζ) obtained with wave gauge and float, respectively. A comparison of magnitude of relative rundown velocities obtained with the float and the wave gauge for different ζ values are given in Table 3.

The following results are inferred from figures and tables:

(1) Both methods of measuring velocities predict an exponential decrease in relative rundown velocity with increase in ζ from 2.5 to 10.10.

(2) Relative rundown velocity plot with float (Figure 9) indicates that, for ζ greater than 8, the wave period has significant influence over the magnitude of relative rundown velocity. However, this trend has not been indicated by the velocity plot (Figure 8) obtained with the wave gauge.
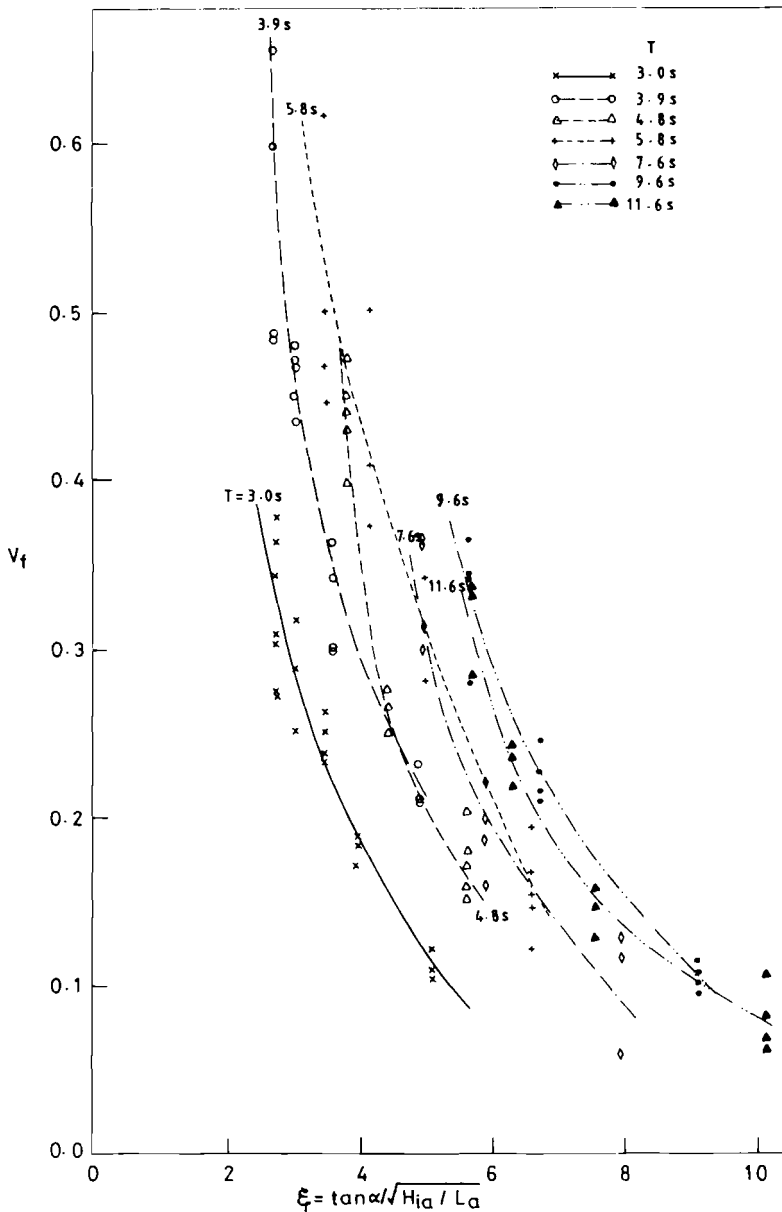
Figure 9.   Variation of rundown velocity with ξ.

(3) Both figures indicate a substantial reduction in the magnitude of the relative rundown velocity (*viz.*, of the order of 80 to 90%) for an increase in ϵ from 2.5 to 6.0. In addition, the trend curves indicate that there is a possible upper boundary beyond which further increase in wave period does not influence rundown velocity. Pres-

ent results suggest that this upper boundary corresponds to a wave period of T = 9 seconds.

(4) Table 3 indicates the magnitude of relative rundown velocity for different ζ values obtained with both methods discussed earlier. Comparison of magnitudes suggests that for small values of ζ (less than 6), the float method predicts a higher

Table 3. *Run down velocities with float and wave gauges for different ζ values.*

$\dfrac{\tan \alpha}{\sqrt{Hia/La}}$	T (sec)	V_w	V_f	Ruw (m/sec)	Ruf (m/sec)	% + or −
3.0	3.0	0.171	0.279	0.943	1.540	63
	3.9	0.260	0.470	1.43	2.59	81
	4.8	0.365	>1.0	2.01	>5.0	
	5.8	0.400	0.645	2.206	3.56	61
	7.6	0.298	>1.0	1.643	>5.0	
	9.6	0.362	>1.0	1.996	>5.0	
	11.6	0.270	>1.0	1.49	>5.0	
6.0	3.0	0.036	0.071	0.198	0.391	97
	3.9	0.066	0.158	0.364	0.871	139
	4.8	0.094	0.145	0.518	0.799	54
	5.8	0.128	0.212	0.706	1.169	65
	7.6	0.116	0.196	0.639	1.081	69
	9.6	0.141	0.292	0.777	1.610	107
	11.6	0.120	0.271	0.661	1.494	126
9.0	3.0	0.014	0.005	0.077	0.027	−65
	3.9	0.021	0.060	0.116	0.331	185
	4.8	0.031	0.045	0.171	0.248	45
	5.8	0.043	0.050	0.237	0.275	16
	7.6	0.041	0.062	0.226	0.342	51
	9.6	0.056	0.110	0.309	0.607	96
	11.6	0.044	0.106	0.243	0.584	140
12.0	3.0	0.006	0.002	0.033	0.011	−67
	3.9	0.011	0.014	0.061	0.077	26
	4.8	0.018	0.006	0.099	0.033	−66
	5.8	0.020	0.002	0.110	0.011	−90
	7.6	0.030	0.002	0.165	0.011	−93
	9.6	0.022	0.010	0.121	0.055	−54
	11.6	0.023	0.049	0.127	0.270	113

value of rundown velocity (by 70%) compared to the wave gauge method. For $6 < \zeta < 12$, the increase is of the order of 50 to 100 percent.

DISCUSSION OF RESULTS

Experimental techniques adopted in the determination of rundown velocity along the slope of the breakwater with float has proved to be a simple method involving no complexities in data acquisition. Use of other systems such as current meters to measure the rundown velocity might experience problems with recording velocities as the flow during rundown is predominantly a mixture of air and water. The consistency of results on rundown velocity obtained with the float method proves its superiority over the wave gauge method.

The test results have shown consistently a higher value of rundown velocity with the float compared to that with the wave gauge. The probable reasons follow:

(1) Peak velocities were measured by the float,

as the float was released and its path recorded, when the rundown reaches its peak.

(2) In the wave gauge method, top and bottom limits of wave rundown were considered in the calculation of rundown length along the breakwater slope, and a corresponding duration was used to compute the rundown velocity. For a certain incident wave climate, the rundown profile was comprised of two portions:

(1) A steep rundown portion followed by
(2) A flat rundown (Figure 10).

Considering either (1) or (2) or both in the determination of the duration of rundown velocity makes the difference. In practice, engineers would be interested to know the peak rundown velocity which is quite important in the design aspect either for stability of armour block or for the blocks at the toe of the breakwater. The float method employed under the present studies has paved the way for determination of critical rundown velocities for breakwater design, as opposed to the wave
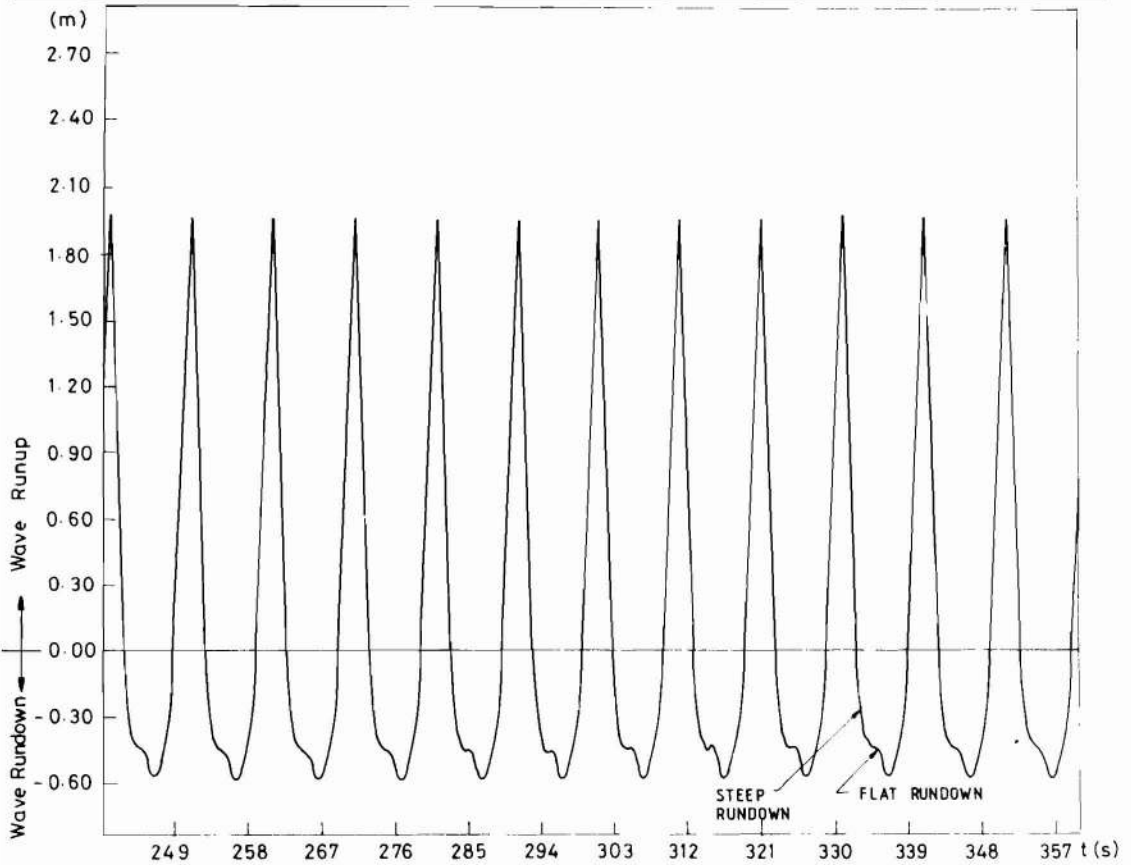
Figure 10.   Wave runup and rundown for H_{ia} = 0.83 m, T = 10.0 sec.

gauge method. The following example is worked out to emphasize the above aspect:

Given: A wave period of T = 3.9 sec, wave steepness Hia/La of 0.063 and water depth at toe of breakwater h_t = 3.10 m.

With the wave gauge method, Figure 6 predicts a relative rundown velocity of 0.304 leading to a rundown velocity of 1.67 m/sec. However, with the float, a maximum V_f of 0.570 is predicted by Figure 7 giving a velocity of 3.14 m/sec.

During experimental studies the influence of wave steepness on wave runup and rundown was observed. For wave steepness less than 0.01 (Hia/La < 0.01), the waves approaching the breakwater range along its slope. Thus, runup and rundown of wave were concentrated near still water level. However, for Hia/La ≥ 0.01, wave breaking causes the toe of the breakwater to become exposed during rundown indicating the extent to which the armour blocks are subjected for forces due to rundown.

APPLICATION OF RESULTS FOR RUBBLE MOUND BREAKWATER

The runup curve given in the SHORE PROTECTION MANUAL (1977) for a rubble mound structure with a slope of 1:1.5 was compared with that of present run up results for condition, viz., d_s/H_0' > 3.0 (d_s: water depth at the toe of the structure and H_0' : unrefracted wave height). The comparison is shown in Figure 11. Close agreement between the results was not a surprise as the slope and porosity in both cases were the same. It is, therefore, quite reasonable to extend present results on rundown to rubble mound breakwater. This suggests that rundown velocities determined in the present case can be applied for the rubble mound structures.
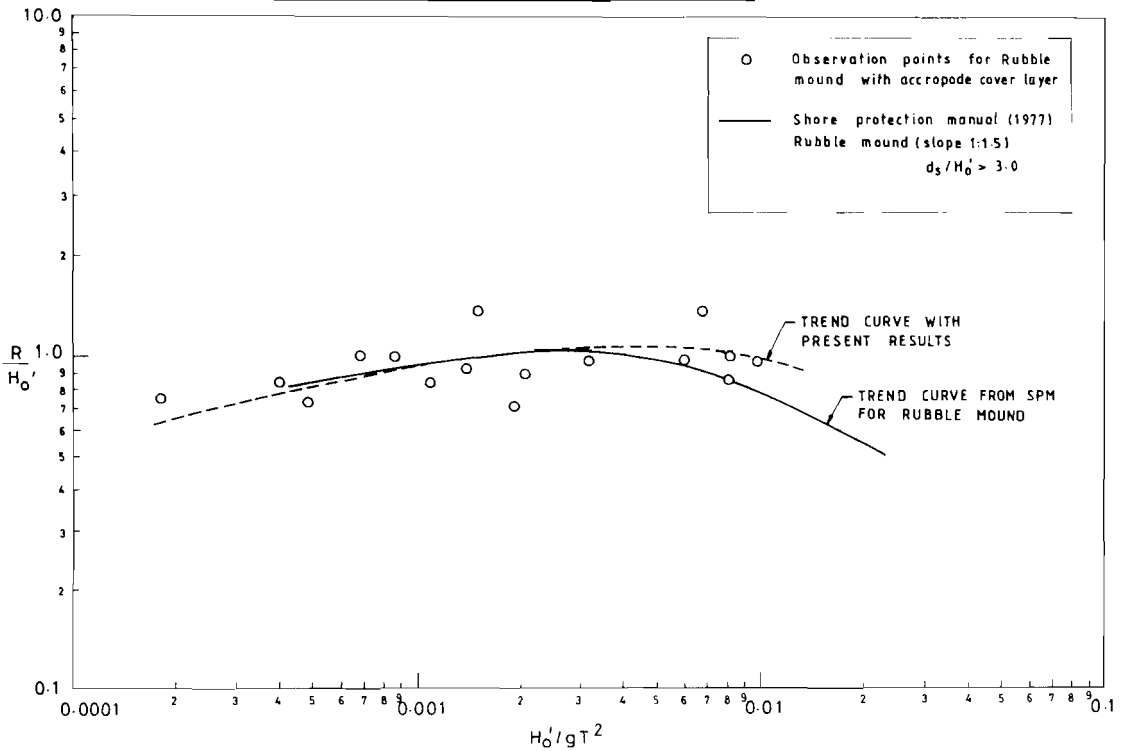
Figure 11. Run-up comparison for accropode and rubble.

PROTOTYPE APPLICATION OF RESULTS FOR A RUBBLE MOUND BREAKWATER

The following example is given to demonstrate the use of design curves given in Figures 6 and 7.

Determine:

Rundown velocity for a rubble mound breakwater for the following environmental conditions.

$$\text{Wave height (H)} = 2.75 \text{ m}$$

$$\text{Wave period (T)} = 10.0 \text{ sec}$$

$$\text{Water depth (h)} = 12.0 \text{ m}$$

Seaward slope of the breakwater = 1:1.5

Solution:

Determination of wave length La and Hia from Tables of functions given in the SHORE PROTECTION MANUAL (1977) for deep water wave parameters:

For T = 10 sec deepwater wave length Lo is

$$\text{Lo} = 156 \text{ m}$$

$$\frac{h}{Lo} = \frac{12}{156} = 0.0769$$

From Tables of function:

$$\frac{h}{La} = 0.1205 \quad \text{and} \quad \frac{H}{Hia} = 0.9591$$

$$\therefore \text{La} = 99.6 \text{ m}$$

$$\text{Hia} = \frac{2.75}{0.9591} = 2.87$$

$$\therefore \frac{\text{Hia}}{\text{La}} = 0.029$$

From Figure 7, for Hia/La = 0.029 and T = 10 sec, the magnitude of rundown velocity parameter V_f is = 0.545 and this leads to a rundown velocity of 5.90 m/sec. As Hia/La is greater than 0.010, the results can be applied to check (i) stability of armour blocks near the toe of the breakwater, and (ii) extent of toe protection needed to safeguard the breakwater from scour near the toe.

CONCLUSIONS

(1) Relative rundown velocity increases exponentially with an increase in wave steepness. For the range of wave steepness (0.004 to 0.077), the increase is a function of wave period. For small wave periods (less than 5 sec), a steady rise in rundown velocity is predicted; whereas for large wave periods (greater than 5 sec), a steep rise is predicted.

(2) Relative rundown velocity obtained with floats consistently indicates a higher magnitude compared to those with wave gauges. For wave steepness less than 0.01 and T less than 5 sec, the increase is of the order of 400 percent; however, for wave steepness greater than or equal to 0.01 and T greater than 3 sec, the increase varies between 50 and 200 percent.

(3) A substantial reduction (on the order of 80 to 90%) in the magnitude of relative rundown velocity is predicted for an increase in ξ from 2.5 to 6.0, regardless of the wave period.

(4) The experimental trend curves for the variation of rundown velocity either with Hia/La or ϵ indicates that there is a possible upper boundary below where all trend curves lie regardless of the variation in wave period.

(5) Determination of rundown velocity using a float has proved to be a simple and reliable method without involving any complexity in data acquisition.

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