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Effect of armour unit layers and placement mode in the determination of stability of geotextile sand container (GSC) breakwaters

Tom Elias *, Tiruveedula Geetha, Kiran G. Shirlal

Department of Water Resources and Ocean Engineering, National Institute of Technology, Karnataka, Surathkal, Mangaluru, 575025, India

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ABSTRACT

Geosynthetic Sand Containers (GSCs) are increasingly harnessed for their coastal protection capabilities. Recent studies point to its efficacy to be used even as armour units of breakwaters. The current investigation aims at understanding the effect of armour unit layers and placement modes in altering the stability of GSC breakwaters. Single-layered and double-layered GSC structures with slope parallel and perpendicular placement are tested for stability against wave conditions of the Mangaluru coast. A 1:30 scaled monochromatic wave flume model study is adopted to detail the damage levels and stability of various GSC breakwaters. It is observed that the stability of structure increased by up to 17% when supplemented with double layers. Structure tends to be stable with increasing armour units size and fill percentage. Larger bags stacked to double layers is found to be the most stable configuration. 80% filled, slope parallel placement exhibited the least stability. The paper dealt with all factors affecting structure stability and deduced stability nomograms helpful for coastal engineers to design GSC breakwaters.

1. Introduction

Ocean waves can often cause severe damage to the coastline, livelihood, properties and also disturb the tranquillity in ports and harbours, causing threats to berthed ships (Sindhu et al., 2015). Increasing instances of major cyclones, associated storm surges and coastal inundations create major havoc to coastal areas (Albert and Bhaskaran 2020; Krishnan et al., 2021; Sreelakshmi and Bhaskaran 2020). Global climate change and sea level rise can also be fatal to low lying coastal zone (Parthasarathy et al., 2020). As a result, coastal protection is inevitable to our coastline, coastal communities so as to retain our natural beaches, which constitute the first line of coastal defence. The solution of coastal protection can be classified into two genres, namely hard solution and soft solution. While Seawalls, Dikes, Groins, Artificial Breakwaters etc, serve as hard solutions, beach restoration, plantation, sandbags, sand bypassing, dune replenishment etc., are considered as the soft solutions. Hard solutions or grey solutions mainly involve the construction of breakwaters, usually comprised of natural rocks, artificial armour units, etc., which are difficult to be constructed and maintained. Moreover, non-availability of natural rock of required weight and size and cost of machinery and equipment required to carry it from quarry to the field of construction aggravates the issue (Kudale et al., 2014).

Geotextiles are an emerging technology and are used in various marine applications such as revetments (Bezuijen and Pilarczyk 2012), embankments (Nishold et al., 2014), groins, breakwater (Hornsey et al., 2011), armour units of breakwaters (Elias et al., 2021) and various other coastal protection structures (Elias and Shirlal 2021; Kiran et al., 2015; Kudale et al., 2014; Pilarczyk 2000; Shin and Oh 2007; Sundar et al., 2009). Geotextiles are permeable polymeric fabric that allows the flow of water through and retains the material by which it is filled. The most attractive feature of the geotextile constructions is the insitu filling capability of the tube or containers with locally available materials, making the construction cost-effective and rapid (Pilarczyk 1997). There may arise queries on how these huge units can be filled, lifted and placed with precision in position. Filling in slurry from can be equipped with pumps (Shin and Oh 2003) whereas filling in dry from can use techniques like J-bin technology (Jackson 2016). Split bottom barges with Global Positioning System can be harnessed for the accurate positioning of the geotextile sand containment units (Borrero et al., 2010; Jackson et al., 2012; Recio and Oumeraci 2009).

The efficacy of single-layer GSC units in serving as the armour units of emerged breakwaters is discussed in detail in Elias et al. (2021). The study analysed the damage by varying the size and sand fill ratio of

* Corresponding author.
E-mail addresses: tomelias00@gmail.com (T. Elias), geethace41@gmail.com (T. Geetha), kshirlal@gmail.com (K.G. Shirlal).

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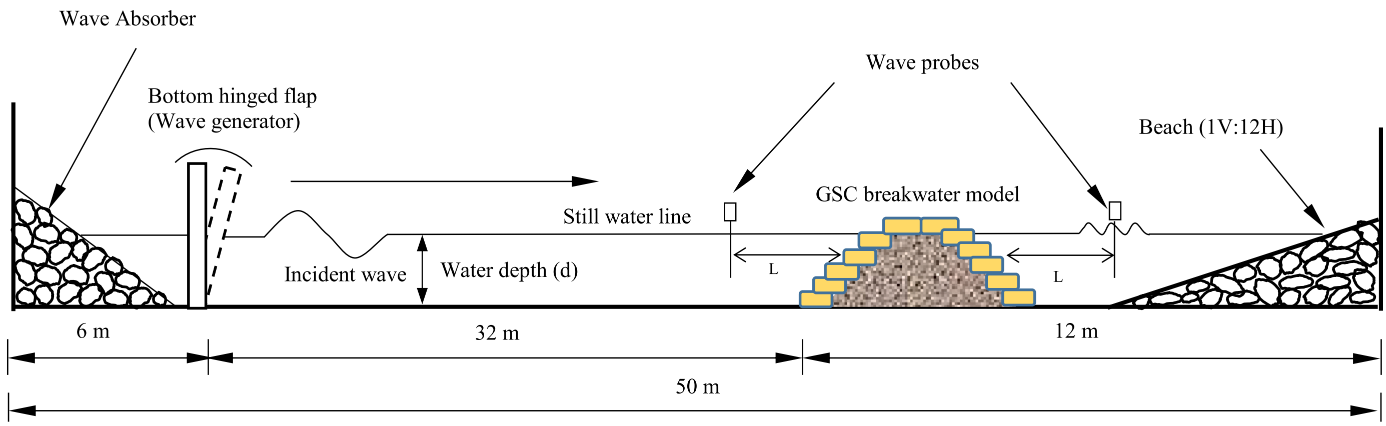

Fig. 1. Layout of GSC breakwater model at Wave Mechanics laboratory, NITK, India.

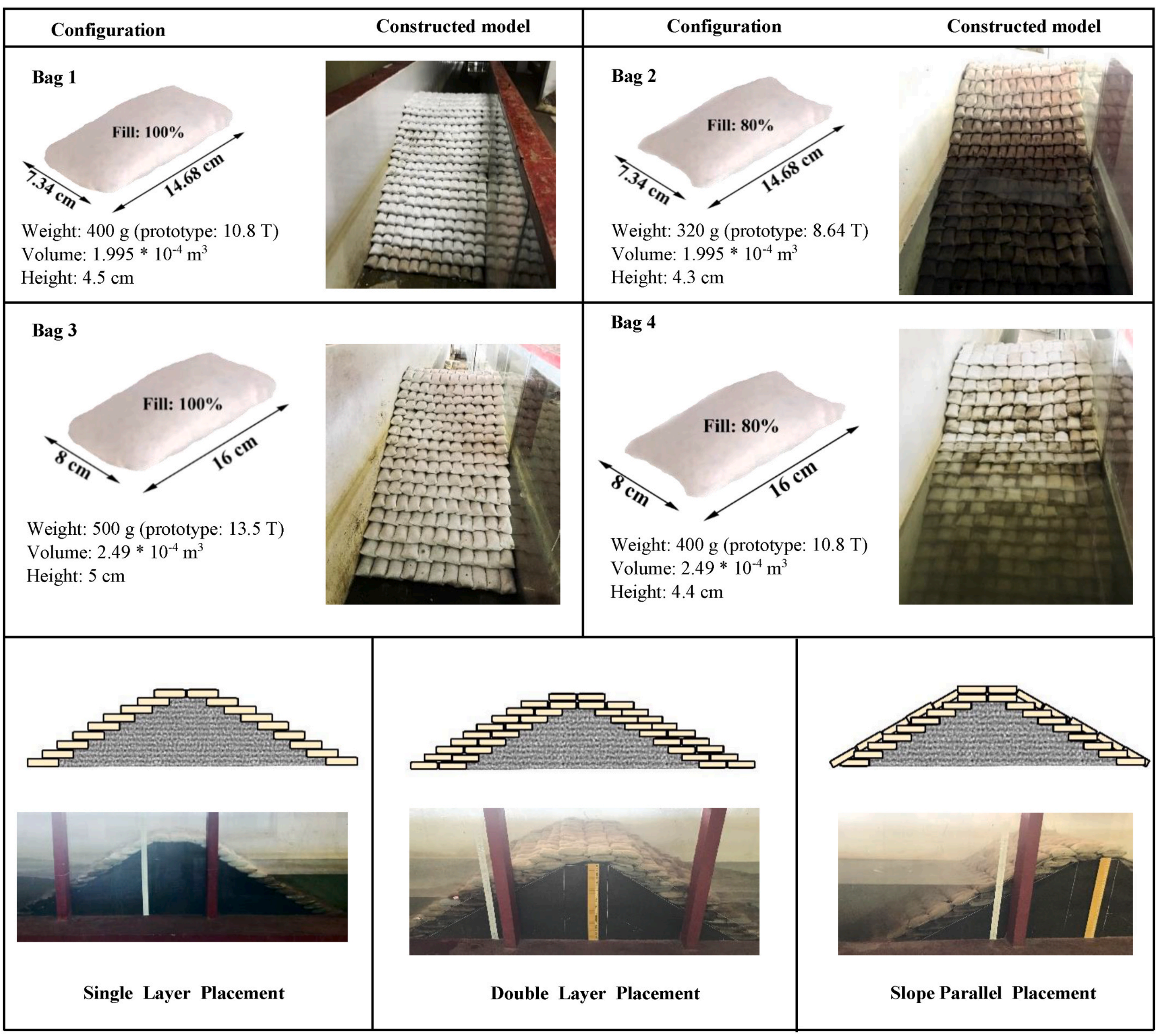

Fig. 2. Dimensions and placement modes of various GSC units used in the model studies.

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)	P	2005 kg/m^3
GSC armour weight	W	320–500 g
Slope		1V:2H
Crest height	H	0.70 m
Crest width	B	0.32, 0.29 m
GSC material		Non-woven

Table 2
Non-dimensional 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
Relative water depth (d/gT^2)	0.007–0.023
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
a. Geotextiles	
Type	Non-woven
Material	Polypropylene
Colour	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
Apparent opening size	0.2 mm
b. Sand	
Location	NITK Beach
Specific gravity	2.65
D_{10}	0.18 mm
Median grain size D_{50}	0.35 mm
c. Core	
Material	M-sand
Specific gravity	2.78
D_{10}	0.22 mm
D_{50}	0.45 mm

GSCs, finally concluding that the bags with the higher dimension and 100% sand fill are more stable than other test cases. The present paper investigates the variation of stability parameters when the number and placement modes of armour unit layers are altered. Double layer placement of the armour units in a breakwater structure is feasible based on the armour units used. The key aspect of double-layer placement of the armour units is interlocking which may not be possible in all types of units available, for example, cube armour units (Muttray and Reedijk 2008). In the case of GSC breakwaters, secondary layer armour units act as a separator for the first layer. The units in the primary layer tend to rock, detach or displace from the structure resulting in core exposure in the absence of a second armour unit layer. In due course of experimentation, some detaching GSC units are observed to readjust themselves parallel to the structure slope, exhibiting higher stability. The present investigation also explores the possibility of such 'slope parallel placement' of GSC units which may help in enormous reduction of construction materials if proved stable. Collectively, the present paper attempts to,

- Analyse the effect of the number of armour unit layers in describing the stability parameters of the structure.
- Investigate the effect of armour unit placement mode in determining stability.
- Compare the damage pattern of various configurations of GSC breakwaters
- Provide stability curves and design guidelines for GSC breakwaters.

2. Physical modelling

2.1. Wave flume

The physical model studies were carried out in the regular wave flume available in the Department of Water Resources and Ocean Engineering at the National Institute of Technology Karnataka, Surathkal,

Table 4
GSC damage classification criteria by Dassanayake and Oumeraci (2012).

Damage Classification I (Single GSC)				
Considering only a single GSC in the most vulnerable position (Critical GSCs)				
"Stable"	Horizontal displacement <10% of GSC length (or width)/ Upward rotation < 10°			
"Movement"	10% of GSC length (or width) < Horizontal displacement <50% of GSC length (or width)			
"Detachment"	Horizontal displacement >50% of GSC length, width, Upward rotation > 45°			
Damage Classification II (GSC-Structure)				
Considering all critical GSC layers of GSC-Structure				
No Damage [DC0]	Incipient Motion [DC1]	Minor Damage [DC2]	Medium Damage [DC3]	Total Failure [DC4]
<10% of critical GSCs moved. No critical GSCs detached	10%–50% of critical GSCs moved. <5% of critical GSCs detached	>50% of critical GSCs moved. 5%–20% of critical GSCs detached	20%–40% of critical GSCs detached	>40% of critical GSCs detached

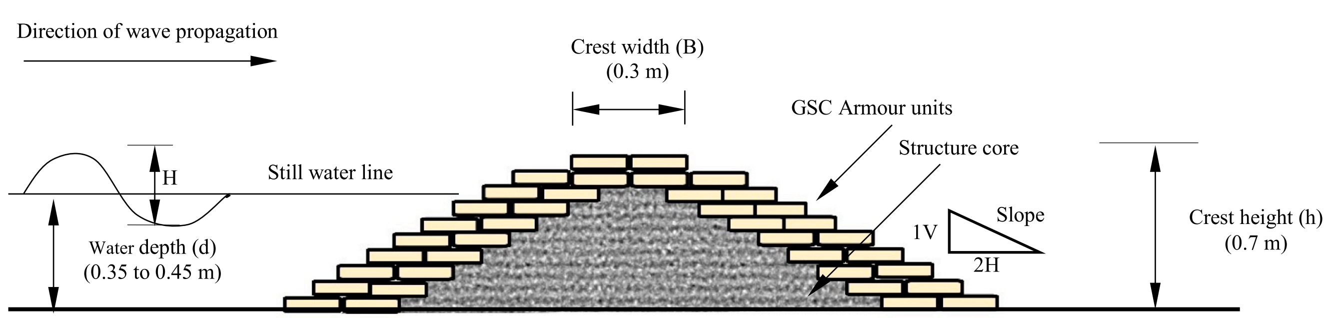

Fig. 3. Schematic representation of GSC breakwater model.

Fig. 4. Bag 1 Double layer configuration, (a.) Stable (DC0) after exposure of 0.06 m wave heights, (b.) Total Failure (DC4) after exposure to 0.16 m wave heights.

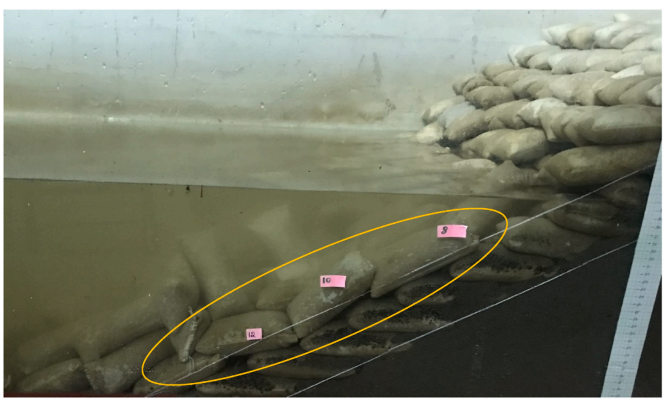

Fig. 5. Readjusted primary layer forming slope-parallel arrangement for Bag 1, Double Layer configuration.

India (Fig. 1.). From the findings of Faraci (2018), we concluded that there is no significant difference in results of wave response of GSC structure with monochromatic and random waves. Additionally, more conservative stability results can be obtained while experimenting with monochromatic waves. Hence it is decided to proceed with regular waves, even when it is not a state of the art technology nowadays. The flume dimensions include width of 0.74 m, depth of 1.1 m and length of 50 m, of which 25 m length is provided with glass panels facilitating photography and observation of the model placed. The beach end of the flume is supplied with a 1:12 sloped rip rap stone placement to diminish the wave energy. The other end is provided with a 'bottom-hinged flap' type wave generator capable of generating regular waves. Waves are generated by the flap movements controlled by an 11 kW, 1450 rpm induction motor. Waves of period 0.8 s–4 s and length, 0.02 m–0.20 m, can be generated with the available facilities up to a water depth of 0.50 m. Confining the Mangaluru coast conditions, a model scale of 1:30 is adopted for the present investigation confining Froude's Similitude criteria.

2.2. Instrumentation

Capacitance probes, amplification unit and data acquisition system together constitute the instrumentation for the present study. Capacitance probes measure the capacitance difference between water and the copper conductor. These digital readings are converted into wave period and height and are displayed on the EMCON wave recorder software. One capacitance probe is fixed at 'L' (wavelength) distance seaside to know the wave characteristics interacting with the structure, and another probe is set on the lee side to observe wave transmission (Fig. 1.). The readings that are observed can be estimated as ±3% accurate.

2.3. GSC breakwater model construction

This experimental study includes testing different sizes and placement modes of the geotextile sand containers. Increased puncture resistance, friction factor, abrasion resistance and less cost favours non-woven textiles to be increasingly used in coastal engineering applications (Elias et al., 2021; Heerten et al., 2000; Kriel 2012). Additionally, the study conducted by Dassanayake and Oumeraci (2012) showed a 40% higher stability for non-woven textiles compared to woven ones. Procured geotextile roll is cut into the required dimensions, locally sewn, and are filled to various percentages (by weight) with the fill material, which is beach sand collected from NITK beach. The volume of individual bags are calculated in accordance with Robin (2004). Sand fill is varied from 100% to 80% of the bag weight as a result extensive literature survey as elaborated in Elias et al. (2021).

A 1:30 scaled model is placed in the flume, which is facilitated with glass panes for visual observation. Froude's similitude criteria are adopted for scaling the models. Scaling of geotextiles is practically impossible, as it would be challenging to fabricate a 900 times thinner fabric. Initially, the core is constructed to a slope of 1V:2H using M-sand. Geotextile sand encapsulated structures can withstand steeper slopes up to 1V:1H, but the present investigation is limited to a single slope of 1V:2H to facilitate a comparative analysis with similar sloped structures. The sand containers are placed over the core in three different placement modes i.e, Single Layer Placement, Double Layer Placement and Slope Parallel Placement (see Fig. 2.). In single and double layer placements, sand containers are placed with 50% overlap with its adjacent layers, having its longer dimension parallel to the direction of wave attack. The Longer dimension is placed parallel to the structure slope in 'Slope Parallel Placement'. After the placement of the models, the flume is filled to the required depth of water, completing the breakwater model construction. The range of non-dimensional wave characteristics and properties of construction materials are discussed in

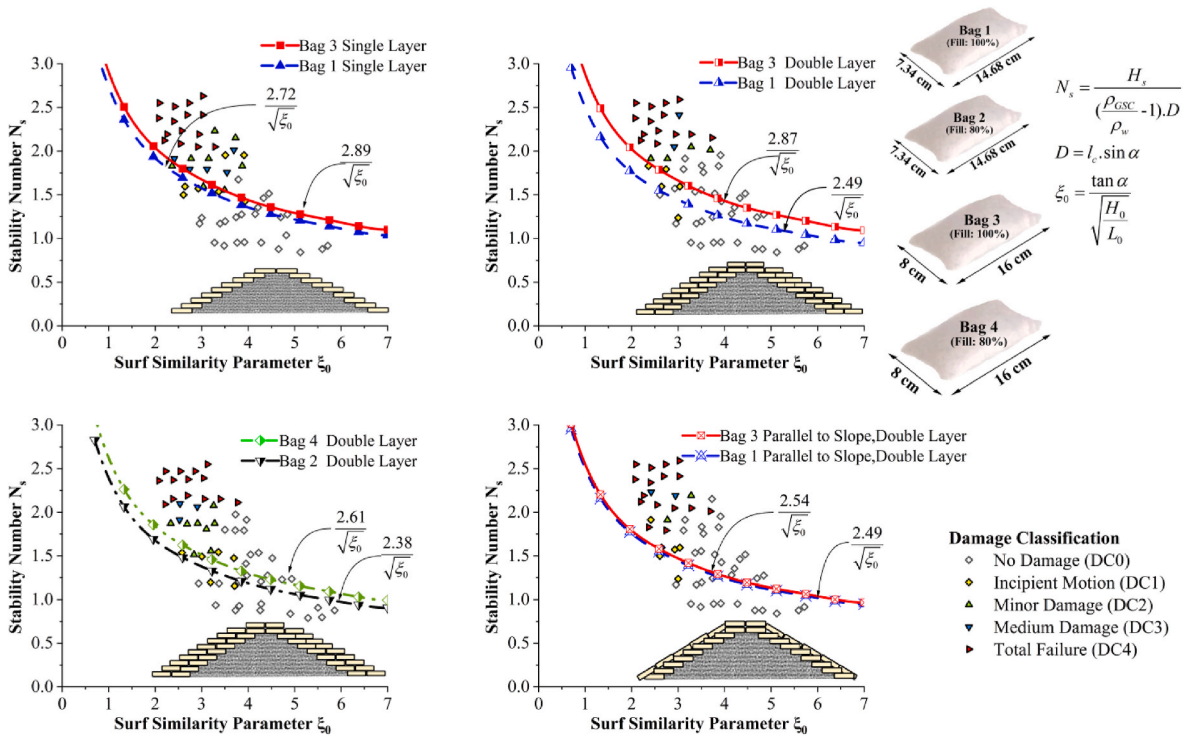

Fig. 6. Effect of armour unit size on stability of GSC breakwaters.

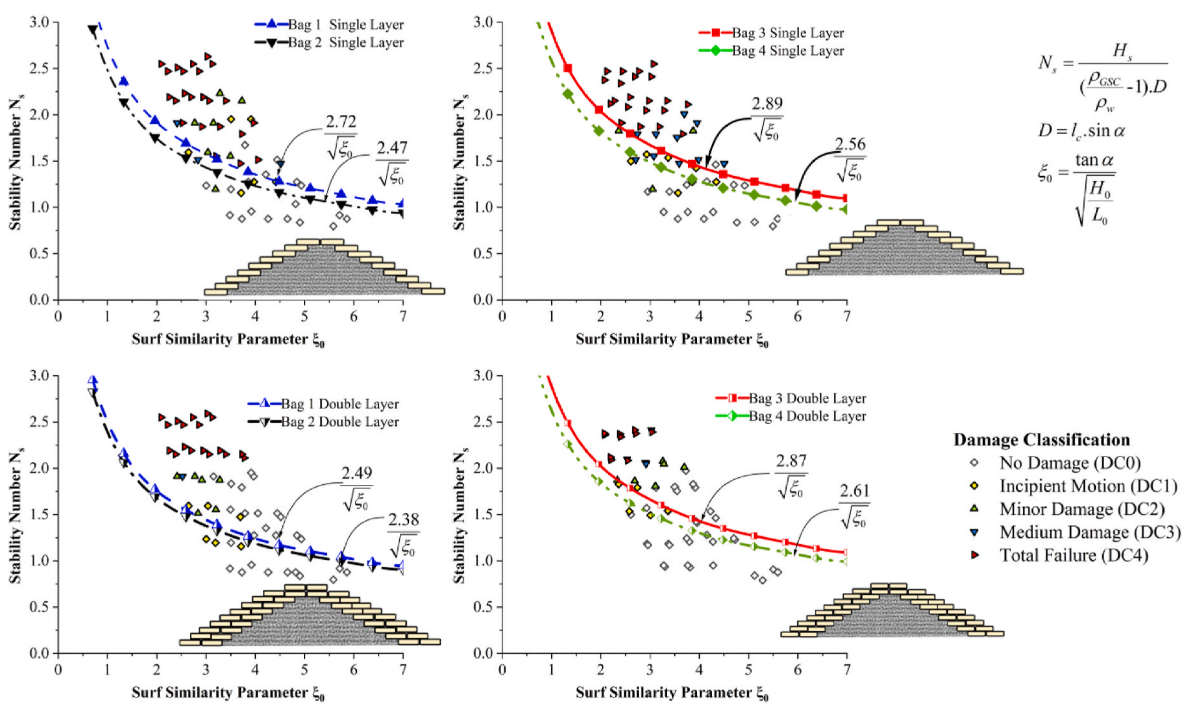

Fig. 7. Graphs showing comparative analysis of the stability of 100 and 80% filled GSC units.

Tables 1 to 3 and Fig. 3.

2.4. Test procedure

As mentioned in the instrumentation section, one probe is fixed at the seaside, and another is fixed on the lee side. While the former measures the incident wave characteristics, the latter is used to measure the wave transmission. The entire arrangement is connected to the data acquisition system. The model is exposed to waves of fixed wave period and the smaller wave height (0.06 m) initially and further increased to higher wave heights (0.16 m). The waves are sent in a burst of five to eight waves to prevent its superposition due to the reflection from the structure. The procedure is followed until the waves are run for all the required wave periods.

Damage analysis of GSCs cannot be carried out like conventional structures; therefore, damage criteria provided by Dassanayake and

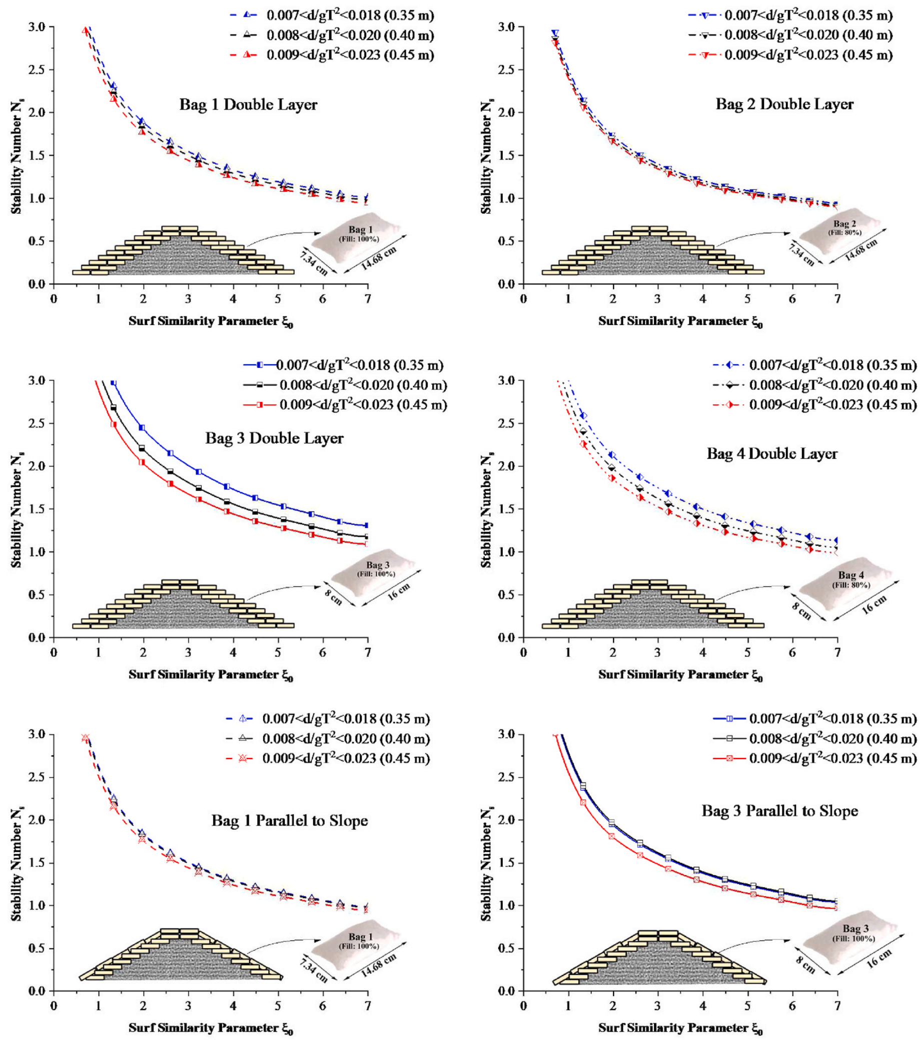

Fig. 8. Stability curves of GSC breakwaters with varying water depth.

Oumeraci (2012) is used in the present study (see Table 4). This involves identifying critical layers and quantifying the number of units detached or displaced from those layers. The test models are placed to different damage levels ranging from DC0 to DC4 according to the severity of the damage, with DC0 being the most stable and DC4 being the total damage case. According to Elias et al. (2021), stability against a storm duration of 3000 waves are required to confirm a stable structure. Stability curves are drawn using the 'DC'1 incipient motion cases, as discussed in Elias et al. (2021).

2.5. Assumptions in physical modelling

The replica of field conditions to be generated in the laboratory is often quite a difficult task. Hence the following assumptions are made in this experimental study.

1. The difference in density and other properties of the seawater and the water used in the flume is neglected.
2. The sea bed of the wave flume is horizontal and rigid type; hence sediment movement is not considered.
3. Regular waves are generated in the laboratory, whereas the prototype is always subjected to irregular wave attack.
4. All the assumptions of the Froude's similitude are included as the scaling is done according to it.
5. Geotextiles and sand used in the experiments are not scaled to 1:30.

3. Results and discussions

Stability estimations and damage analysis are carried out following the guidelines from various published sources (Dassanayake and Oumeraci 2012; Elias et al., 2021). Initially, the experiments were conducted with double layer of GSC units. The structure tends to be more stable when supplemented with two GSC layers than a single layer placement. The primary failure mode observed was the detachment of GSC units. The structure can be stable and protected with the second layer even when the primary layer shows displacement. The structure generally showed more serious damage with increasing incident wave height and period, changing from DC0 to DC4 (Fig. 4). It is observed that the units detached from the primary layer got readjusted themselves to form a layer of slope parallel units (Fig. 5). Those units, in slope parallel condition, are observed to possess higher stability and resisted further displacement. This observation lead us to experiment with the 'Slope Parallel' arrangement in detail. However, damage progression in 'slope parallel' placement is observed to grow faster once GSC unit detachment is initiated (more details in section 3.6). The effect of other structural parameters in the stability of GSC breakwaters has been analysed in the following sections.

For such analysis, stability curves of the breakwaters have to be deduced. As reported by Dassanayake and Oumeraci (2012) and Elias et al. (2021) incipient motion (DC1) curves can serve as suitable tool to demarcate the stability of a particular case. C_w value is calculated for

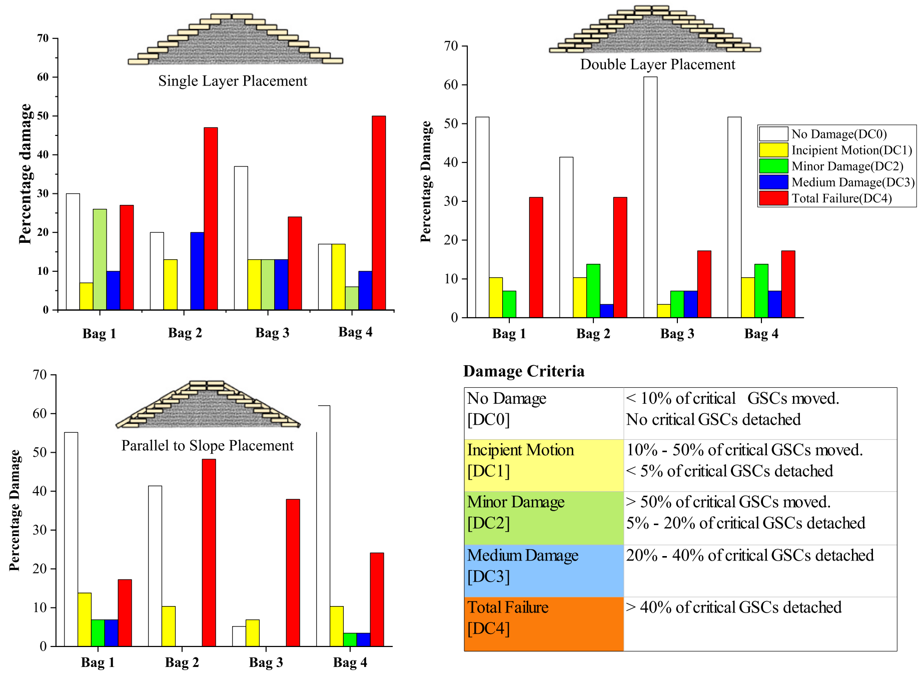

Fig. 9. Damage levels exhibited by various test configurations.

each incipient motion points eqn (1) and its average value is used in (2) for drawing the stability curves.

$$C_w = N_s \cdot \sqrt{\xi_0} \tag{1}$$

$$N_s = \frac{C_w}{\sqrt{\xi_0}} \tag{2}$$

Where, N_s is the stability number and ξ_0 is the surf similarity parameter and is represented by (3) and (4). H_s is the incident significant wave height, ρ_w and ρ_{GSC} corresponds to the density of seawater and GSC, D is the thickness of armour layer, α is the slope angle of the geosynthetic structure, L_0 is the deepwater wavelength, equals to $gT^2/2\pi$, where T is wave period.

$$N_s = \frac{H_s}{\left(\frac{\rho_{GSC}}{\rho_w} - 1\right).D} \tag{3}$$

$$\xi_0 = \frac{\tan\alpha}{\sqrt{\frac{H_0}{L_0}}} \tag{4}$$

But it should be realised that for low ξ_0 values, this line is very close to the data points with significant failure and therefore, additional measurements are necessary when these low values of ξ_0 (around 2) are expected during design conditions. This issue is due to the inaccuracy in conversion of measurement points to stability curves. Therefore readers has to note that, the stability curves are in disagreement with the measured data (even when the curves are on the safer side), especially in lower surf similarity values.

3.1. Effect of armour unit size

Two different armour unit sizes were examined. Fig. 6, shows that Bag 1 and Bag 2 are of smaller size than Bag 3 and Bag 4. In all the tested cases, bigger bags exhibited higher stability, with double-layer configuration showing a maximum stability difference of 28.83% and slope parallel placement showing a minimum difference of 2.62% between bigger and smaller bags. Bag 3 stacked to double layer is observed to have the highest stability, which is 17.8% higher than the same bags stacked to single layer. Slope parallel placement showed up to 32.3% lower stability compared to all other configurations. Bigger bags possess a higher self-weight resulting in higher stability of the structure. As a result, a more significant wave force is required to overturn or displace bigger armour units (Recio and Oumeraci 2009). Additionally, the interlock between bags is also a parameter to determine the stability of the structure as the top bag layered ½ on the top bags are less stable than that layered 1/3 of the bottom bag. However, this effect is less pronounced in slope parallel placement since the curves represented by larger (Bag 3) and smaller (Bag 1) bags are nearly aligned, as observed from Fig. 6. This can be due to the fact that a component of the bag weight is only contributing towards the stability of the structure in case of slope parallel placement. Additionally, it is observed that chances of sliding down of units are high in the case of slope parallel placement after initial detachments, unlike other placement modes. 2.6–28.83% higher stability is observed for larger bags due to its increased self-weight.

3.2. Effect of sand-fill ratio

Sand filling percentage of bags is varied from 100 to 80% in order to study the effect of fill percentage on the stability of the structure. In Fig. 7, Bag 1 and Bag 3 are fully filled bags, whereas Bag 2 and Bag 4 are 80% filled bags. 100% filled bags exhibited higher stability in all the cases than their corresponding 80% filled ones. 4.68–12.8% increase in stability is observed when the fill percentage is varied from 80 to 100% in various configurations. 80% filled bags contain a large amount of free spaces, which permits sand movements when exposed to ocean waves. As a result, bags tend to displace and detach much more effortless than fully filled units.

3.3. Effect of water depth

The stability of the structure is found to be decreasing with increasing water depth since all experimental results at minimum water depth exhibited higher stability. All configurations showed minute stability differences with water depth (less than 7%) except in the case of

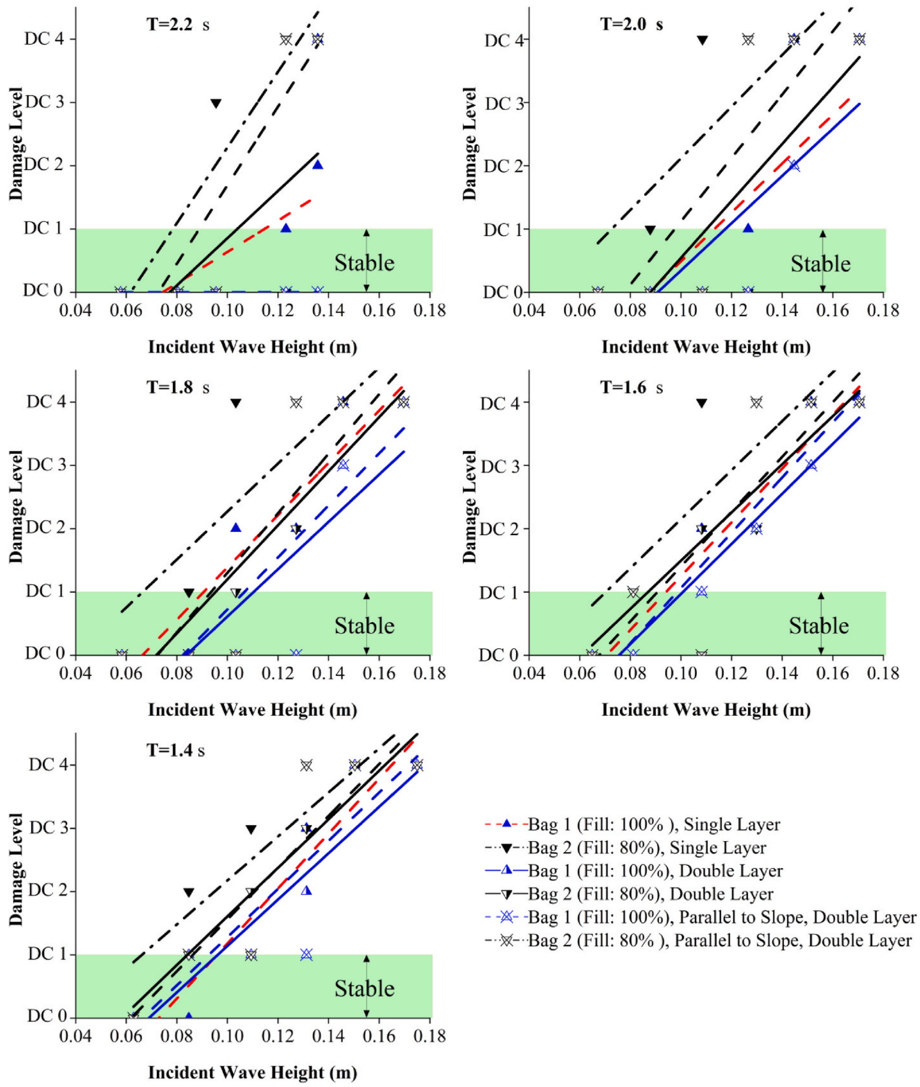

Fig. 10. Graphs representing non-damaging and damaging incident wave height showed by various configurations involving Bag 1 and Bag 2.

bigger bags (Bag 3 and Bag 4) in double-layer placements (up to 21.52%). This is attributed to the aligned nature of stability curves, owing to the independence of stability with water depth. Similar results showing less dependence of water depth on stability has been reported by Elias et al. (2021), where stability difference was as low as 4.4% with varying water depths.

As observed from Fig. 8, bigger bags (Bag 3 and Bag 4) showed up to 21.52% higher stability in lower water depths. This can be due to the fact that wave runup and rundown is less in lower water depths, resulting in a lesser number of units getting exposed to wave activity. This reduces the displacement and detachment of units, leading to improved stability at lower water depths. Additionally, 80% filled bags with lower stability is not examined for slope parallel placement.

3.4. Damage levels

Fig. 9 shows the level of damage exhibited by different armour units for different placement modes. It is observed that Single layer and slope parallel placements are highly unstable, as it produced nearly 50% of Total Damage (DC4) cases for 80% filled bags. Double layer arrangement shows fewer DC4 cases (less than 30%) and increased stable cases (40–60%) for all armour units. In the case of slope parallel placement, the stable level is high, nearly 60% in certain cases, but damage progress very fast as instability of units occur. This is evident from Fig. 9, as intermediate damages DC2 and DC3 are less or never reported in slope parallel placement. Damage rapidly progresses to Total Failure DC4 from Incipient Motion DC1 compared to single and double layer placements.

3.5. Effect of incident wave height

Fig. 10, shows the plot of the Damage levels with the incident wave height, DCO and DC1 damage levels are considered to be stable according to Dassanayake and Oumeraci (2012). Therefore, non-damaging incident wave heights for various arrangements with Bag 1 and Bag 2 have been identified from Fig. 10. The breakwater model with Bag 1 stacked to two layers stood stable to waves up to 0.117 m in the model scale, which is 3.51 m in the prototype. The breakwater model with Bag 2 placed in a single layer exhibited the least performance as it could withstand a maximum of 0.078 m wave in the flume, which would be a 2.34 m wave in the actual sea. All other models exhibited a maximum non-damaging wave height between 1.98 m and 3.3 m. Additionally, in all cases, damaging wave height is found to be decreasing up to 22.2% with reducing wave periods.

Fig. 11, shows the plot of damage level with the incident wave height. DCO and DC1 damage levels are considered to be stable according to Dassanayake and Oumeraci (2012). Therefore, non-damaging incident wave heights for various arrangements with Bag 3 and Bag 4

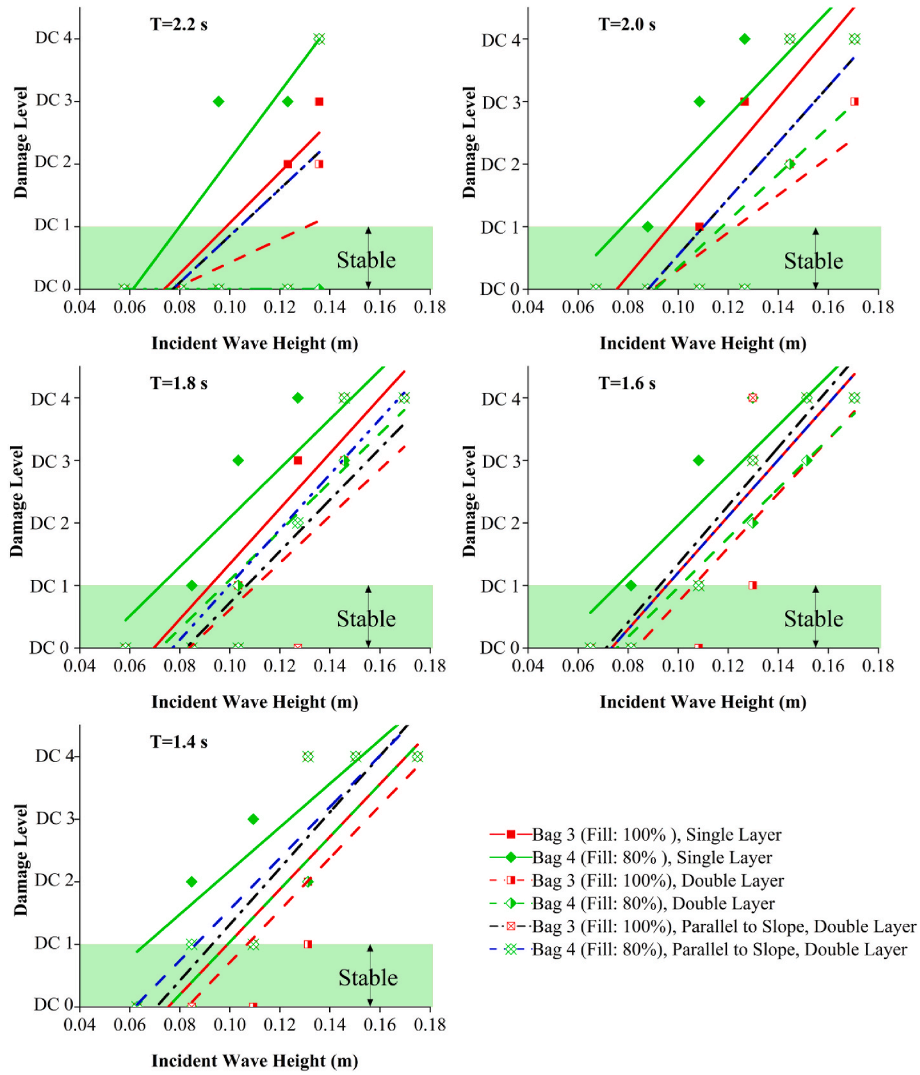

Fig. 11. Graphs representing non-damaging and damaging incident wave height showed by various configurations involving Bag 3 and Bag 4.

have been identified from Fig. 11. Double layer placement with Bag 3 is found to be stable up to a wave height of 0.132 m in model scale, which will be 3.96 m in the prototype. Bag 4 single layer exhibited the least performance, as it could only withstand waves up to 0.08 m in the flume, indicating a 2.4 m wave in the prototype. The best performing model showed a 22.2% increase in non-damaging wave height when the wave period is varied from 1.4 to 2.2 s, complimenting the gentle and less destructive nature of long-period waves.

3.6. Effect of placement method

Fig. 12, represents a comparative analysis of various placement modes for Bag 1, Bag 2, Bag 3 and Bag 4. It can be observed that curves for double-layer placement have 2.6–17.8% higher stability in all the tested cases compared to the single-layer placement. Higher stability can be attributed to the increased self-weight and porosity. As the porosity of the structure increases, more wave dissipation takes place on the structure slope reducing the disturbing wave forces on the structure. Slope parallel placement is observed to have up to 10.7% lower stability compared to all single layer placements. It is observed that in slope parallel placement, damage progression is faster as the displacement of a unit would result in the sliding down of units from its upper layer. Similar sliding movement is not observed in single or double-layer placements. Additionally, units are readjusted to form a new stable arrangement in single and double layer placements.

An important conclusion deduced is that stability of the breakwater increases with the number of layers (single or double). Hydraulic parameters like reflection, runup and rundown can reduce, as more wave dissipation can take place in double-layer structure due to increased porosity and void spaces. But stability has considerably decreased when the units are placed parallel to the slope because of the sliding down of armour units.

3.7. Stability nomograms

This section compiles the results of all the previous sections. The stability nomograms reveal that maximum stability is for bigger bags (Bag 3 in the present case) placed in double layers (see Fig. 13). Bag 3 is found to be up to 17.8% stable when placed in double layers than when placed in a single layer. Similarly, Bag 1 is found to be up to 5.38% stable in double-layer placement. 80% filled bags are less stable in all cases, with slope parallel placement being the most unstable configuration. These nomograms are the major research outcome as they can be used in field applications for planning and designing GSC breakwaters.

4. Concluding remarks

The study aided in analysing the effect of armour unit placement

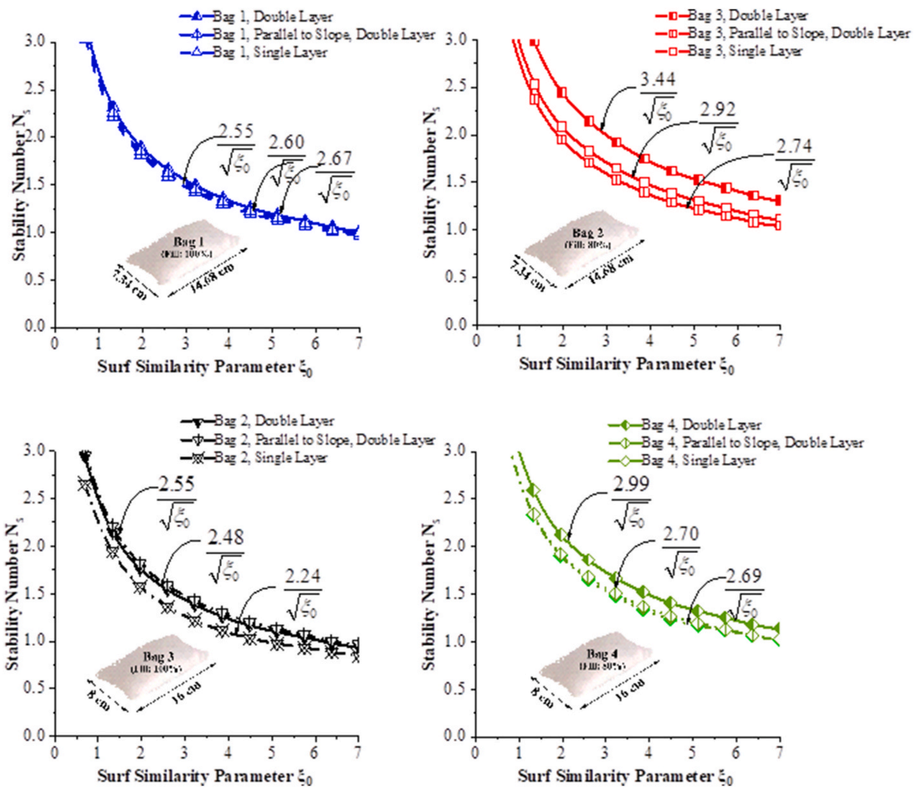

Fig. 12. Graphs representing comparative analysis of stability curves of different placement modes.

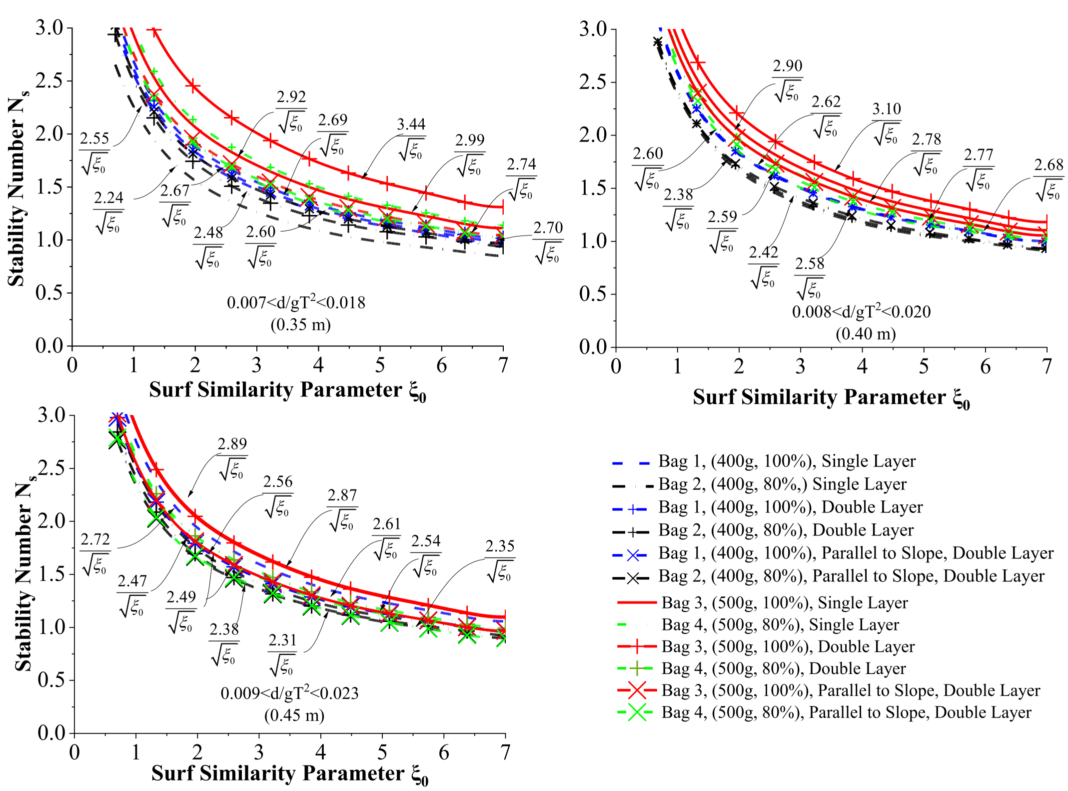

Fig. 13. Stability nomograms for GSC breakwaters of different relative water depths.

modes in describing the stability of GSC breakwaters. On a general note, GSC breakwater is found to perform better when supplemented with double layers of armour units. Each factor affecting the structure's stability has been extensively reviewed, and the following concluding remarks have been deduced.

- As far as the armour unit size is concerned, larger units are found to be 2.6–28.83% higher in stability than their smaller counterparts. Increased self-weight and stability is concluded to be the reason.
- 4.6–12.8% increase in stability is observed when the sand filling of the bags is varied from 80% to 100%. Increased self-weight of units, lack of sand migration within units, lack of empty spaces in units makes 100% filled bags more stable.
- Stability of the structure decreased with increasing water depth as runup, rundown and destructive wave forces are more at higher water depth. Bigger bags tend to be up to 21.5% stable in lower depth.
- As far as damage levels are concerned, double layer placement tends to have a lesser number of 'Total Failure" cases (less than 30%). Single and Slope parallel placements exhibited up to 50% total failure cases, with slope parallel placement rapidly reaches total failure once displacement of units initiates.
- Double layer placement with Bag 3 is found to be stable up to a wave height of 0.132 m on the model scale, which will be 3.96 m in the prototype.
- Out of all placement modes, double layer placement has 2.6–17.8% higher stability, whereas slope parallel placement has up to 10.7% lower stability compared to all single layer placements.

The major conclusion deduced is that the stability of structure increases with armour unit weight, sand fill ratio and the number of armour unit layers. Bag 1 and Bag 3 (fully filled bags) showed 5.38 and 17.8% higher stability when placed to double layers than a single layer. 80% filled bags are found to be less stable in all cases, with slope parallel placement being the most unstable configuration. The stability nomograms can be projected as the major research outcome, as it aids coastal engineers in designing and planning of GSC breakwaters. Geosynthetics in hydraulic and coastal engineering.

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