Experimental Investigation of the Hydraulic Performance of Breakwater Structures with Geotextile Armor Units

Tom Elias, S.M.ASCE[1]; and Kiran G. Shirlal[2]

Abstract: Geotextile sand containers (GSCs) gained popularity recently as a modern age coastal protection measure. Its usability as an ecofriendly alternative for traditional breakwaters overcomes issues such as scarcity and quarrying prohibition of natural rocks. The current work involves a 1:30 scaled physical experimentation on the hydraulic performance of an emerged, nonovertopping breakwater model with GSCs. Four configurations of GSC structures are analyzed for their runup, rundown, and reflection characteristics confining to wave parameters of Mangaluru. The study revealed that the reflection coefficient (K_r) for GSC structures could range from 0.26 to 0.69. In addition, reducing GSC fill percentage from 100 to 80 is found to be more effective (up to 64%) in reducing reflection, runup, and rundown rates, than altering GSC size. These results can serve as a practical guideline for designing GSC breakwaters. **DOI: 10.1061/(ASCE)WW.1943-5460.0000708**.

Author keywords: Geotextiles; Breakwater; Reflection coefficient; Wave runup; Wave rundown.

Geotextile Sand Containers, Hydraulic Performance, and Existing State of the Art

Geotextiles gained momentum in civil and coastal engineering applications as a new engineering material by the late 20th century. Factors such as ready availability, use of locally available sand and dredged materials, reduction in construction time, and reduced cost make geotextile sand containers (GSCs) a suitable coastal engineering material. Breakwaters are coastal structures erected to obstruct and dissipate wave energy. Traditionally, breakwaters are constructed using huge granite stones weighing tonnes as primary armor units. Later, extensive research resulted in the invention of numerous artificial armor units, differing in weight, shape, material, interlocking, and other hydraulic responses (van Gent et al. 1999; Melby and Turk 1997). Expansion in geotextile containment systems is also reflected in breakwater constructions, as geotubes started replacing conventional units in many coastal protection structures wherever feasible (Elias and Shirlal 2021). Constructions such as submerged breakwaters, seawalls, revetments, and groynes started to be built using the geotextile containment system (Elias et al. 2018). Increasing cost of natural rock, reduced availability, and prohibition of quarrying created demands for viable alternatives to rock structures (Jackson 2016). At the same time, factors such as reduced cost, ecofriendliness, ease of modification or reshaping, and reduction in construction time make geotextile armor units favorable for breakwater construction (Shin and Oh 2007). Stability analysis of GSC structures has been carried out by various researchers (Elias et al. 2021), but wave structure interaction for a GSC breakwater is rarely discussed. This paper aims to bridge this knowledge gap by detailing the hydraulic performance of GSC breakwaters, which include wave reflection, runup, and rundown characteristics.

Wave Reflection

Studies related to wave reflection from coastal structures are crucial as it can lead to toe scouring due to sediment transport, ultimately leading to the failure of structures (Oumeraci and Kortenhaus 2011). Some critical investigations on wave reflection from GSC structures examined the range of reflection coefficient and its dependence with various parameters. Experimental investigation by Oumeraci and Recio (2018) revealed a reflection coefficient (K_r) of 0.5 to 0.7 for GSC revetment structures. Physical model studies by Kriel (2012) on stacked, sand encapsulated geotube breakwaters reported a reflection coefficient range from 0.27 to 0.67. Values of K_r ranging from 0.22 to 0.54 are obtained when GSCs are used as the core for rubble mound breakwaters (geocore breakwater) (Oumeraci and Kortenhaus 2011). Similar investigation using geobags as the core of rubble mound breakwaters by Nasar et al. (2004) reports a K_r range of 0.41 to 0.56, which is up to 8% higher than that of rubble cored breakwater. Experimental studies conducted by Faraci (2018) on geocontainer submerged breakwaters also exhibited a range of K_r from 0.1 to 0.58. Emerged GSC structures, when adequately protected with certain components, can reduce reflected waves. Nishold et al. (2019) discuss geotube structures covered with rock gabions resulting in a 50% reduction of reflection coefficient due to increased crest width and porosity.

Various factors that govern the reflection from geotextile structures may include incident wave heights, water depth, wave period, and structure roughness. Kriel (2012) reports an increasing K_r with respect to increasing wave period and wavelength. Muttray et al. (2006) reports a negligible relationship with incident wave heights, whereas Kriel (2012) and Faraci (2018) show a decreasing trend with increasing incident wave heights. Most literature suggests an inverse relationship for K_r with water depth. From the preceding investigations, it has been concluded that geotextile armored structures exhibit K_r up to 0.7, which is higher than that of traditional breakwaters (Oumeraci and Recio 2018). This is due to the lack

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of pore spaces, which helps to create a turbulent interaction of water particles leading to increased energy dissipation. However, stability, cost reduction, and ease of construction make GSCs an effective alternative, when appropriately designed to reduce wave reflection. The present investigation aims at identifying configurations and conditions that result in a less reflective GSC structure.

Wave Runup

Wave runup is the vertical distance between still-water level and the point of maximum uprush of water on the structure. Study on wave runup is crucial as it decides the maximum crest elevation of a coastal structure. When runup exceeds crest elevation of the structure, water overtops, resulting in its transmission toward the leeward side. As a result, runup knowledge is required to design a structure either overtopping or nonovertopping. Attempts for quantifying runup on sandbag structures are significantly less. However, some available published resources discussing runup studies on sandbag or geotextile containers are reviewed. Kobayashi and Jacobs (1985) used empirical equations proposed by Ahrens and McCartney (1975) for predicting runup on sandbag revetments. This equation uses two empirical constants and surf similarity parameter for runup prediction and is found to be unreliable, as thickness and other parameters of sandbags are not considered (Rasmeemasmuang et al. 2014). It is to be noted that after Kobayashi and Jacobs (1985) a comprehensive study of runup on sandbag structures is reported only by Rasmeemasmuang et al. (2014). During this period, there has been much research related to GSC structures, but most of it focused on stability parameters and wave transmission. Rasmeemasmuang et al. (2014) carried out extensive experimental analysis on smooth and sandbag slopes and formulated the following equation, which relates relative runup and surf similarity parameter, along with empirical coefficients and thickness of sandbags:

$$\frac{R}{H} = a_1 \xi^b \left[1 - a_2 \left(\frac{d}{H}\right)^c\right] \quad (1)$$

where R/H = relative wave runup; a_1 and b = parameters for smooth slopes; a_2 and c = empirical coefficients related to relative roughness height (d/H), where d = roughness height or thickness. For smooth slopes, roughness height d will be equal to zero; thus, Eq. (1) reduces to

$$\frac{R}{H} = a_1 \xi^b \quad (2)$$

The values of parameters are calculated to be $a_1 = 0.98$, $b = 0.94$, $a_2 = 0.34$, and $c = 0.15$. Eq. (1) for the sandbag slope holds good with experimental results, with a correlation coefficient equal to 0.86. It is concluded that the increase in relative roughness height is beneficial in reducing runup. This is due to the increase in surface roughness resulting in enhanced friction, which in turn reduces water uprush on the structure. Relative runup is observed to be 26% to 40% lower for sandbags slopes compared with smooth slopes. In other words, an increase in roughness height reduces runup rates. Relative runup ranged from 0 to 2 for sandbag slopes and up to 2.8 for smooth, impermeable slopes.

Shankar and Jayaratne (2003) estimated a relative runup range of 1.2 to 2.8 for smooth impermeable breakwater. Shirlal et al. (2006) found a range of 0.5 to 1.08 for reef defensed breakwater. Physical model studies conducted by Rao et al. (2008) on berm breakwaters revealed a relative runup range of 0.55 to 1.15. In a broad perspective, relative runup values of existing breakwater structures range from 0.5 to 3.1 (Van der Meer and Stam 1992; Schimmels et al. 2012; Diwedar 2016). GSC structures also exhibit runup in a similar range, with higher rates compared with rubble mound breakwaters.

Wave Rundown

Wave rundown is the vertical distance between the still-water level and the maximum extent of down rush of retarding waves on the face of the structure. The highest potential for structural damage occurs in this region between still-water level and point of maximum down rush (Yamini et al. 2018). This is due to the fact that uplift forces and the head difference will be maximum in this region. This leads to the need for accurate demarcation of rundown limits so that potential damage areas can be easily identified. In addition, rundown calculation is essential in computing the required elevation of the structure under the still-water level (Oumeraci et al. 2010). Foyer (2013) reports that runup and rundown values are nearly identical around the still-water level. Laboratory investigations and physical model studies of rundown on GSC structures are less compared with runup studies. Relative rundown values generally range from 0.5 to 2.5 for conventional porous breakwaters (Battjes and Ary 1976; Pilarczyk 1987; Oumeraci et al. 2010; Foyer 2013; Yamini et al. 2018).

To conclude, rundown calculations are essential before implementing a structure on the field. The important factors affecting rundown are wave height, surf similarity parameter, geometry, surface roughness of the structure, and permeability of the structure slope. Since rundown leads to sliding instability, a good structure should be effective in resisting wave down rush.

Physical Modeling

Wave Flume

Physical modeling was carried out at the Wave Mechanics Laboratory, Department of Water Resources and Ocean Engineering, National Institute of Technology Karnataka (NITK), India. The available monochromatic, two-dimensional, fixed-bed wave flume is $50 \times 0.75 \times 1.1$ m (length × width × height) with a 25 m length provided with glass panels facilitating observation and photography. A "bottom-hinged flap"-type system kept as a $6.3 \times 1.5 \times 1.4$ m (length × width × height) chamber generates regular waves. A 1:12 slope beach is provided at the other end of the wave flume. Flap movements generate waves, controlled by an 11 kW, 1,450 rpm induction motor. The motor is regulated by an inverter drive of 0–50 Hz, having a speed range 0–155 rpm. The wave flume is capable of generating regular waves with wave heights 0.02 to 0.20 m and wave period 0.8 to 4 s, for a maximum water depth of 0.50 m.

Instrumentation

Four capacitance-type wave probes (accuracy 0.001 m) are equipped for measuring incident, reflected, and transmitted wave heights. Three probes are kept at the seaside for reflection computation, and one is kept at the leeside of the structure to measure transmission, if any. Capacitance-type wave probes, an amplification unit, and a computerized data acquisition system together comprise the instrumentation facility. The capacitance difference between water and copper conductor measured by the probes is converted to wave height and wave period by wave recorder software.

GSC Breakwater Model Construction

The GSC breakwater model comprises a core made of m-sand and a single layer of GSC armor units. Dimensions of the core and armor unit layers are illustrated in Fig. 1. Four different configurations of GSC armor units were tested and are elaborated in Fig. 2. Geotextile roll was cut and locally sewn into units of required dimension. Stitched bags were then filled with a calculated amount of sand collected from the NITK beach. Breakwater core was constructed in the flume bed at a distance of 12 m from the beach end. Once the core was constructed, GSC units were stacked with a 50% overlap keeping its longer dimension aligned to the direction of wave incidence. Water was pumped to the required depth after the model construction was completed. Properties of geotextiles, filling material (sand), and core (m-sand) are listed in Tables 1–3. A schematic representation of the GSC breakwater model in wave testing facility is illustrated in Fig. 3. A scale of 1:30 was adopted to represent the flume capacities and Mangaluru (Karnataka state, India) coastal conditions. Froude's similitude criteria was adopted for scaling the models. Scaling of geotextiles is practically impossible, as it would be extremely difficult to fabricate fabric that is 30 times thinner.

Test Procedure

To compute the hydraulic performance of GSC breakwater, the constructed model was exposed to waves of calculated heights and periods. For a fixed wave period, the structure was exposed to smaller waves (0.06 m) initially and then increased up to 0.16 m at an interval of 0.02 m. Waves reflected from the structure could reach the back of the wave generator and re-reflect, causing alteration of intended wave conditions. To avoid such issues, the wave attack on each case was limited to a burst of maximum eight waves so that generator would be shut before the interaction of reflected waves from the model. To dampen the wave energy, brief intervals were provided between each test case. To compute statically significant hydraulic parameters (runup, rundown, and reflection), the structure was exposed to three sets of wave trains comprising eight waves each. The average value of the three sets were reported. Three probe method discussed by Isaacson (1992) were used to compute the K_r. For the same, three wave probes were kept at the leeward side at a distance of L and $L/2$ from the breakwater model. Wave amplitudes from the three probes were used to compute the reflection coefficient K_r. Runup and rundown values were computed using the strip charts attached to the glass panels of wave flume. Maximum limits of uprush and downrush on the structure, measured vertically from the still-water level, is reported as runup and rundown, respectively. For all the tested cases, there was no overtopping of waves observed. As a result, there was no wave transmission observed in the experimentation. In addition, the flume beach was provided with porous materials aiding the wave dissipation, ultimately curbing beach reflection.

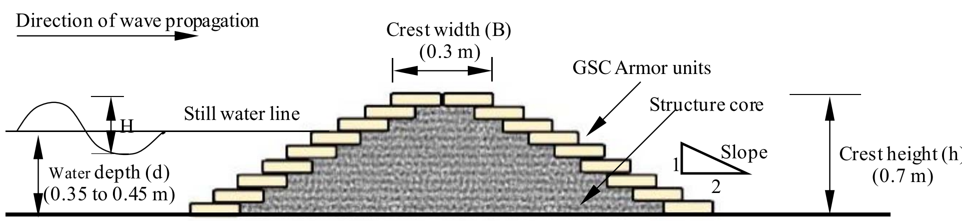

Fig. 1. Schematic diagram of GSC breakwater model.

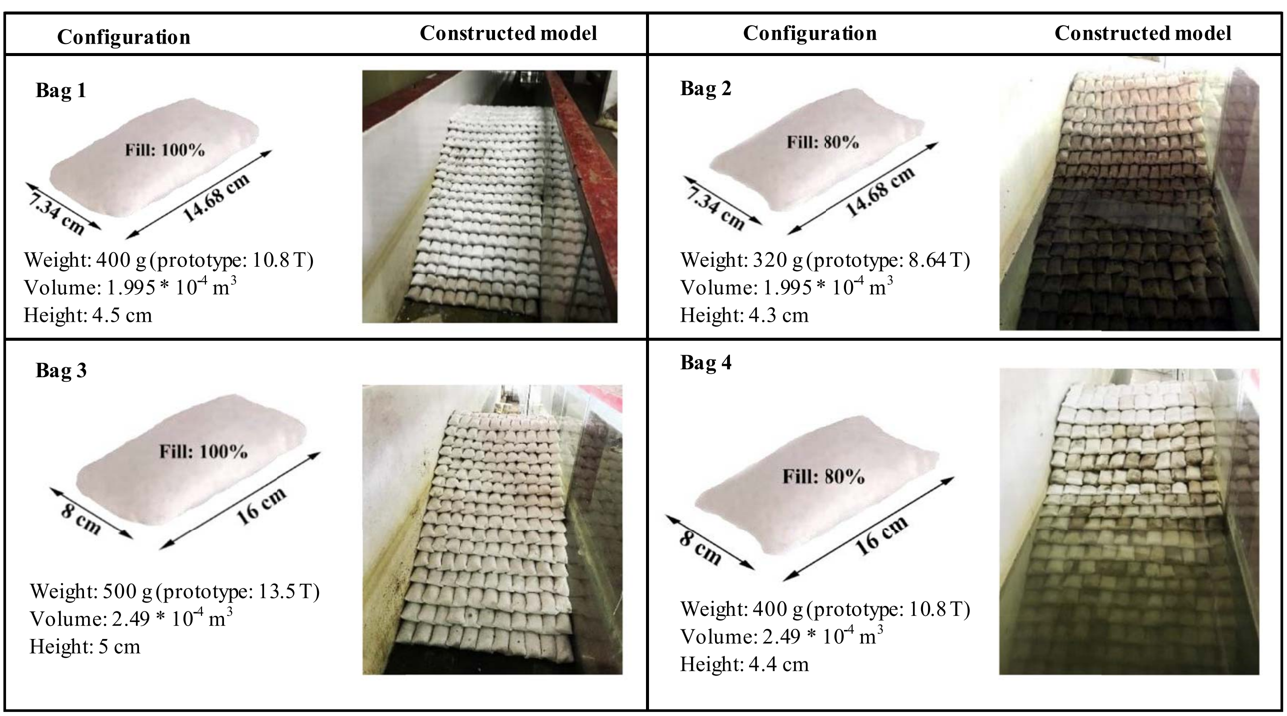

Fig. 2. Details of various test configurations.

Table 1. Range of governing variables

Variable	Expression	Range
Wave height	H	0.06, 0.08, 0.10,0.12, 0.14,0.16 m
Wave period	T	1.2, 1.4, 1.6, 1.8, 2, 2.2 s
Water depth	d	0.35, 0.40, 0.45 m
Angle of attack	F	90°
Mass density (GSC)	ρ	2,005 kg/m^3
GSC armor weight	W	400–500 g
Slope		1V:2H
Crest height	h	0.70 m
Crest width	B	0.32, 0.29 m
GSC material		Nonwoven

Table 2. Nondimensional model and wave characteristics

Variable	Range
GSC Breakwater model characteristics	
Slope	1V:2H
Relative height (h/d)	1.55–2
Relative crest width (B/d)	0.644–0.91
Structure height to depth ratio (h/d)	2, 1.75, 1.56
Wave characteristics	
Wave steepness (H_0/gT^2)	0.00126–0.0083
Surf similarity parameter [$\tan\alpha/(H_0/L_0)^{0.5}$]	2.18–5.68

Table 3. Properties of construction materials used

Property	Range
Geotextiles	
Type	Nonwoven
Material	Polypropylene
Color	White
Mass	200 GSM
Tensile strength	12 kN/m
Elongation at max tensile strength	30%
Permeability	6×10^{-2} m/s
Thickness	1.2 mm
Sand	
Location	NITK Beach
Specific gravity	2.65
D_{10}	0.18 mm
Median grain size D_{50}	0.35 mm
Core	
Material	M-sand
Specific gravity	2.78
D_{10}	0.22 mm
D_{50}	0.45 mm

The experimental setup is illustrated in Fig. 3. The results obtained are analyzed in the following sections.

Assumptions in Physical Modeling

Modeling a coastal structure requires certain simplifications or assumptions since actual field conditions cannot always be mimicked in flume experiments. Therefore, the present experimentations adopt the following assumptions.

- Seabed is assumed to be horizontal and wave motion is not affected by sediment movement.
- Toe scoring due to sediment transport is not considered.
- Scaling of geotextiles and sand is not considered.
- Difference in density between seawater and freshwater (used in wave flume) is not considered.

Results and Discussion

Effect of Deepwater Wave Steepness

Variation of Relative Runup (R_u/H_0) with Deepwater Wave Steepness (H_0/gT^2)

Fig. 4 represents the variation of relative runup (R_u/H_0) with respect to deepwater wave steepness (H_0/gT^2) for a structure height to depth ratio (h/d) of 2 (0.35 m water depth), 1.75 (0.40 m water depth), and 1.56 (0.45 m water depth) for different configurations of geotextile breakwater. The maximum and minimum runup observed among all configurations were 2.81 and 0.92 times the deepwater wave heights, respectively, and is decreasing with increasing deepwater wave steepness (H_0/gT^2). The trend lines of tested configurations showed higher relative runup than conventional rubble mound breakwaters [Shore Protection Manual (SPM) 1984] (20.20% to 95.65%). Wave runup values observed at $h/d = 1.56$ (0.45 m water depth) are up to 17.09% and 48.9% higher than those reported at h/d 1.75 (0.40 m) and 2 (0.35 m water depth), respectively, indicating a rise in runup with increasing water depth. In all water depths, configuration with Bag 1 (100% filled 400-g bags) exhibited maximum relative runup followed by Bag 3, Bag 2, and Bag 4 configurations. Relative runup exhibited by Bag 1 configuration is 72.5% to 30.47% higher than that of Bag 4, that is, variation between maximum and minimum trend lines. When the geotextile armor units are filled to its maximum capacity, the bags act like solid units, thereby reducing the absorption of water into these units. This is evident from Fig. 4, where Bag 1 showed 12.05% to 56.3% more runup than same bags filled to its 80% volume (Bag 2). Similarly, 24.3% to 64.05% increase in relative runup is recorded when the fill of a larger bag is changed from 80% to

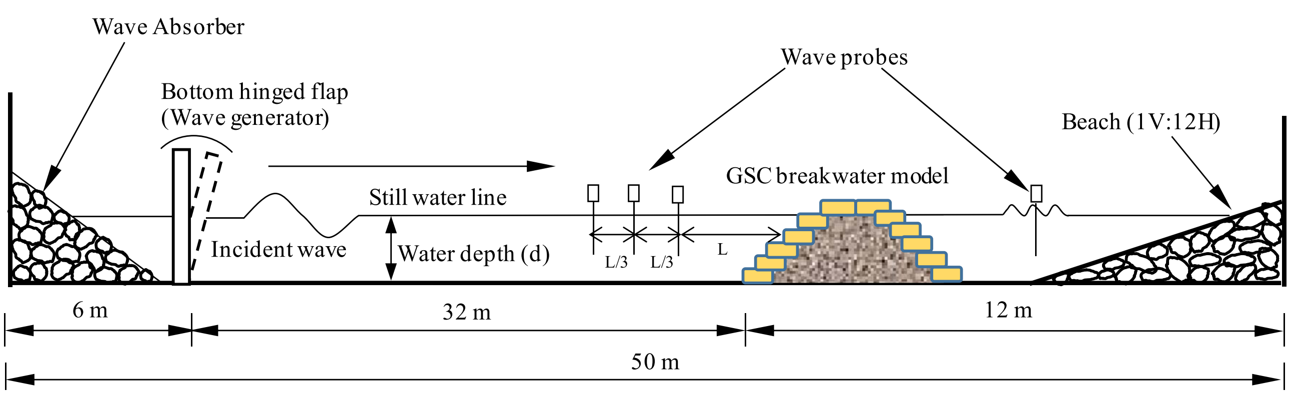

Fig. 3. Schematic representation of GSC breakwater model at Wave Mechanics Laboratory, NITK.

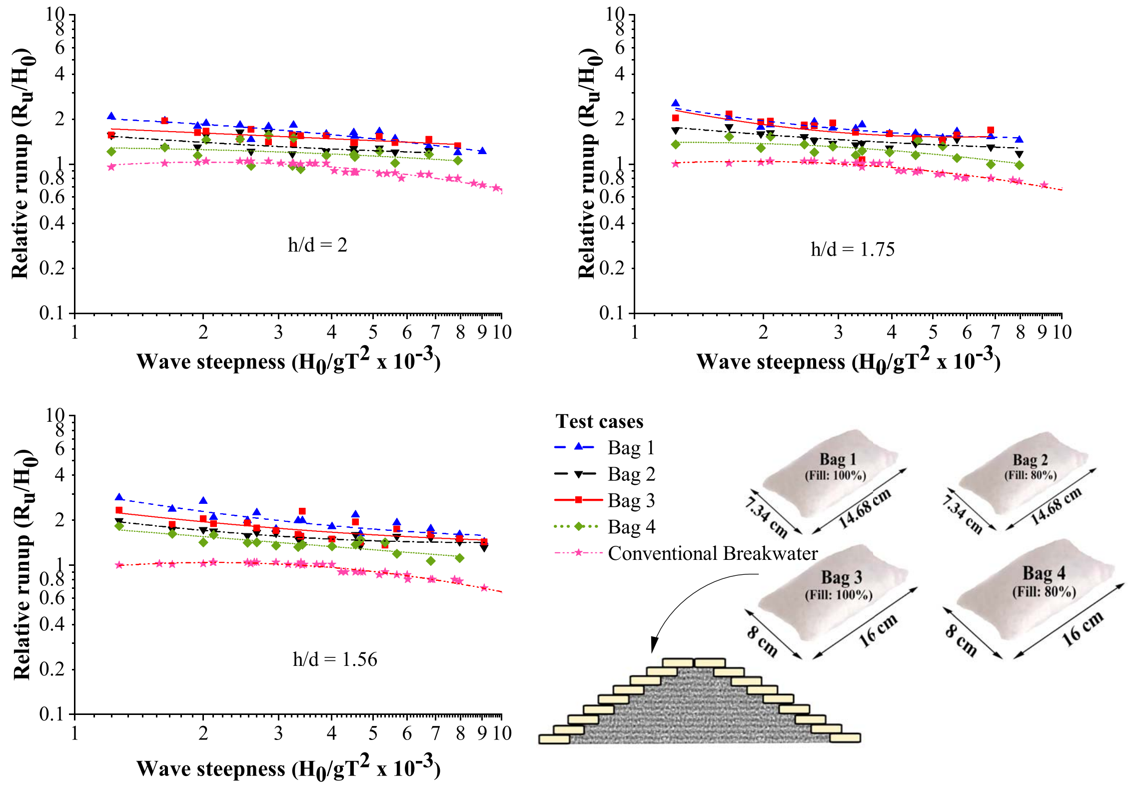

Fig. 4. Variation of relative runup (R_u/H_0) with respect to deep water wave steepness (H_0/gT^2) for various relative water depths (h/d) for different configurations of geotextile breakwater.

100% (Bag 4 to Bag 3). This indicates that filling the bags to its maximum capacity would result in a higher wave runup, which may result in overtopping of waves.

Larger bags (Bags 3 and 4) when arranged as primary armor units produced more interunit spaces or pore spaces compared with smaller bags (Bags 1 and 2). Higher pore spaces aid in absorption and wave energy dissipation, resulting in 7.4% to 34.48% less relative runup for larger bags. Similarly, for 80% filled bags, void spaces between bags and increased space within the bag makes them better at absorbing, and therefore, Bag 4 showed 4% to 24.2% lesser relative runup.

From the current example, it can be summarized that changing the fill from 100% to 80% resulted in 12.05% to 64.5% reduction of runup, whereas increasing the size of bag has helped only up to 34.8% reduction in runup. Reduction in percentage fill reduces wave runup considerably compared with changing bag size.

Variation of Relative Rundown (R_d/H_0) with Deepwater Wave Steepness (H_0/gT^2)

Fig. 5 represents the variation of relative rundown (R_d/H_0) with respect to deepwater wave steepness (H_0/gT^2) for a structure height to depth ratio (h/d) of 2 (0.35 m water depth), 1.75 (0.40 m water depth), and 1.56 (0.45 m water depth) for different configurations of geotextile breakwater. Relative rundown (R_d/H_0) of all configurations shows a wide range varying from 0.91 to 2.81 and decreases with increasing deepwater wave steepness (H_0/gT^2). The trend lines of tested configurations showed higher relative rundown than conventional rubble mound breakwater. The rundown data for conventional breakwater are adopted from the experimental studies conducted by Shirlal et al. (2006). Configuration with Bag 1 exhibited maximum relative rundown followed by Bag 3, Bag 2, and Bag 4. When the geotextile armor units are filled to full capacity, the bags act like solid units, thereby reducing the absorption of water into these units. This is evident from Fig. 5, as Bag 1 showed 5.4% to 36.40% more rundown than the same bags filled to its 80% volume (Bag 2). Similarly, 10.90% to 45.23% increase in relative rundown is recorded when the fill of the larger bag is changed from 80% to 100% (comparison between Bag 4 and Bag 3). This indicates that filling the bags to its maximum capacity would result in higher wave rundown.

Larger bags (Bags 3 and 4) when arranged as primary armor units produced more interunit spaces or pore spaces compared with smaller bags (Bags 1 and 2). Higher pore spaces aid in absorption and wave energy dissipation, resulting in 10.20% to 44.04% lesser relative rundown for a 100% filled larger bag (Bag 3) than a 100% filled smaller bag (Bag 1) configuration. Similarly, for 80% filled bags, void spaces between bags and increased space within the bag makes Bag 4 better at absorbing. As a result, 80% filled bags control the down rush of water. Therefore, Bag 4 showed 9.73 to 34.5% less relative rundown than Bag 2. Maximum reduction percentage is more (up to 30%) in bigger bags, as 80% filled bigger bags (Bag 4) have more space within the bags than 80% filled smaller bags (Bag 2), leading to improved absorption.

From the mentioned trials it can be summarized that changing the fill from 100% to 80% resulted in 5.45% to 45.23% reduction of rundown, whereas increasing the size of bags has helped only up to 34.5% reduction in rundown. Thus, reduction in percentage fill reduces wave rundown considerably compared with changing bag size.

Effect of Water Depth

Variation of Relative Runup with Water Depth

The influence of water depth on wave runup is considered in this section. Fig. 6 shows the variation of relative runup of various configurations for three different relative water depths. Out of the three

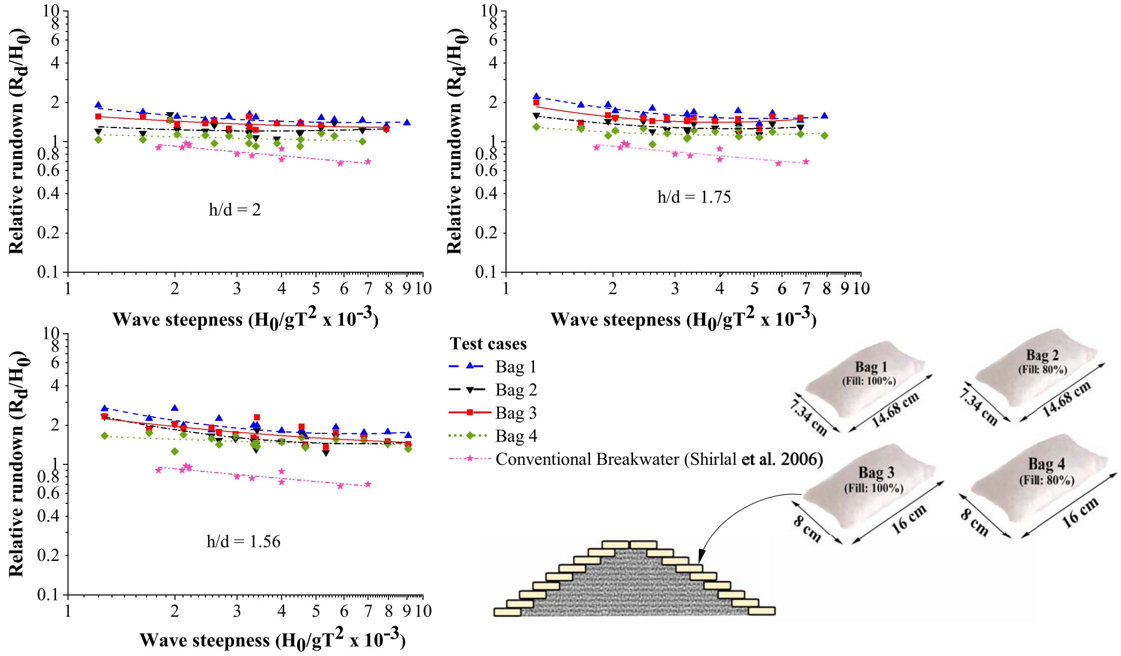

Fig. 5. Variation of relative rundown (R_d/H_0) with respect to deepwater wave steepness (H_0/gT^2) for various relative water depths (d/gT^2) for different configurations of geotextile breakwater.

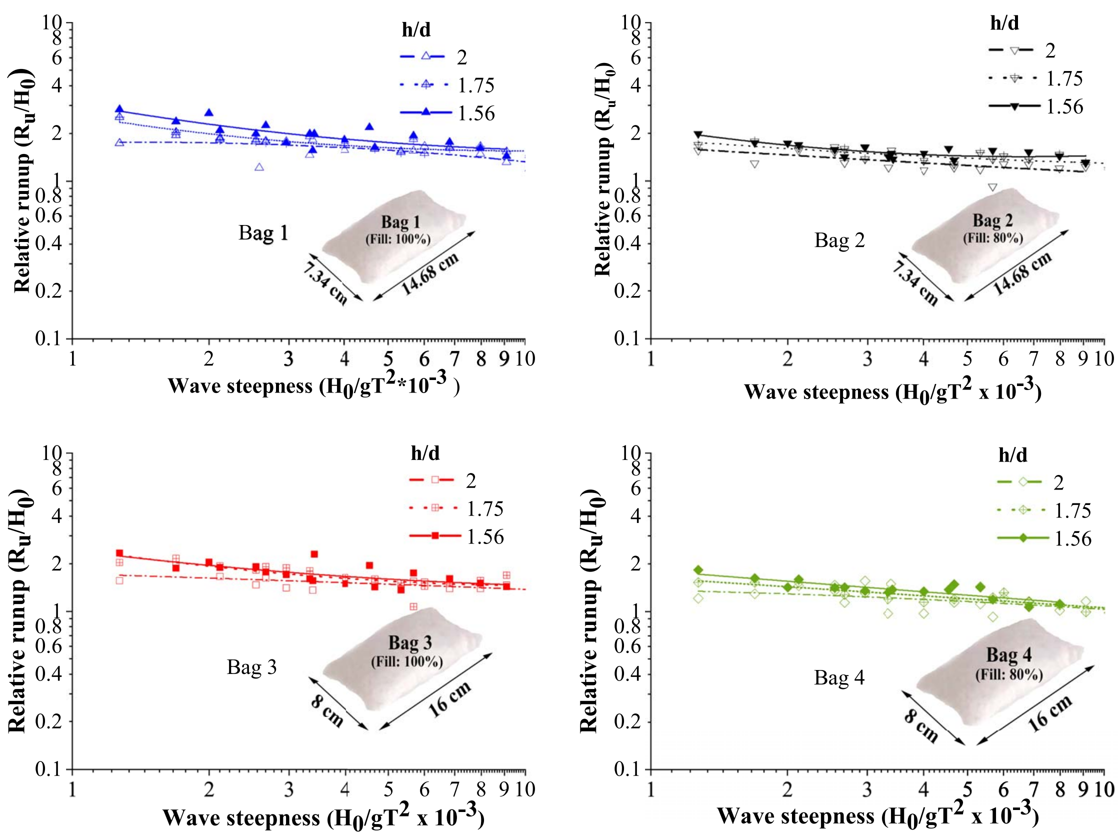

Fig. 6. Variation of relative runup of various configurations for different relative water depths.

water depths considered, $h/d = 1.56$ (0.45 m water depth) condition represented a higher runup for all four configurations. Bag 1 at a structure height to depth ratio (h/d) of 1.56 showed 12.5% to 63.37% and up to 11% higher relative runup than those at h/d, 2 and 1.75, respectively. Similarly, Bag 2 at h/d 1.56 showed 14.3% to 26.11% and up to 17.5% higher relative runup than h/d 2 and 1.75 cases. Bag 3 at higher water depth showed 6.25 to 41.66% and up to 3% higher relative runup than that of 2 and 1.75 (h/d). Bag 4 at 0.45 m water depth showed up to 33.58% and 15.8% higher relative runup than 0.35 and 0.40 m water depths, respectively. To sum up, relative runup at the maximum water depth tested ($h/d = 1.56$) exhibited 6.25% to 63.37% and

3% to 17.5% higher values than *h/d* equal to 2 and 1.74, respectively. It is observed that runup values increase as depth increases. Increased water depth can sustain higher unbroken waves, leading to increased uprush of water resulting in higher runup at a structure height to depth ratio (h/d) of 1.56 (0.45 m water depth).

Variation of Relative Rundown with Water Depth

Fig. 7 shows the variation of relative rundown of various configurations for a structure height to depth ratio (h/d) of 2 (0.35 m water depth), 1.75 (0.40 m water depth), and 1.56 (0.45 m water depth) with respect to deep water wave steepness. Out of the three water depths considered the 0.45-m water depth ($h/d = 1.56$) condition represented higher rundown for all four configurations. Bag 1 at a structure height to depth ratio (h/d) of 1.56 showed 19.58% to 49.14% and up to 17.8% higher relative rundown than those at *h*/*d*, 2 and 1.75, respectively. Similarly, Bag 2 at a relative depth of 1.56 showed 9.58% to 54.48% and up to 28.6% higher relative rundown than *h*/*d*, 2 and 1.75, respectively. Bag 3 at 1.56 *h*/*d* showed 15.9% to 45.03% and up to 11.11% higher relative rundown than 2 and 1.75 *h*/*d* respectively. To sum up, relative rundown at higher water depth exhibited 9.58% to 62.6% and 8.5% to 33.57% higher values than those shown by *h*/*d* corresponding to 2 and 1.75, respectively. It is observed that rundown values increase as depth increases. This can be due to waves possessing higher energy resulting in a higher rundown. Increased water depth can sustain waves with more considerable heights (consequently higher wave energy), resulting in increased downrush in higher water depths.

Effect of Surf Similarity Parameter on Relative Runup and Rundown

Relative runup and rundown are plotted against surf similarity parameter to analyze the relationship. The surf similarity parameter for the whole experimental setup ranged from 2.18 to 5.6. Representation with respect to the surf similarity parameter gives additional information regarding the breaking of waves. According to SPM (1984) collapsing or surging waves are observed after a surf similarity value of 3.3. As a result, waves breaking on a structure tend to uprush, increasing runup on the structure slope. This is observed from the progressive relative runup value in Fig. 8. The trend observed by different configurations of GSC structure is attributed to the difference in fill-percentage and GSC size, as discussed in section 4.1. A similar trend is observed for relative rundown and is illustrated in Fig. 9. Relative runup and rundown show nearly identical range, but deviation from conventional breakwater is found to be greater for relative rundown values than runup. It should be mentioned that, owing to continuous interaction of consecutive waves, the measurement of rundown values of faster waves ($t < 1.8$ s) showed up to 9% variation.

Wave Reflection Analysis

Fig. 10 represents the reflection coefficient values with respect to wave steepness for all the test cases conducted for Bag 1 configuration. This type of representation is essential for deducing an overall impression on the reflection behavior of the structure. From Fig. 10, the values of the K_r appear to scatter over a range of 0.26 to 0.68. This representation is quite difficult for comprehensively analyzing the results but helps in understating the entire range of the reflection coefficient. On a very general note, reflection coefficient reduces with the increase in wave steepness. But these trends can be clearly understood from the further detailed analysis.

Fig. 11 represents the variation of K_r with respect to wave steepness, keeping the periods fixed to 1.4, 1.8, and 2.2 seconds. Fig. 11 clearly indicates the effect of the incident wave period on the reflection trend. For the relative water depths considered, wave steepness

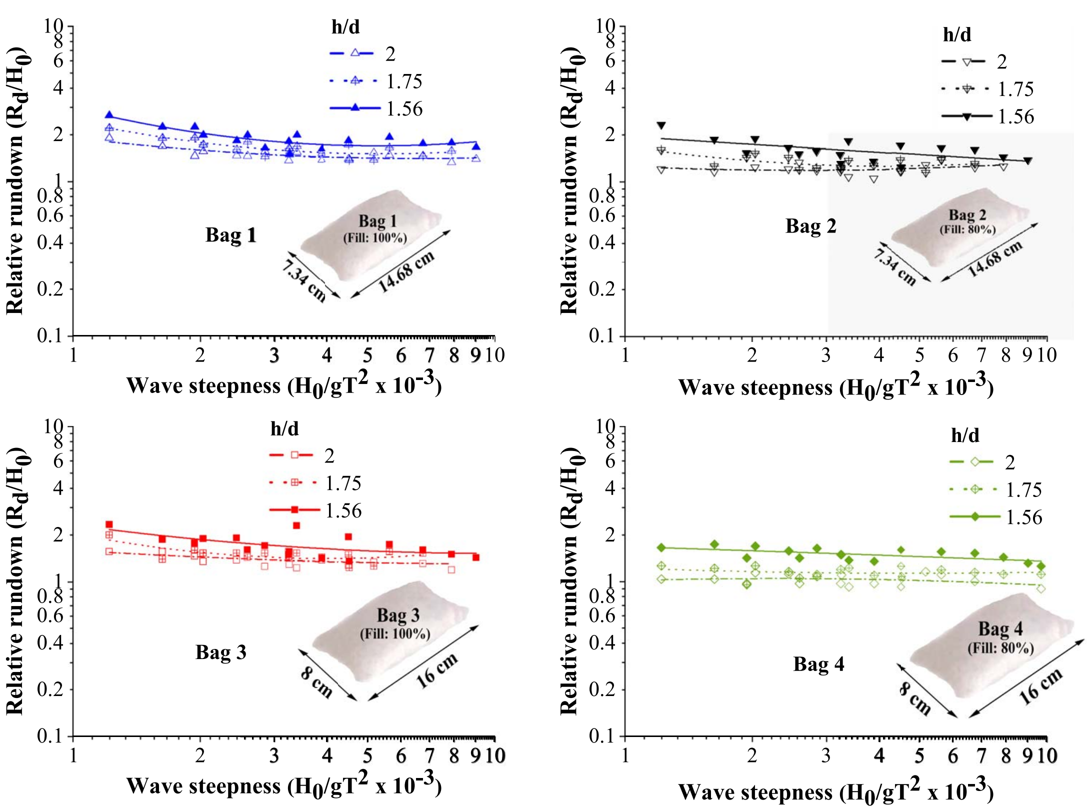

Fig. 7. Variation of relative rundown of various configurations for different relative water depths.

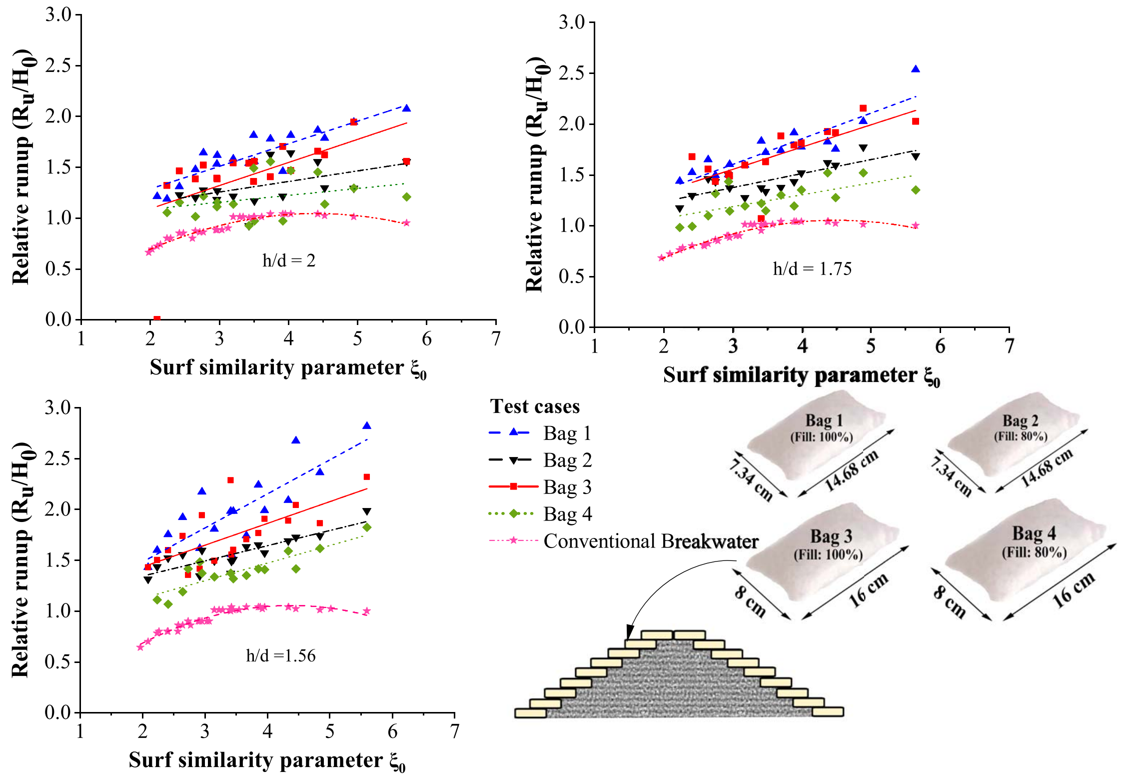

Fig. 8. Variation of relative runup of different configurations with surf similarity parameter.

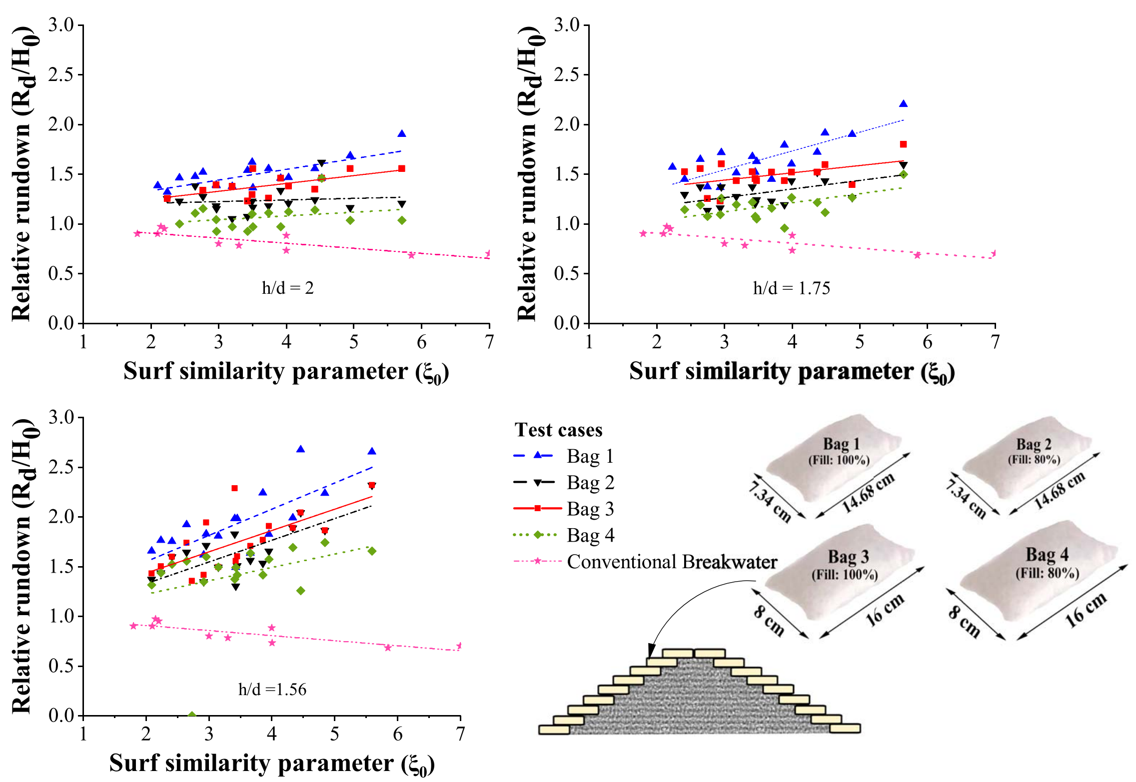

Fig. 9. Variation of relative rundown of different configurations with surf similarity parameter.

reduces with the increasing wave period. It is also observed that the reflection coefficient increases with the progressing wave period. Of all the tested cases for Bag 1, 2.2 s waves exhibited 1.49% to 3.57% and 11.53% to 33.33% higher reflection coefficients than 1.8 and 1.4 s waves, respectively. We can conclude that for a particular configuration, there exists an inverse relation between the wave period and reflection coefficient. A reduction of 11.53% to 33.33% in K_r is observed when the period of waves is altered from 2.2 to 1.4 s.

Considering the effect of water depth, K_r reduced from 0.61 to 0.29, 0.64 to 0.37, and 0.69 to 0.36 for a structure height to depth ratio (h/d) of 2 (0.35 m water depth), 1.75 (0.40 m water depth), and 1.56 (0.45 m water depth), respectively. Of the three water depths considered, deeper water depth showed 4.68% to 21.62% and 11.59% to 19.44% less reflection compared with 1.75 and 2 structure height to depth ratio (h/d), respectively. A possible reason for decreasing reflection with increasing water depth can be attributed to the increased runup at higher water depths (as concluded from section Variation of Relative Runup with Water Depth). When runup increases, uprushing water comes in contact with more GSC units, resulting in the increased absorption of water. As a result, reflected wave energy is reduced.

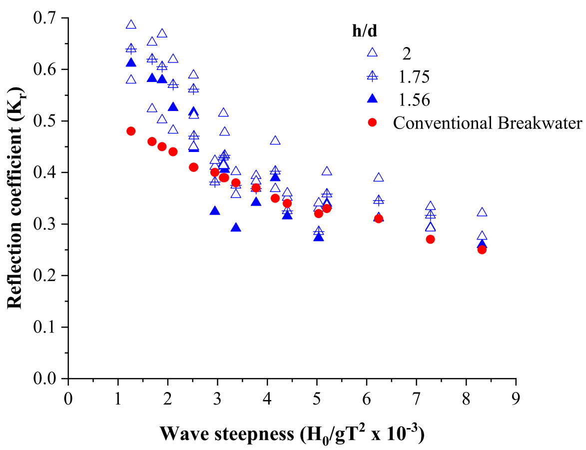

Fig. 10. Reflection coefficient (K_r) values with respect to wave steepness for all the test cases conducted for Bag 1.

Effect of Incident Wave Height on Wave Reflection

Fig. 12 shows the wave reflection of the configuration with Bag 1 for minimum and maximum incident wave heights used in physical modeling (0.06 and 0.16 m). Here, K_r of 0.06-m waves varied from 0.42 to 0.68, while that of 0.16-m waves varied from 0.26 to 0.36. It is observed that the reflection coefficient reduces as the incident wave height increases. The 0.06-m waves were 38.09% to 47.05% more reflective than the 0.16-m waves. Existing literature such as Kriel (2012) points out a decreasing trend of reflection coefficients (10% to 15%) with increasing incident wave heights. However, in the present study, the effect of incident wave height is very prominent on reflection behavior. As wave height increased from 0.06 to 0.16 m, a decrease of up to 47% was reported. This range is higher than expected and can be due to the fact that higher waves interact more with GSC units. Unlike stone or other concrete armor units, GSC units are highly absorbent in nature. As incident wave height increases, more runup occurs, leading to higher water absorption into the structure.

The dependence of wave period and incident wave height on reflection behavior has been identified from previous sections for configuration with Bag 1. In general, K_r tends to increase with increasing wave period and decrease with increasing incident wave height. To be precise, there is 10.35% to 25% decrease in K_r when the wave period is varied from maximum to minimum in the experimental range. Similarly, a 38.09% to 47.05% decrease

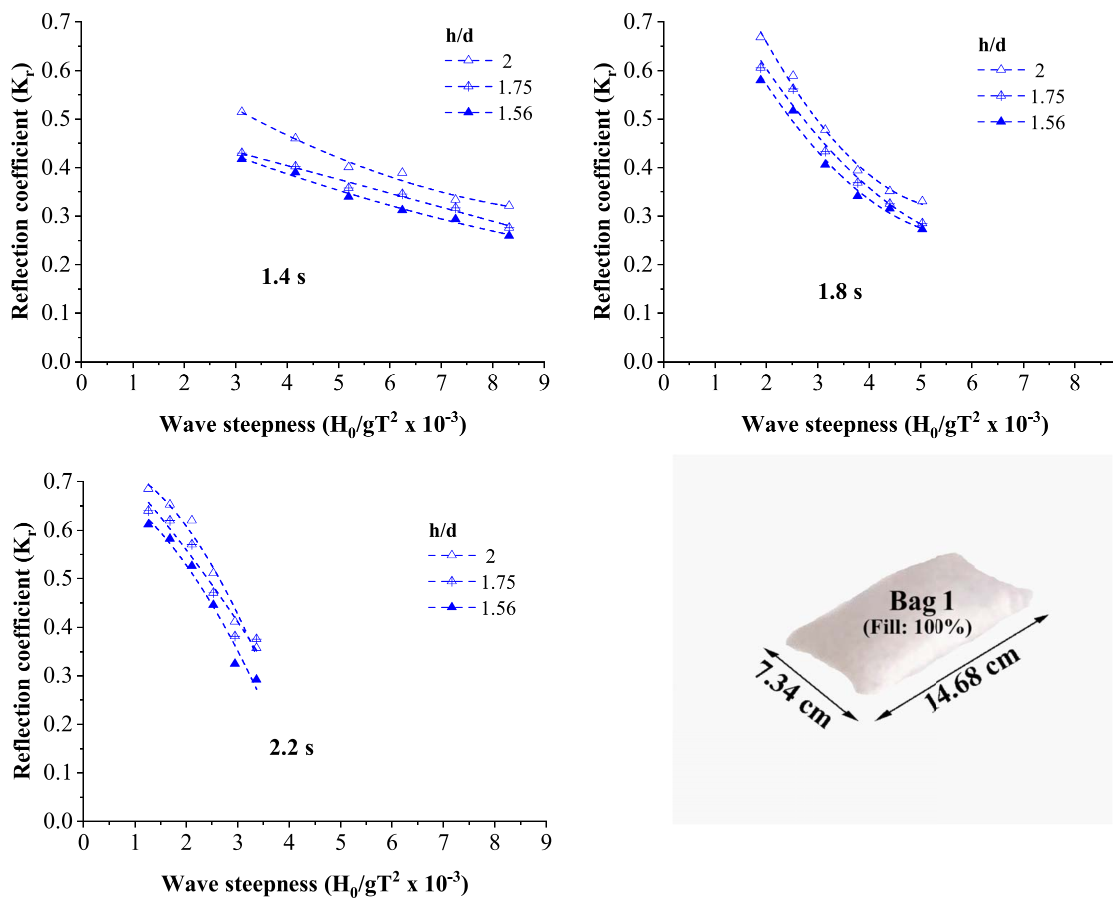

Fig. 11. Plots showing dependence of wave period on reflection coefficient for different configurations of GSC breakwaters stacked with Bag 1.

in reflection coefficient is observed when the incident wave height is varied from 0.06 to 0.16 m.

Influence of Surf Similarity Parameter (ξ) on Reflection Coefficient

In order to analyze the relationship, K_r was plotted against ξ. The surf similarity parameter for the whole experimental setup ranged from 2.18 to 5.6. Representing K_r with respect to surf similarity parameter gives additional information regarding the breaking of waves. According to SPM (1984), collapsing or surging waves are observed for $\xi \geq 3.3$. As a result, the breaking of waves on

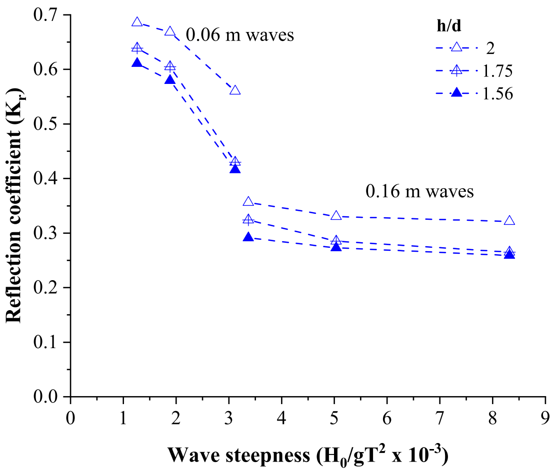

Fig. 12. Variation of reflection coefficient of Bag 1 with respect to wave steepness (incident wave height 0.06 and 0.16 m) for different relative water depths.

the structure reflects more energy as it cannot be effectively absorbed. This is observed from the progressive reflection value in Fig. 13. The trend observed by different configurations of GSC structure is attributed to the difference in fill-percentage and GSC size, as discussed in the preceding sections.

The present experimentation results are compared with the existing reflection coefficient formulas proposed by Seeling and Ahrens (1981) and Zanuttigh and van der Meer (2008) (Fig. 14). It is observed that the experimental results for 80% filled bags represent a high degree of agreement with both the formulas, whereas the formulas are underestimated in the case of 100% filled bags. To accommodate the present experimental data with Eq. (3) proposed by Zanuttigh and van der Meer (2008), the curve representing Eq. (3) is refitted by calibrating the values for a and b as

$$K_r = \tanh(a \cdot \xi_0^b) \tag{3}$$

Where the values of coefficients a and b can be estimated using the following equations, as suggested by Zanuttigh and van der Meer (2008):

$$a = 0.167 \cdot [1 - \exp(-3.2 \cdot \gamma_f)] \tag{4}$$

$$b = 1.49 \cdot (\gamma_f - 0.38)^2 + 0.86 \tag{5}$$

where γ_f = roughness factor as estimated by overtopping analysis. Various available reports have deduced the roughness factor for the present GSC breakwater. In general, the roughness factor for smooth-surfaced structures is 1, whereas it varies from 0.4 to 0.85 for rough-surfaced structures (Shankar and Jayaratne 2003). A roughness factor of 0.60 is reported for geocore breakwater structures (Oumeraci and Kortenhaus 2011). Here, γ_f is reported 0.40 for permeable rock structures and 0.55 for impermeable rock structures (Zanuttigh and van der Meer 2008). Considering all the preceding values, an approximated γ_f value of 0.5 is used for the present

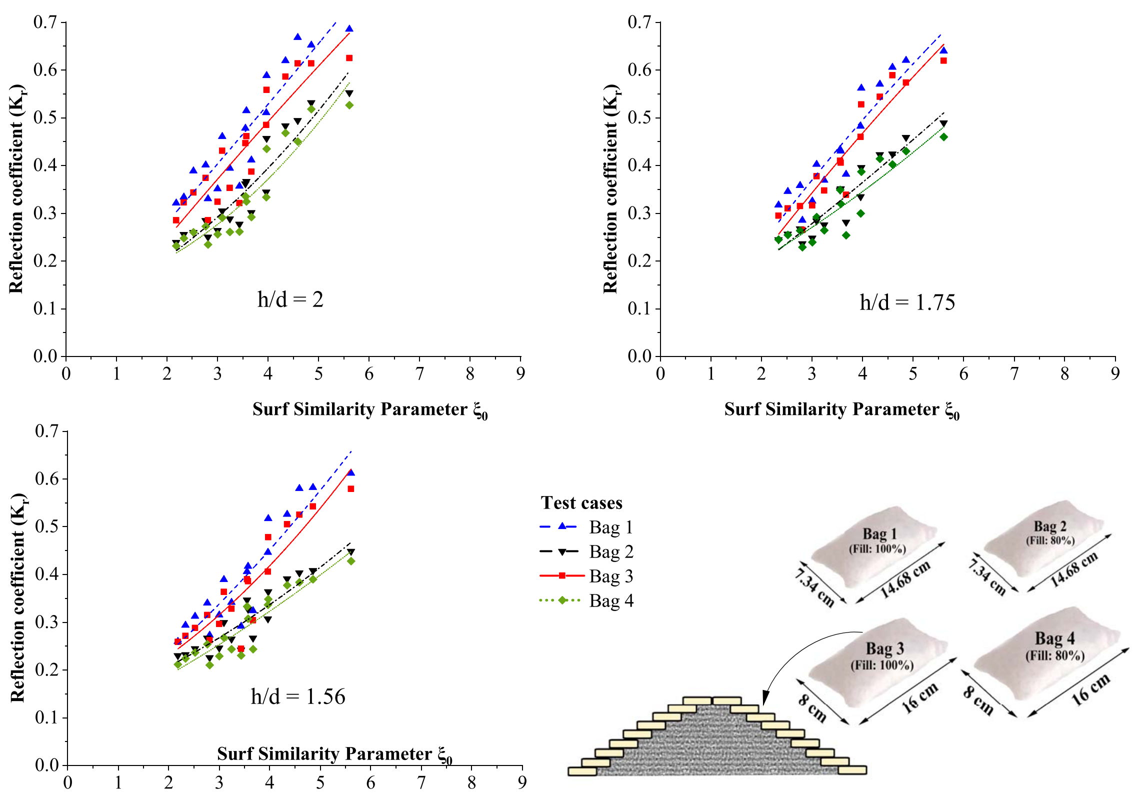

Fig. 13. Variation of reflection coefficient with respect to surf similarity parameter.

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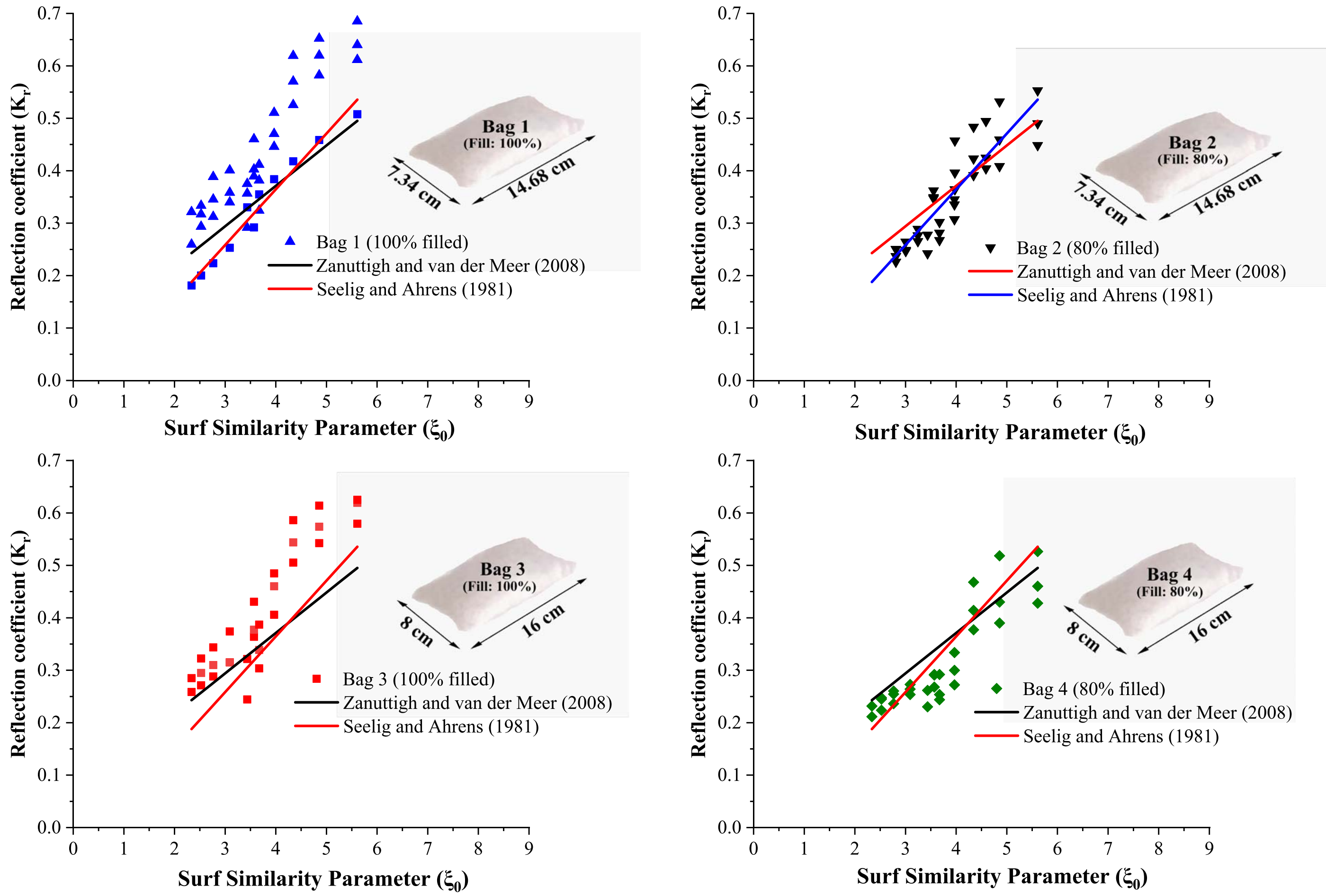

Fig. 14. Comparison of the experimental results with the existing reflection coefficient formulas proposed by Seeling and Ahrens (1981) and Zanuttigh and van der Meer (2008).

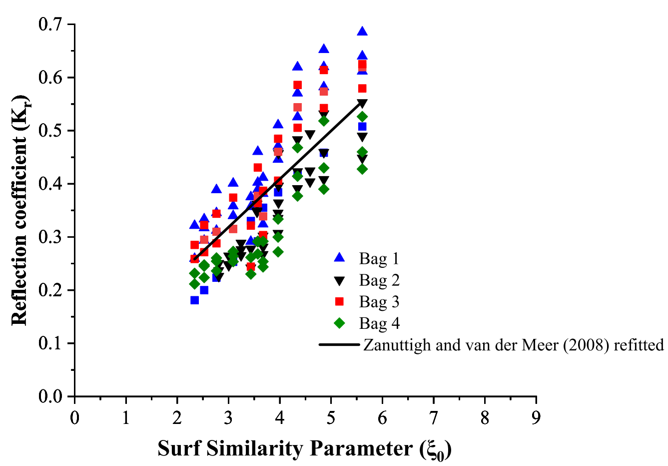

Fig. 15. Comparison of refitted Eq. (3) with entire range of experimental data.

investigation. Thus, the values of a and b for GSC breakwater has been estimated as 0.133 and 0.88, respectively, and the refitted curve is shown in Fig. 15. The refitted formula can serve as an indicative nomogram for the experimental data, as it fairly accommodates the entire range of data points. However, fine-tuning of the calibration of coefficients a and b are suggested, as a maximum of 25% error can be observed in the plot (Fig. 15).

Reflection Curves

A comprehensive analysis of all the configurations would light more on the response of each configuration for different incident characteristics of waves. Fig. 16, shows the reflection behavior of all the four tested configurations for varying relative water depths. The maximum K_r observed is 0.69 for Bag 1 and minimum is 0.21 for Bag 4. Of the four configurations, Bag 1 shows the highest reflection followed by Bag 3, Bag 2, and Bag 4. This is due to the fact that dimensions of Bags 1 and 2 [$0.148 \times 0.073 \times 0.05$ m (length × breadth × height)] is smaller than Bags 3 and 4 [$0.16 \times 0.08 \times 0.05$ m (length × breadth × height)], resulting in the lesser interbag spaces when packed as the outer layer of geotextile breakwater. This reduces the wave energy dissipation due to the turbulence caused by the interaction of water waves with the pore spaces in the outer surface of the structure. As a result, more wave energy is increasingly reflected. Absorption of water into the bags being the same for both the cases, structure with more pore spaces succeeds in energy dissipation leading to a lesser reflective behavior. Therefore, configuration comprising bigger bags with more pore spaces showed up to 10.07% less reflection than smaller bags, when both were filled to their maximum capacity. Bags filled to 100% exhibits higher reflection than the same bags filled to 80%. Bags 1 and 3 (100% filled bags) showed 16.30% to 43.7% and 18% to 37.67% higher reflection than their respective 80% filled counterparts, Bags 2 and 4. This is mainly because 80% filled bags have 20% empty space within a bag. This leads to additional water absorption and reduced wave energy available for reflection.

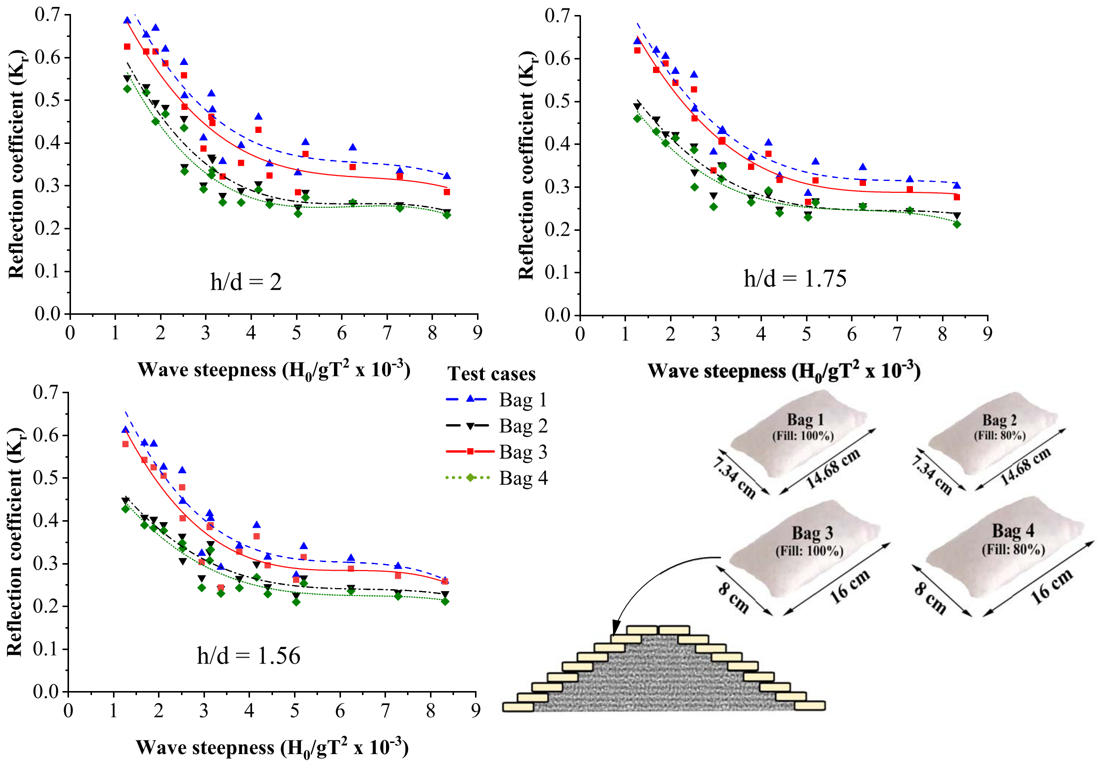

Fig. 16. Reflection curves of different configurations of GSC breakwaters for varying relative water depths.

Therefore, 80% filled bags tend to be less reflective in nature. Thus, reducing the fill percentage is beneficial in lowering the reflection from the structure. At the same time, reduction in filling percentage reduces the stability of the structure, pointing to the need for a thorough optimization. It can be concluded that Bags 1 and 4 showed maximum and minimum reflections for particular water depth, respectively. This trend is followed for all the relative water depths tested. Of the three depths, least depth ($h/d = 2$) showcases the higher reflection. This implies that in higher depths waves tend to be less reflective in nature due to increased absorption of uprushed waves. From all the cases it has been understood that reflection behavior shows 16.3% to 43.7% decrease when the fill is reduced from 100% to 80% and up to 10.07% when the bag size is increased. It is concluded that lowering the fill percentage reduces reflection to 20%–40% rather than increasing bag size.

Conclusions

Extensive physical experimentations helped in gaining a proper understanding of the hydraulic performance of GSC breakwaters. The present investigations on reflection, runup, and rundown characteristics of GSC breakwater aided in formulating the following conclusions:

- GSC breakwaters exhibit higher reflection, runup, and rundown trends than conventional rubble mound breakwaters due to its lesser porosity. Nevertheless, GSC structures can be ecofriendly and efficient substitutes for conventional breakwaters under similar/or conducive parameters such as favorable water depths and wave heights.
- Changing the bag fill percentage from 100% to 80% resulted in 12.05% to 64.5% reduction in wave runup rates. The 80% filled bags exhibited 5.45% to 45.23% smaller rundown rates than 100% filled bags. When the percentage of filling is reduced, more empty spaces are created inside bags leading to increased infiltration of water, resulting in decreased runup.
- Increasing the size of armor units resulted in up to 34.8% reduction in runup rates. Similarly, rundown values were found to be reduced up to 34.5%. Breakwaters stacked with larger bags (Bags 3 and 4) possess more pore spaces, resulting in increased interaction of water particles leading to higher energy dissipation. This results in decreased runup and rundown in configurations with these bags.
- Reflection coefficient (K_r) shows a wide range from 0.29 to 0.69 and tends to increase with increasing wave period, wavelength, and surf similarity parameter, whereas K_r exhibited an inverse relationship with wave steepness and incident wave height.
- A reduction of 11.53% to 33.33% in K_r is observed when the period of waves varied from 2.2 to 1.4 s. waves tend to be less reflective when incident wave height and water depth increased.
- Changing bag fill percentage from 100% to 80% resulted in 16.3% to 43.7% reduction in K_r due to increased absorption of 80% filled bags. However, increasing bag size resulted in up to 10.07% reduction in K_r due to increased interbag spaces, signifying the importance of fill percentage in K_r reduction.
- Reflection behavior can be approximated to the formula proposed by Zanuttigh and van der Meer (2008). For a GSC breakwater, the values for coefficients a and b are obtained as 0.133 and 0.88, respectively.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Ahrens, J., and B. L. McCartney. 1975. "Wave period effect on the stability of riprap." In *ASCE Speciality Conf. on Civil Engineering, in the OCEANS III*, 1019–1034. Newark, DE: Delaware Univ.

Battjes, J. A., and R. Ary. 1976. "Characteristics of flow in run-up of periodic waves." In *Proc., 15th Int. Conf. on Coastal Engineering*, 781–795. Reston, VA: ASCE.

Diwedar, A. I. 2016. "Investigating the effect of wave parameters on wave runup." *Alexandria Eng. J.* 55: 627–633. https://doi.org/10.1016/j.aej.2015.12.012.

Elias, T., A. S. Kiran, and V. Ravichandran. 2018. "Analysis of berthing sub-structures using Plaxis 2D." In *Proc., INCHOE-2018, Indian Society for Hydraulics and Central Water & Power Research Station*. Pune, India: Central Water & Power Research Station.

Elias, T., and K. G. Shirlal. 2021. "Coastal protection using geosynthetic containment systems—An Indian timeline." *Lect. Notes Civ. Eng.* 106: 439–450. https://doi.org/10.1007/978-981-15-8506-7_38.

Elias, T., K. G. Shirlal, and E. V. Kajal. 2021. "Physical model studies on damage and stability analysis of breakwaters armored with geotextile sand containers." *Geotext. Geomembr.* 49 (3): 604–618. https://doi.org/10.1016/j.geotexmem.2020.12.001.

Faraci, C. 2018. "Experimental investigation on hydro-morphodynamic performances of a geocontainer submerged reef." *J. Waterway, Port, Coastal, Ocean Div.* 144 (2): 04017048.

Foyer, G. 2013. *Prediction formulae for processes on and in porous bonded revetments – An experimental and numerical study*. Braunschweig, Germany: Technical University Carolo-Wilhelmina Braunschweig.

Isaacson, M. 1992. "Measurement of regular wave reflection." *J. Waterway, Port, Coastal, Ocean Eng.* 117 (6): 553–569. https://doi.org/10.1061/(ASCE)0733-950X(1991)117:6(553).

Jackson, L. A. 2016. "Coastal stabilisation – advancement in geotextile design & construction methods as an alternative to rock." In *Proc., 3rd Int. Conf. on Coastal Zone Engineering and Management in the Middle East (Arabian Coast 2016)*, 321–342. Dubai, U.A.E: Dubai Municipality.

Kobayashi, N., and B. K. Jacobs. 1985. "Stability of armor units on composite slopes." *J. Waterway, Port, Coastal, Ocean Eng.* 111 (5): 880–894. https://doi.org/10.1061/(ASCE)0733-950X(1985)111:5(880).

Kriel, H. J. 2012. "Hydraulic stability of multi-layered sand-filled geotextile tube breakwaters under wave attack." M.Sc. thesis, Dept. of Port and Coastal Engineering, Stellenbosch Univ.

Melby, J. A., and G. F. Turk. 1997. *CORE-LOC concrete armor units*. Washington, DC: U.S. Army Engineer Waterways Experiment Station.

Muttray, M., H. Oumeraci, and E. T. Oever. 2006. "Wave reflection and wave run-up at rubble mound breakwaters." In *Proc., 30th ICCE*, 4313–4324. Singapore: World Scientific.

Nasar, T., R. Balaji, and V. Sundar. 2004. "Hydrodynamic characteristics and stability of rubble mound breakwater with geobags as the core." In *Proc., 3rd Indian National Conf. on Harbour & Ocean Engineering*, 492–497. Chennai, India: National Institute of Oceanography.

Nishold, S. P., R. Sundaravadivelu, and N. Saha. 2019. "Physical model study on geo-tube with gabion boxes for the application of coastal protection." *Arabian J. Geosci.* 12: 164.

Oumeraci, H., and A. Kortenhaus. 2011. "Core made of geotextile sand containers for rubble mound breakwaters and seawalls: Effect on armor stability and hydraulic performance." *Ocean Eng.* 38: 159–170. https://doi.org/10.1016/j.oceaneng.2010.10.014.

Oumeraci, H., Recio, J., 2018. "Geotextile sand containers for shore protection." In *Handbook of coastal and ocean engineering*, edited by Y. C. Kim, 775–822. Singapore: World Scientific.

Oumeraci, H., T. Stall, S. Pfortner, and G. Ludwigs. 2010. "Hydraulic performance, wave loading and response of ELASTOCOAST revetments and their foundations." In *Proc., 11th National Coastal Engineering Days - Civil Engineering*, 709–740. Braunschweig, Germany: TU Braunschweig - Leichtweiss Institut.

Pilarczyk, K. W. 1987. *Dutch guidelines on dike protection*. Rep. W.B. No. 87110. Delft, Netherlands: Dutch Ministry of Transport and Public Works Road and Hydraulic Engineering Dept.

Rao, S., K. Subrahmanya, B. K. Rao, and V. R. Chandramohan. 2008. "Stability aspects of nonreshaped berm breakwaters with reduced armor weight." *J. Waterway, Port, Coastal, Ocean Eng.* 134: 81–87. https://doi.org/10.1061/(ASCE)0733-950X(2008)134:2(81).

Rasmeemasmuang, T., W. Chuenjai, and W. Rattanapitikon. 2014. "Wave run-up on sandbag slopes." *Maejo Int. J. Sci. Technol.* 8: 48–57.

Schimmels, S., D. W. Michalis Vousdoukas, K. Becker, F. Gier, and H. Oumeraci. 2012. "Wave run-up observations on revetments with different porosities." In *Proc., 33rd Int. Conf. on Coastal Engineering*, 1–14. Spain: Spanish Society of Civil Engineers.

Seeling, W. N., and J. P. Ahrens. 1981. *Estimation of wave reflection and energy dissipation coefficients for beaches, revetments, and breakwaters*. Washington, DC: U.S. Army Corps of Engineering Coastal Engineering Research Center.

Shankar, N. J., and M. P. R. Jayaratne. 2003. "Wave run-up and overtopping on smooth and rough slopes of coastal structures." *Ocean Eng.* 30: 221–238. https://doi.org/10.1016/S0029-8018(02)00016-1.

Shin, E. C., and Y. I. Oh. 2007. "Coastal erosion prevention by geotextile tube technology." *Geotext. Geomembr.* 25: 264–277. https://doi.org/10.1016/j.geotexmem.2007.02.003.

Shirlal, K. G., S. Rao, V. Ganesh, and Manu. 2006. "Stability of breakwater defenced by a seaward submerged reef." *Ocean Eng.* 33: 829–846. https://doi.org/10.1016/j.oceaneng.2004.11.017.

van der Meer, J. W., and M. Stam. 1992. "Wave runup on smooth and rock slopes of coastal structures." *J. Waterway, Port, Coastal, Ocean Eng.* 118: 534–550. https://doi.org/10.1061/(ASCE)0733-950X(1992)118:5(534).

van Gent, M. R., E. Berendsen, G. B. H. Spaan, J. W. van der Meer, and K. d'Angremond. 1999. "Single-layer rubble mound breakwaters." In *Proc., Int. Conf. Coastal Structures*, 231–239. London: Thomas Telford.

Yamini, O. A., M. R. Kavianpour, and S. H. Mousavi. 2018. "Wave run-up and rundown on ACB Mats under granular and geotextile filters condition." *Mar. Georesour. Geotechnol.* 36: 895–906. https://doi.org/10.1080/1064119X.2017.1397068.

Zanuttigh, B., and J. W. van der Meer. 2008. "Wave reflection from coastal structures in design conditions." *Coast. Eng.* 55: 771–779. https://doi.org/10.1016/j.coastaleng.2008.02.009.