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Technical note

Stability of berm breakwater with reduced armor stone weight

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Abstract

The basic principle involved in the design of S-shaped breakwater is the provision of a wide berm at or around the water level with smaller size armor stones than that used in conventional design, which are allowed to reshape till an equilibrium slope is achieved. An attempt is made to assess the influence of wave height, wave period, and berm width on the stability of S-shaped breakwater with reduced (30% reduction in armor stone weight) armor unit weight. From the investigation, it is found that the berm breakwater with 30% reduced armor weight would be stable for the design wave height if the berm width is 60 cm and wave period 1.2 s. For higher wave periods studied, zero damage wave height reduces by 20–40% of the design wave height. Wave period has large influence on the stability of berm breakwaters. The runup increases with decrease in weight up to $W_o/W = 0.9$.

Keywords: Stability; Berm breakwater; Laboratory investigation regular waves

1. Introduction

Breakwaters are the structures constructed to provide protection to the port and harbor facility from dynamic forces of the ocean waves. The traditional and most commonly used breakwaters are of the rubble mound type which consists of one or two layers of armor stone, one or two filter layers and a core of quarry. The design of the breakwater section, which is normally of a trapezoidal shape, is described in great details in the Shore Protection Manual. The design involves use of Hudson

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Nomenclature

B	berm width
d	water depth
d/L	relative depth
g	acceleration due to gravity
H'_o	deep water wave height
H_{zd}	zero damage wave height
H'_o/gT^2	deep water wave steepness
L	wave length
L_o	deep water wavelength
R_u	runup
R_u/H'_o	relative runup
W	weight of armor unit calculated using Hudson formula
W_o	weight of reduced armor unit
γ_a	specific weight armor unit
K_D	stability coefficient in Hudson formula
α	angle of seaward slope of structure

equation (SPM, 1984) or Van der Meer (1988) equation usually supported by physical model studies. The conventional breakwaters are designed in such a way that no damage or only little damage is allowed on the structure. This criterion necessitates the use of large and heavy rock or artificial concrete units for armoring. A more economic section could be a structure with smaller armor unit, where profile development is being allowed in order to reach a stable profile. A single slope rubble mound breakwater subjected to waves undergoes some rearrangement of armor stones and gets stabilized to the "S-shaped profile". Once the equilibrium stage is reached the severity of wave action on the structure decreases, even for higher waves. The statically stable breakwaters are characterized by wave height parameter ($H/\Delta D \leq 3$) and dynamically stable breakwaters are characterized by wave height parameter ($H/\Delta D \geq 6$). S-shaped breakwaters belongs to the category having ($H/\Delta D$) between 3 and 6 (Van der Meer, 1992).

Many coastal engineers have proved that S-shaped breakwaters are more stable than conventional breakwaters. Priest et al. (1964) states that it would be practical to design such a section that would be stable for the design incident wave height but with smaller stones than would be required by conventional formula. Brunn and Johannesson (1976) describe the hydraulics of S-shaped breakwater and recommended the use of S-shaped breakwater geometry, instead of continuous single slope, for an increased safety and economy. Aysen et al. (1989), conducted series of test on three slope composite rubble mound breakwater concluded that under the same test condition, same wave height, period range, water depth, and same armor stone, the three slope berm type section produce up to 90% less damage relative to the 1:2 single slope section. Also the increase in wave height 2.3 times the design wave height, the alternate section received damage ranging between 5% and 12% for the wave period tested.

Earlier experiments done in the Marine structures laboratory, N.I.T.K. Surathkal, on berm breakwaters have shown that increase in berm width reduces the damage to a large extent and it is possible to reduce armor size by providing the berm, for the same wave parameters (Subba Rao and Balakrishna, 2002). In the present study, the stability of S-shaped breakwater models with 30% less armor weight than that would be obtained from conventional formula was tested. The damage to the breakwater was assessed by comparing initial and final profile and obtaining A/D_{50}^2, where A is the erosion area in cross section of sea ward profile and D_{50} is the nominal diameter of armor stone used (Van der Meer et al. 1984). Van der Meer's damage criteria, start of damage $S = 2$, used to calculate zero damage wave heights. The parameter $H/\Delta D_{50}$ is called the "wave height parameter" or "stability number", N_s and damage parameter, $S = A/D_{50}^2$, were used to explain the effect of different parameters on the stability of breakwater.

Where: Δ, relative mass density of armour unit $((\rho_a/\rho_w) - 1)$; ρ_a, mass density of armour unit; ρ_w, mass density of water; $D_{50} = (W_{50}/\gamma_a)^{1/3}$, nominal diameter of stone; W_{50}, weight of the armour such that 50% of the stones have a weight larger than W_{50}.

2. Experimental setup

2.1. Wave flume

The wave flume is of 50 m length, 0.71 m width and 1.1 m depth (Fig. 1). It has a 42 m long smooth concrete bed. About 25 m length of the wave flume is provided with glass panels on one side to facilitate observations and photography. It is provided with an inverter type wave generator at the other end. At this end, the flume is widened to 1.5 m and deepened to 1.4 m. The generating chamber is 6.3 m long. Gradual transition is ensured between the normal flume bed level and that of generating chamber by a ramp. The wave filter consists of a series of vertical asbestos sheets spaced at about 10 cm distance from each other and kept parallel to the

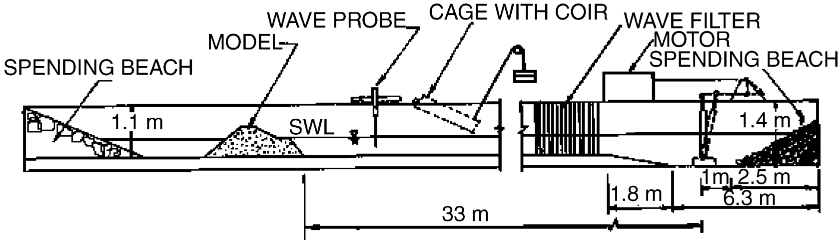

Fig. 1. Wave flume—elevation.

length of the flume. The purpose of the filter is to damp the disturbance caused by successive reflection and to smoothen the generated waves. Granite stones forming a slope act as an absorber behind the flap in the generating chamber. The flume is provided with iron railings on the top of the sidewalls to enable the movement of a trolley carrying the sounding rods or wave profiler mechanism system along the flume.

2.2. Instrumentation and data acquisition

Capacitance type wave probes along with amplification units supplied by Delft Laboratories were used for acquiring the data. One such probe was used during the experimental work, for acquiring incident wave height as well as reflection envelope. During the experimentation, the signals from wave channels were verified with digital oscilloscope along with computer data acquisition system. The main parameters, wave surface elevation on seaward side of model were converted into electrical signals. These electrical signals were stored as digital signals by software controlled 12-bit A/D converter with 16 digital input/output. During the experiment, every time after three waves pass the structure, transmitted waveform for 10 s duration was acquired using the software ADTRIG-T.C.

3. Breakwater model

The conventional breakwater was designed for zero damage wave height $H = 10$ cm, mass density of the armor stone $\rho_w = 2.74$ g/cc, $K_D = 3.5$, $\cot\alpha = 2$. The primary armor weight (W), determined using Hudson's formula (SPM, 1984) was 74.3 g and primary armor layer thickness 7 cm, secondary filter layer thickness 3.2 cm. The slope of breakwater section on both sides 1V: 2H. Breakwater models with reduced armor weight were tested. The weights of armor stone reduced to (W_o) 52 g that was 30% of the weight obtained by Hudson formula. Filter layer stone weight was 5.2 g. The crest width provided was 15 cm. Fig. 2 shows the cross section of breakwater model studied. The size distribution of the rubble material was determined in terms of weight. The aggregates are carefully hand picked so that they were roughly cubical in shape. The weight of the stones used for primary

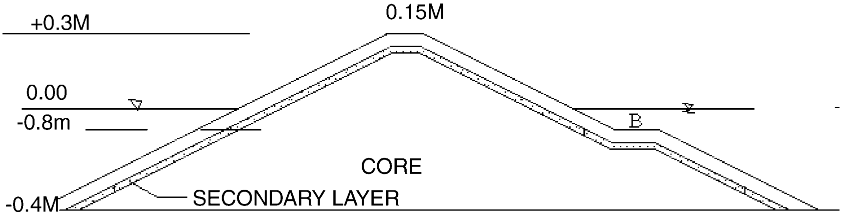

Fig. 2. Cross section of breakwater model.

layer ranged from 0.75 to 1.25 W_o (39 to 65 g) with secondary layer stone ranges from 3.6 to 6.7 g.

The model was constructed at a distance of 33 m from the generator flap. The primary armor layer was divided into three zones; crest ward slope, berm and toe ward slope and the units in these regions were colored as black, white and red, respectively, to identify the movement of each stone. The cross section of breakwater denoting layers was drawn on the glass panel. The core material was placed first to the required level and the secondary layer and primary armor layer were constructed to the marked level. Regarding the placement of the armor units, a casual placement of each individual stone was done to obtain fitted surface.

4. Experiments

The experiments were conducted for a configuration of model shown in Fig. 2. The test models were subjected to waves ranging from 10, 12 and 16 cm with wave periods of 1.2, 1.6, 2.0 and 2.6 s, in water depth of 40 cm. A list of governing variables together with the possible range of application is listed in Table 1. All the models were studied for monochromatic waves and normal wave attack. The water depth in front of the structure was kept constant i.e., 40 cm. The berm was provided at 32 cm above the bed level (0.8 times the depth of water level, Priest et al., 1964). It was observed from the literature review that after the attack of 3000 waves, the effect of waves on damage tends to be constant. Hence, each run was subjected to a maximum of 3000 waves. The initial profile of seaward slope of the berm breakwater was surveyed with the help of surface profiler consisting of nine sounding rods mounted on the wooden frame, which could be moved along the longitudinal direction. Readings were taken at an interval of 10 cm longitudinally.

Table 1
Range of experimental variables

Sl. no.	Variable	Expression	Range
1	Wave height	H	10,12,16 cm
2	Wave period	T	1.2,1.6,2.0,2.6 s
3	Berm width	B	15,30,45,60 cm
4	Storm duration	N	3000 waves
5	Angle of wave attack	ψ	90°
6	Water depth	d	40 cm
7	Armor stone weight	W_{50}	52 g
8	Nominal diameter	D_{50}	2.6 cm
9	Shape of the armor stone		Angular rounded
10	Crest height		30 cm
11	Crest width		15 cm
12	Initial slope above the berm		1:2
13	Initial slope below the berm		1:2
14	Specific gravity of armor stone γ_a		2.74

Soundings were made to an accuracy of 1 mm. The average of nine soundings was considered for drawing the profile. The breakwater was considered to be failed when the secondary layer was exposed. The model was rebuilt for after each experiment.

5. Results and discussion

5.1. Computation of zero damage wave height

To find the zero damage wave height, damage level (S) versus stability number (N_s) graphs are drawn for different B/L_o values. Fig. 3 shows the variation of

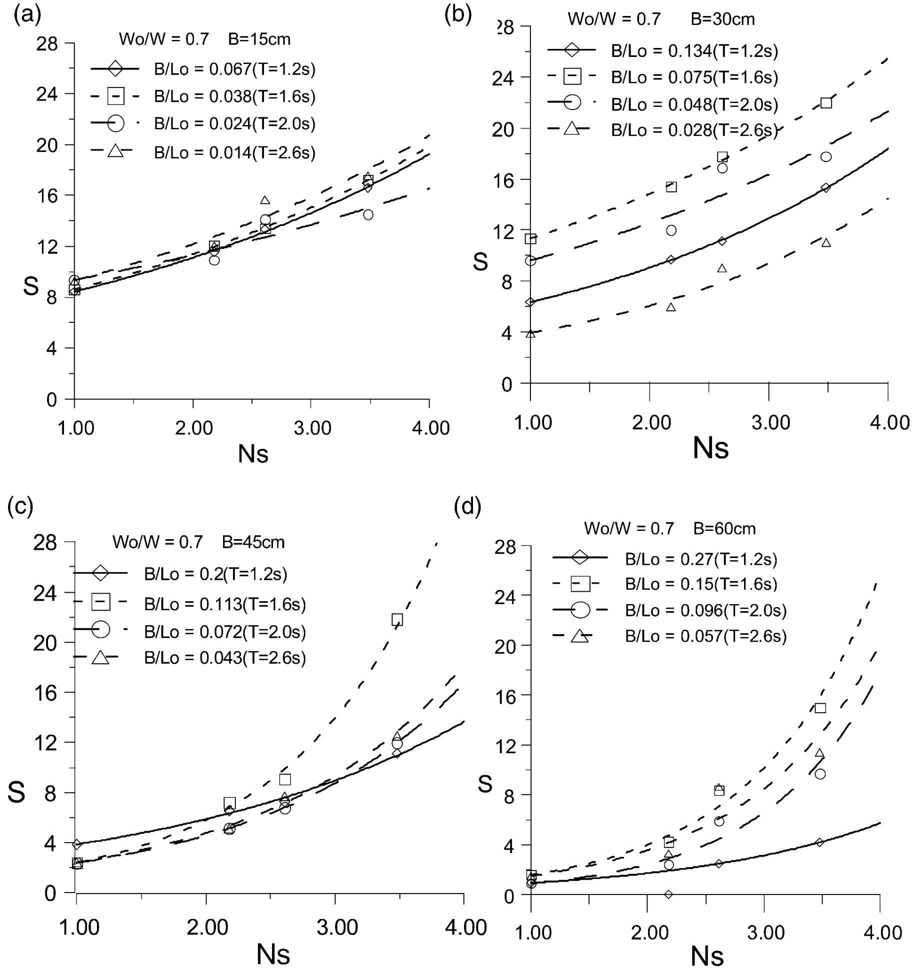

Fig. 3. Damage level versus stability number for different berm widths.

damage level (S) with stability number (N_s) for $W_o/W = 0.7$. The zero damage wave heights are obtained from these graphs as the wave heights corresponding to the damage level $S = 2$. From Fig. 3a,b, zero damage wave height (H_{zd}) calculation is not possible as, for each of the B/L_o values, damage level is more than 2. From Fig. 3c, the zero damage wave height is 3.7 cm for B/L_o values of 0.113, 0.072 and 0.043, respectively. From Fig. 3d, the zero damage wave heights are 10.8, 6.2, 8.7, 6.2 cm for B/L_o values of 0.27, 0.15, 0.090 and 0.057, respectively. Table 2 gives a comparison between the zero damage wave heights for different armor weights, $W_o/W = 1$, $W_o/W = 0.9$, $W_o/W = 0.7$. It can be concluded that as the berm width increases the zero damage wave height of breakwater section also increases indicating greater stability. Armor weight calculated using Hudson formula for design wave height of 10 cm can be reduced by 30% by providing S-shaped breakwater with 60 cm berm width for wave period 1.2 s only. For higher wave periods studied zero damage wave height reduces by 20–40% of the design wave height indicating that breakwater is not stable. Hence, 30% reduction in armor weight is not possible.

5.2. *Effect of stability number on stability*

The effect of wave height on the stability is investigated through the wave height parameter (stability number) N_s. The variation of damage level (S) with stability number (N_s) for different wave periods are shown in Fig. 3. From the graphs, it is observed that the damage level increases exponentially with the increase in stability number. Comparison of the variation in damage level (S) with stability numbers (N_s) for different armor sizes and for different berm widths is shown in Fig. 4 and also indicates that the damage increases exponentially with the stability number for different armor stone sizes. The trend of variation of damage with the N_s is found similar for $W_o/W = 1$, $W_o/W = 0.9$, and $W_o/W = 0.7$. From the above discussions, it may be concluded that as stability number increases damage level increases exponentially.

5.3. *Effect of wave period on stability*

From Fig. 3, it is observed that wave period 1.6 s causes maximum damage to the breakwater cross section for all the berm widths and wave periods studied. This is probably due to as wave period changes from 1.6 to 2.0 s the plunging waves converted to surging except for 15 cm berm width. Hence, when $T = 1.6$ s it is the transition stage which caused more damage. For 60 cm berm width wave period 1.2 s has caused least damage and the model was found safe for design wave height, where as other wave periods 1.6, 2.0, 2.6 s have shown zero damage wave heights which are less than design wave height. For 60 cm berm width the extent of damage as wave period increases from 1.2 to 1.6 s is found to increase 3–4 times and for wave period 2.0 s the damage is found less than that for 1.6 s. For berm widths 60 and 45 cm, wave period 2.6 s

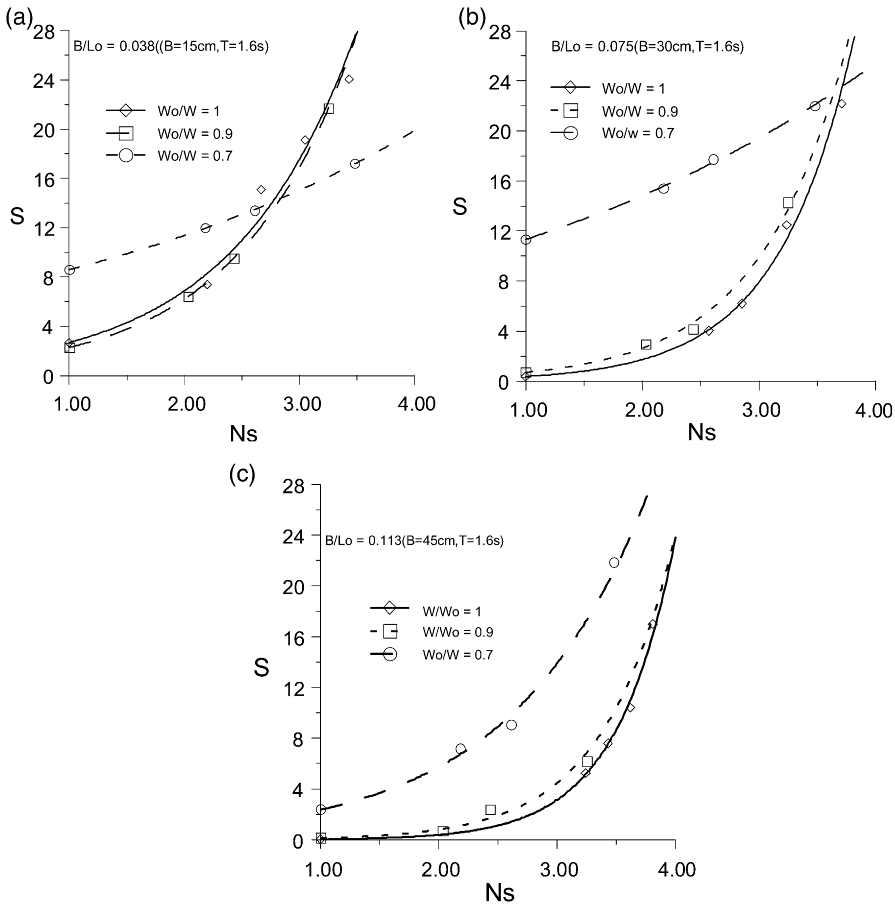

Fig. 4. Influence of armor size on damage level (S) for different stability number (N_s) for wave period 1.6 s.

has shown more damage than 2.0 s. From the above discussion, it can be concluded that wave period has significant influence on the stability of berm breakwaters.

5.4. Effect of berm width on stability

In the present investigation, berm widths of 15, 30, 45 and 60 cm are studied. Each berm width is tested for wave periods of 1.2, 1.6, 2.0 and 2.6 s and wave heights of 10, 12 and 16 cm. The variation of damage (S) with stability number for different width is shown in Fig. 5. From Fig. 5a, it is observed that as berm width increases from 15 to 60 cm the damage decreases for all stability number values. From Fig. 5b,c, it is observed that as the berm width increases from 15 to 30 cm the damage increases and further increase in berm width from 30 to 60 cm damage

Table 2
Comparison of zero damage wave height for different W_o/W values

T (s)	B (cm)	$H_{zd}(W_o/W = 1)$	$H_{zd}(W_o/W = 0.9)$	$H_{zd}(W_o/W = 0.7)$
1.2	15	11.81	10.2	–
	30	13.13	13.8	–
	45	15.75	–	–
	60	–	–	10.8
1.6	15	7.35	6.51	–
	30	12.47	9.22	–
	45	16.2	13.1	3.7
	60	–	–	6.2
2.0	15	9.2	8.38	–
	30	11.3	8.87	–
	45	12.47	10.5	3.7
	60	–	–	8.74
2.6	15	11.81	9.47	–
	30	13.78	10.35	–
	45	15	10.45	3.7
	60	–	–	6.2

level decreases for all the stability numbers studied. This may be due to change in breaker type from plunging to surging as wave period changes from 1.6 to 2.0 s and which caused more erosion of berm in case of 30 cm berm width. For wave period 2.6 s surging type of breaker is found, for which the difference in damage is not much as berm width increases from 30 to 60 m as seen from Fig. 5d. Fig. 6 shows the comparison of damage level (S) with non-dimensional berm width B/d values for different stability numbers. From Fig. 6a, for ($T = 1.2$ s) it is very clear that as B/d ratio increases from 0.375 to 1.5, damage decreases for all stability number studied. From Fig. 6b,c, it is observed that as the B/d ratio increases from 0.375 to 0.75 the damage also increases and further increase in B/d ratio from 0.75 to 1.5 the damage decreases for all the stability number studied. From Fig. 6d, it is observed that for the period 2.6 s and for given stability number, increase in B/d ratio beyond 0.75 is not effective in reducing the damage. From above discussion it may be concluded that in general as the B/d ratio increases there is decrease in damage level and it is influenced by the wave period.

5.5. Effect of armor size on stability

The variations of damage level (S) with stability number (N_s) for different armor sizes and for constant wave period 1.6 s are shown in Fig. 4. From these graphs, it is observed that as armor size decreases damage level increases for all B/L_o values. The magnitude of damage reduces considerably as the berm width increases from 15 to 45 cm. This may be due to the fact that

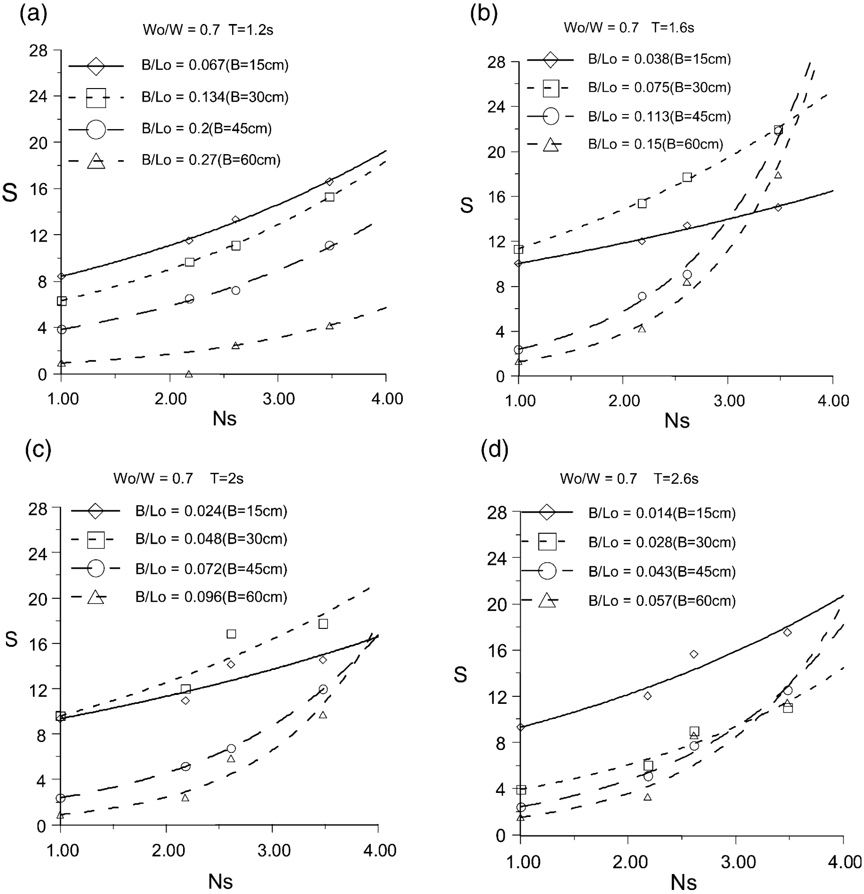

Fig. 5. Influence of berm width on damage level (*S*) for different wave periods.

sufficient berm width is available for the dissipating the incoming wave energy. From the above discussion, it can be concluded that reduction in armor weight, calculated using conventional formula is possible by providing berm of proper width.

5.6. *Effect of armor size on runup*

Comparisons of wave runup characteristics for different armor stone sizes are shown in Fig. 7. From these figures it is observed that as the armor size decreases from $W_o/W = 1$ to $W_o/W = 0.9$, there is an increase in runup. But corresponding to the armor size decrease from $W_o/W = 0.9$ to $W_o/W = 0.7$ the runup is almost same. The initial increase in the runup due to reduced armor

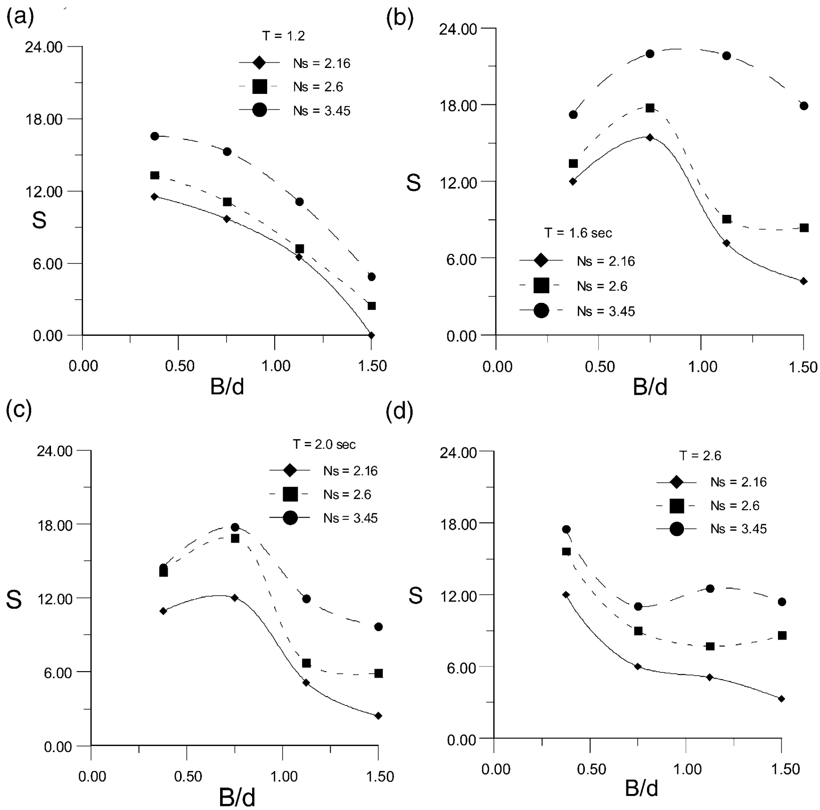

Fig. 6. Damage level (S) as a function of B/d values for different wave periods.

weight may be because of reduction in pore size, resulting in lower energy dissipation. From the above discussion, it can be concluded that the runup increases with decrease in armor weight from $W_o/W = 1$ to $W_o/W = 0.9$ and for $W_o/W = 0.7$ it remains almost same as that for armor weight $W_o/W = 0.9$.

5.7. *Effect of berm width on runup*

The variations of non-dimensional runup values (R_u/H_o) with deepwater wave steepness (H_o/gT^2) for different non-dimensional berm widths are as shown in Fig. 8. From this figure, it is seen that as deepwater wave steepness increases, the runup is also decreasing. This trend of variation is similar to the trend given in SPM (1984). Further from this figure, it is observed that increase in berm width is not effective in reducing wave runup with in the range of experimental variables studied.

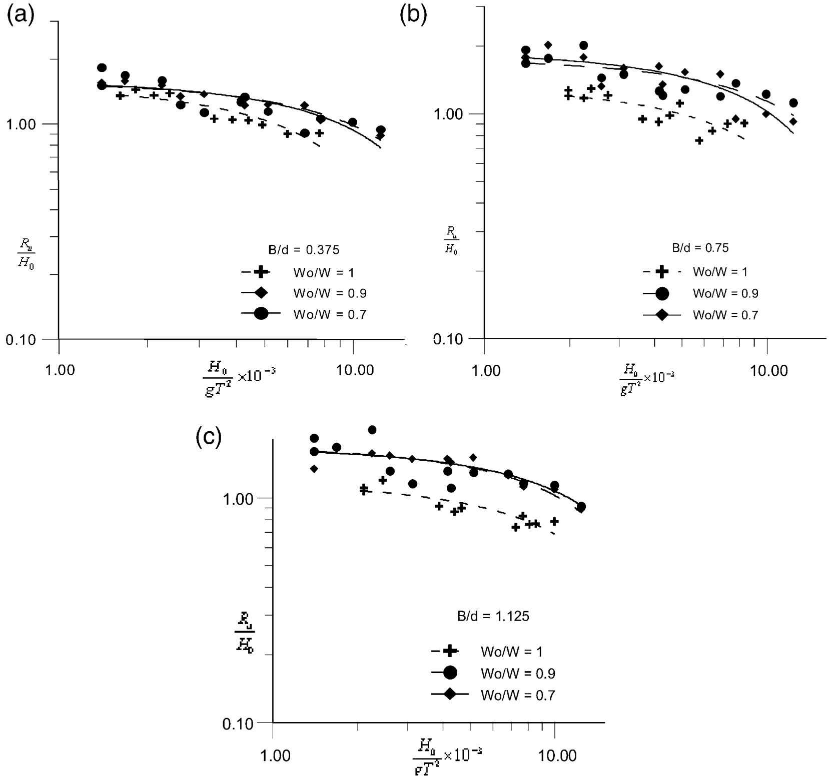

Fig. 7. Wave runup characteristics for different armor sizes.

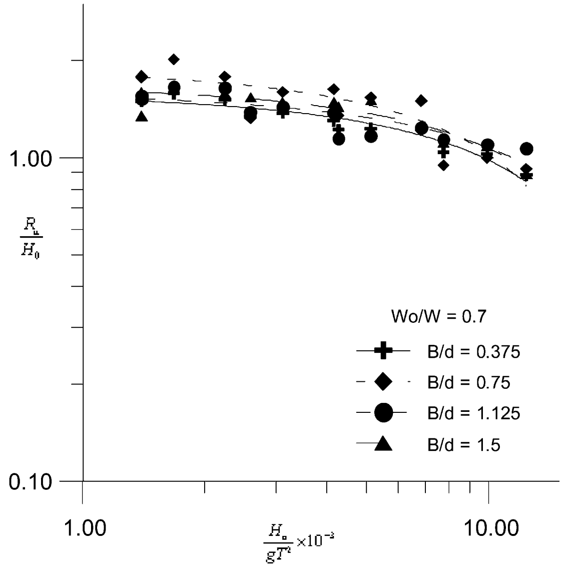

Fig. 8. Wave runup characteristics for different berm widths.

6. Conclusions

Based on the present investigation, the following conclusions can be drawn. As the berm width increases there is a decrease in damage level indicating greater stability of breakwater. Wave period has great influence on the stability of berm breakwaters. Breakwater model studied with 30% reduced armor stone weight is found stable only for 60 cm berm width and 1.2 s wave period. For other wave periods studied, the zero damage wave height obtained is less than design wave height, 10 cm. As the stability number increases damage level increases exponentially. Irrespective of berm width as deepwater wave steepness increases, the runup is also decreasing. Increase in berm width is found to be not effective in reducing runup. The runup increases with decrease in armor weight from $W_o/W = 1$ to $W_o/W = 0.9$ and for $W_o/W = 0.7$ it remains almost same as that for armor weight $W_o/W = 0.9$.

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