

Hydraulic Stability of Submerged GSC structures

V.A.N. Soysa, D.M.D.T.B.Dassanayake and H. Oumeraci

Abstract: Geotextile Sand Containers (GSCs) are used for the construction of coastal structures as a low cost and softer alternative to expensive and hard structures made of concrete or rubble. However, the hydraulic stability of GSC-structures still needs to be investigated for a better understanding of the processes and the parameters of GSCs, which cause the failure. This study focused on the effect of the geotextile material, the sand fill ratio, and the inclination in GSC placement towards the hydraulic stability of submerged GSC structures. Four sets of specifically designed laboratory model experiments were carried out to study the influence of aforementioned parameters on the GSC stability. A new failure mode of GSCs was identified through the model experiments and named as “uplift and drift”. From the test results (wave and damage analysis), new stability curves were developed and compared with each test scenario. The influencing parameters were quantified and the relative importance of each parameter for the hydraulic stability of submerged GSC structures was assessed. Finally, it was concluded that the sand fill ratio is the key influencing parameter among all considered parameters. For the tested sand fill ratios, the hydraulic stability increases, when the sand fill ratio increases. Furthermore, it was concluded that the stability of inclined GSCs is higher than horizontally placed GSCs. However, stability decrement was concluded for GSC made from the woven geotextile material comparative to the nonwoven GSCs. Hence, the type of the geotextile material and the inclination of GSC placement were found to be two important aspects that need to be considered, when designing GSC-structures.

Keywords: Geotextile Sand Containers, Hydraulic Stability, Stability of submerged GSC breakwater, Failure Mechanisms of GSCs

1. Introduction

Use of Geotextile Sand Containers (GSCs) provides much softer, cost effective, flexible and reversible construction alternatives than coastal structures made from rubble and concrete. Hence many number of applications of GSCs in Germany, Australia, (Saathoff et al.[1], Restall et al.[2]Heerten et al.[3]), New Zealand (Jose et al.[4]), United States (Fowler & Trainer, [5]), Dubai (Weerakoon et al.[6]), Portugal (das Neves et al.[7]), Korea (Shin & Oh [8], Kim et al. [9]), Sri Lanka (NAUE [10]) and also in many other parts of the world could be seen during the past few decades. Much research work (Venis [11], Oumeraci et al [12], Recio [13], Mori [14] and Dassanayake & Oumeraci [15]) has been carried out in order to understand the hydraulic processes related to stability of GSCs.

However, several factors related to the hydraulic stability of GSC structures have to be studied for better understanding of the processes. It is also noted that parameters such as types of geotextile material, fill material types, sand fill ratio, slope of the structure, and deformability of GSC are interrelated. Thus the effect of each parameter on the stability of the GSC structure should be investigated with

utmost care in order to distinguish the independent relationship or the sensitivity of the parameter. For the betterment in understanding of the performances of GSCs in several types of coastal structures such as groynes, revetments and breakwater, detail studies should be performed.

Jose et al.[4], das Neves et al.[7], Jackson et al. [16], and Akter et al. [17], have investigated on the stability of GSCs and identified several failure modes of GSCs under wave action. However, design guideline are also still in the stage of development and further experiments on stability issues are required in order to enhance the performance of GSC structures. This paper refers to the study that carried out to investigate the hydraulic stability of submerged GSC structures with respect to identified influencing parameters such as the sand fill ratio of GSC, geotextile material, and the inclination of GSC placement.

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2. Objective

The objective of the study was threefold.
(i) Identification and understand the effects of engineering properties of GSCs on the hydraulic stability of GSC structures.
(ii) Quantification and evaluation the sensitivity and relative importance of identified and selected properties of GSCs on the hydraulic stability of submerged GSC structures through a set of appropriate laboratory experiments.
(iii) Comparison of currently available stability formulae on GSCs with the analysed data from the laboratory experiments.

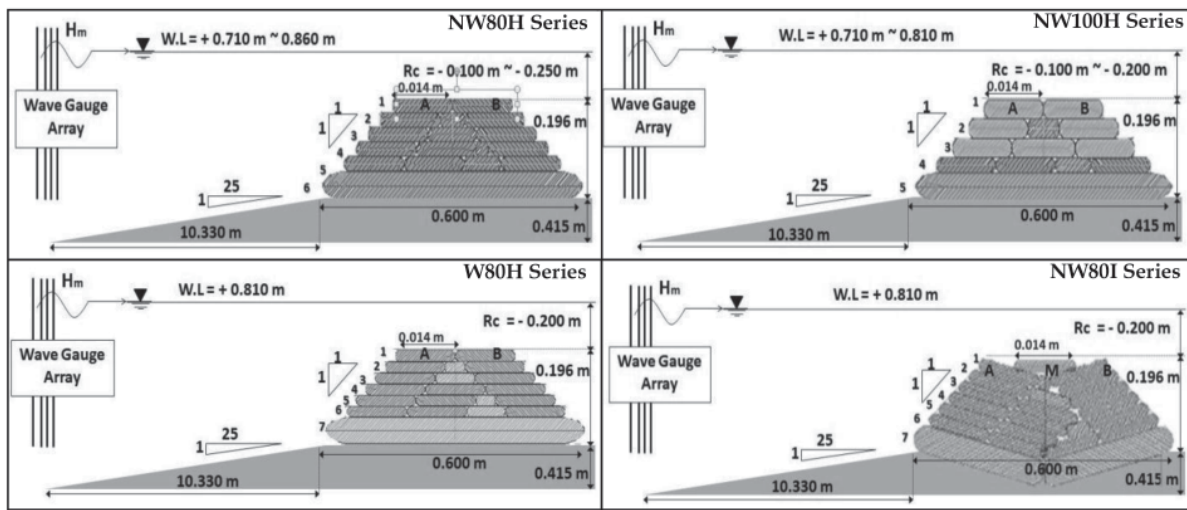
3. Methodology

Present knowledge related to the stability of GSC structures ([4], [7], and [11]), was reviewed and hydraulic processes affecting the stability of GSC structure([14] and [15])failure mechanisms of GSCs ([16] and [17])and available stability formula - Oumeraci et al., [12] and Recio, [13] - were studied. Geotextile material, fill ratio and inclination of GSC placement were identified as key influencing parameters on the hydraulic stability of GSC.

placed GSC (W80H); and Nonwoven, 80 % filled inclined GSC (NW80I).

Wave reflection analysis was conducted to identify the incident and reflect wave conditions as the waves, generated by the wave maker, usually show discrepancy from the nominal input parameter. Wave characteristics which applied on the structure should be carefully identified, for assessing the stability of the GSC. Deformation and damage analysis is to quantify the capability of GSC structure against the resulted wave data from the wave reflection analysis. Visual observation, digital photograph examination, video records analysis, high-speed video captures scrutinise and level measurements taken during the model tests were included in damage analysis.

Finally, effects of influencing parameters on the GSC stability were assessed and quantified by developing stability curve based on the results obtained from the wave analysis and damage analysis. Sensitivity and relative importance of the influencing parameters were also studied. Further, derived stability curves from the study were compared with available stability formulae - Oumeraci et al., [12] and Recio, [13]-



GSC row number: 1,2,3,4,5,6 and 7; GSC location : A, B and M

(Sketches are not to a scale.)

Figure 1 - Four test cases performed in laboratory model experiments

Next, stability of the submerged model GSC structure were tested for selected wave conditions (both regular and JONSWAP spectrum) with different freeboards (R_c) in such way that effect of identified key influencing parameters can be assessed. Figure 1 shows the four test cases as Nonwoven, 80 % filled, horizontally placed GSC (NW80H); Nonwoven, 100 % filled, horizontally placed GSC (NW100H); Woven, 80 % filled horizontally

4. Experimental Model Setup

4.1 Material Selection

In scaled down physical modeling, accuracy of simulation of engineering properties is important. Therefore, interested engineering parameters should be accordingly scaled down considering the Froude similarity.

Satisfaction of all parameters such as thickness, mass per area, permeability, tensile strength, and other interested parameters on geotextile

material cannot be achieved at the same time, thus scale down process of model prototype was based on the available material types of the industry. After the comparison with few available material and the opinions of industrial expertise GRK 201 manufactures by NAUE GmbH was selected for the model GSCs [18]

Particle size and its' distribution are the main consideration in selecting fill material for the GSC. Grain size of the fine particles should be sufficiently larger than the pore size of the geotextile material to ensure that fill material would not be lost significantly during the testing process. Therefore, fill material for the model GSC was selected based on the characteristics grain size (D_{50}) and uniformity coefficient ($C_u = D_{60}/D_{10}$) through a set of sieve analysis on several samples. The properties of selected material were as D_{50} of 0.25 mm and C_u of 1.3 [18]

4.2 Model Size

Nonwoven 80 % filled model GSC unit had dimensions of 14 cm x 7 cm x 2.8 cm, and for woven 80 % filled model GSC unit, dimensions were 14 cm x 7 cm x 2.2 cm. Due to the difference of material thickness in between nonwoven (1.2 mm) and woven (< 0.1 mm), height of the 80 % filled woven GSC was 4 mm lesser than the nonwoven GSC. Apart from above mentioned dimensions for the standard GSC for the model tests, smaller GSCs were used to fill the voids created from the standard GSCs and larger GSCs were used at the base to reduce the number of standard GSC preparation.

height gained for 5 layers of nonwoven GSCs during NW80H test series.

4.3 Model Setup

Figure 3 shows the experimental model setup and instrumentation of stability tests for GSC submerged breakwater at twin wave flumes in *Leichtweiß-Institut für Wasserbau* (LWI). The flumes are about 90 m long, 1.25 m deep, and one has a width of 1.0 m and the other one being 2.0 m wide and model tests were performed in 2m wide flume (Figure 2).

Experimental model setup was instrumented with resistant type wave gauges, pressure transducer, and Acoustic Doppler Velocimeters for the measurement purposes.

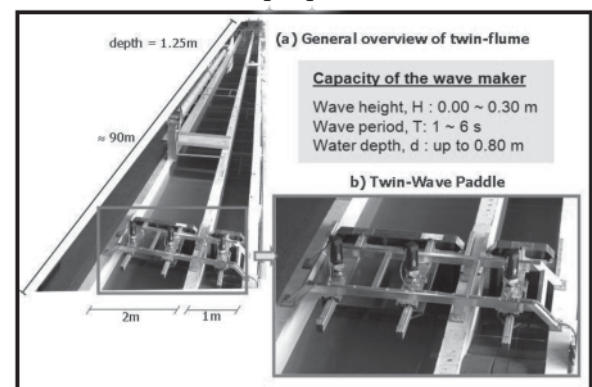


Figure 2 - Wave generation system in twin flumes at *Leichtweiß-Institut für Wasserbau* (LWI)

Apart from instrumentation for the measurements, three high-definition video cameras were placed in three perpendicular axis to capture top, side and front views. In addition, high-speed video records were made from side view.

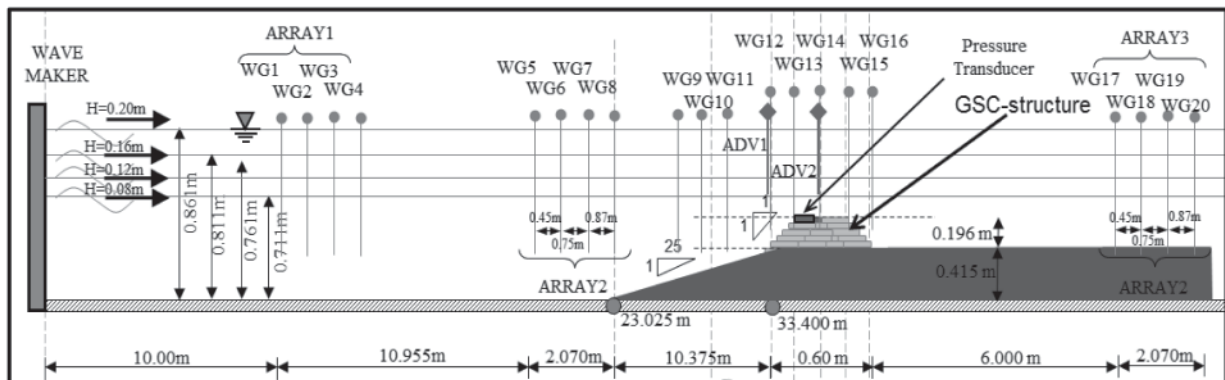


Figure 3- Experimental Model Setup at *Leichtweiß-Institut für Wasserbau* (LWI)

Model GSC structure had a height of 19.6 cm and width of 28 cm at the top and 60 cm at the bottom. As a result of the height difference, 6 layers of woven GSCs had to be used for W80H test series in order to achieve the same structure

Wave parameters, water levels, and freeboard conditions were selected depending on the capacity of the wave maker. Some of the wave conditions were repeated for woven and nonwoven GSC-structures for the betterment in comparative analysis on the influence of

different geotextile types (different surface frictions).

The sand fill ratio was varied from 80 % to 100 % in order to scrutinise the influence of sand fill ratio on the hydraulic stability of GSCs. Furthermore, it was expected that the inclination angle will improve the hydraulic stability. Therefore, few scenarios with relatively high wave conditions were repeated while GSCs were placed inclined (inclination angle is 15° from the horizontal line). However, only 1:1 slope was used during the whole test programme. After each test, the model was either repaired or fully reconstructed to obtain same initial conditions (e.g. crest level, seaward slope, shape of GSCs, etc).

Generally, regular waves were used during the model tests (150 regular wave tests). However, 48 tests were repeated with JONSWAP spectrum. Each regular wave tests consist of minimum 100 waves and the tests with wave spectrums consist of 1000. The model tests with wave spectrums were conducted with the main objective of studying the progressive damage of GSC-structures.

5. Data Analysis

Analysis comprise three sections namely (i) wave reflection analysis, (ii) damage analysis and (iii) sensitivity analysis of influencing parameters (geotextile material, fill ratio and inclination of in GSC placement)

5.1 Wave Reflection Analysis

During the testing process, wave data were recorded through 20 number of wave gauges. However, recorded data from Wave Gauge No 5-9 located at second array shown in Figure 3 were used for the reflection analysis in order to distinguish the wave characteristics at the beginning of the slope.

Wave reflection analysis was performed in accordance to the least square method by Mansard & Funke [19], thus three wave gauges in specific distances based on the wave length are needed. However, inclusion of four wave gauges to the array as shown in Figure 3, led the reflection analysis calculations to perform in all possible combinations. Therefore, careful selection, with recommended plausibility checks on the results from all combinations gives the best suited conditions for each test case, as it is practically inconvenient to adjust the positions of wave gauges to maintain the distance requirement in Mansard & Funke [19] method for each test case.

5.2 Damage Analysis

From the analysis of photographs taken during and after each test, most vulnerable location for damages was identified. According to the results of model experiments, crest layer was identified as the critical layer which showed highest vulnerability for failure. Further, failure modes of GSCs were studied with the help of high speed video records. Damage initialisation and progression were studied using high definition video records.

5.3 Sensitive Analysis

With the results obtained from wave analysis and damage analysis, sensitivity analysis was performed in order to quantify the effects of selected parameters as geotextile material type, fill ratio, and inclination angle over the hydraulic stability of GSC. Finally, comparison with respective cases through the sensitivity analysis paved the path to check the influence of the identified parameters over the GSC stability.

6. Results

From the model experiments, failure mechanisms were identified as uplift and drifting, sliding and overturning. Relationship between stability number and surface similarity parameters could be derived based on the data from the model experiments.

6.1 Failure Mechanisms

When forces exerted on the GSC due to wave is more than the threshold value of stability, and but not strong enough to detach the GSC completely from the structure, incipient motion could be observed.

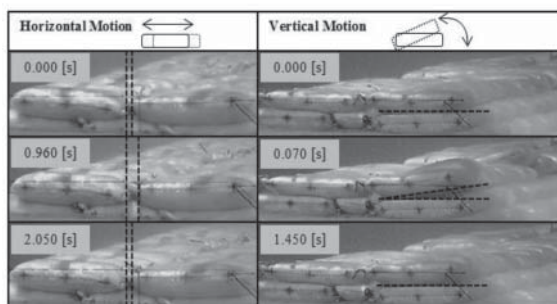


Figure 4- Incipient Motion

As shown in Figure 4 partial sliding and overturn occurred at the time where maximum force from the wave was exerted, but soon, GSC regained its initial location. This incipient

motion was considered in Table 1 for the damage categorisation. For certain test cases, it was observed that incipient motion continued for the whole test duration, however no complete detachment of GSC was resulted. Therefore, when stability of GSC is concerned, three stages were defined as no incipient motion, incipient motion and detachment. High-speed video extracts shown in Figure 5 illustrate the steps in overturn failure mode. Generally overturning was occurred at the front row of the crest layer. Uplift occurred at the front section, and resisting force gained from the GSC at back row against sliding caused the GSC to be overturned.

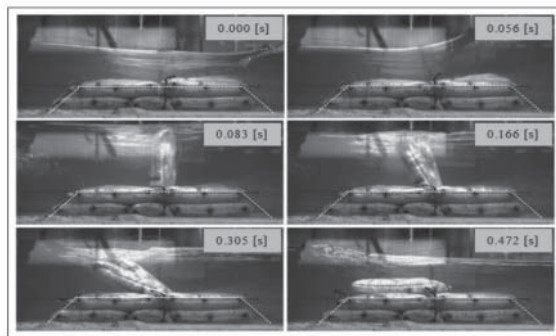


Figure 5 - Overturn Failure Mode of GSC

In sliding failure mode as shown in Figure 6, top GSC displayed lateral displacement relative to the lower GSC. Sliding can occur both instantly (complete detachment with one wave attack) and in progressive way (slight displacement per wave which leads to complete detachment after several wave attacks).

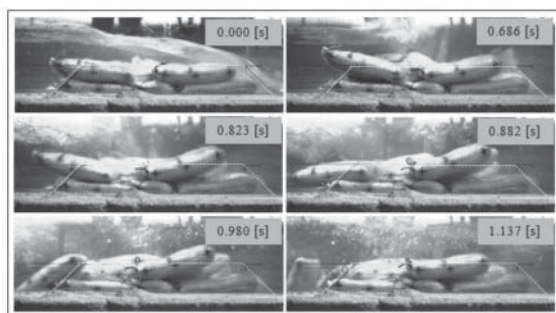


Figure 6 - Sliding Failure Mode of GSC

However, for certain instances as shown in Figure 7, it was observed that top GSC is lifted due to the pressure difference between the top and bottom side of the GSC and then drift with the wave where no surfaces of top GSC are in contacts with bottom GSC. Uplift and drift could be identified from the high speed video extracts, the Figure 8 shows the different between drifting and sliding.

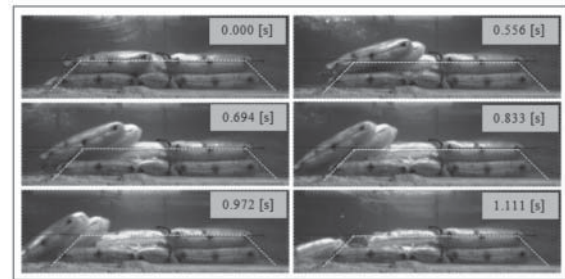


Figure 7 - Uplift and Drifting Failure Mode of GSC

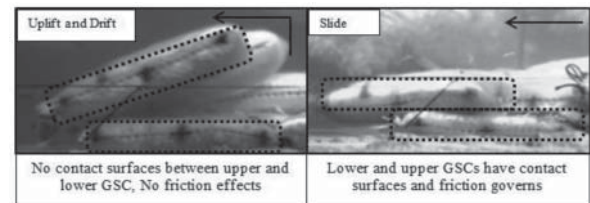


Figure 8 - Uplift and Drift in comparison with Slide

Therefore, in each case, bottom surface of the top GSC and top surface of the bottom GSC are in contact, friction between two surfaces can react against the failure. If not, restrained forces will not be mobilised, thus friction of the geotextile material does not count in failure.

6.2 Damage Categorisation

Damage was categorised based on the observation made on incipient motion, detachment and the failure mechanisms. Due to the regular wave attack, incipient / cyclic motions were observed, therefore, three stages were defined as no incipient motion, incipient motion and detachment considering the stability of single GSC. Damage Categories [DC] shown in Table 1 were defined based on the critical GSC with aforesaid three stages. Although test were conducted for 100 waves in regular wave case, due to the variation of the wave heights observed during the tests, number of waves for some test cases were reduced. However, damage categories were defined with the consideration of 100 waves and also curtailed time frames subjected to a minimum number of 80 waves.

In order to account for practical difficulties in achieving ideal situation in GSC placing during model construction and reconstruction, and non-homogeneity of GSCs, threshold of 10 % and 5 % for moved and detached critical GSC were considered respectively for the beginning of motion category. Therefore according to the damage categorisation, loss of stability begins at category 2, which is termed as Minor Damage. Damage levels were further defined as Medium Damage, Severe Damage and Failure Damage so that damage extension can

be identified with the sensitivity of the wave parameters. With above defined damage categories, video analysis was carried out for damage analysis for all test conditions with tested freeboard levels.

of damage analysis. Derived stability curves for each test case such as NW80H, NW100H, W80H and NW80I were used to study the effect of the influencing parameters.

Table 1 - Damage Categorisation

Damage Categories for Single GSC					
No Incipient Motion		Incipient Motion		Detachment	
Horizontal Displacement < 10% of GSC length, width		10% of GSC length, width < Horizontal Displacement < 50% of GSC length, width		Horizontal Displacement > 50% of GSC length, width	
Upward Movement < 10°		10° < Upward Movement < 45°		Upward Movement > 45°	
Damage Categories for GSC Structure*					
No Damage [DC 0]	Beginning of Motion [DC 1]	Minor Damage [DC 2]	Medium Damage [DC 3]	Severe Damage [DC 4]	Failure Damage [DC 5]
< 10 % of Critical GSCs moved	> 10 % of Critical GSCs moved < 5 % of Critical GSCs detached	> 50 % of Critical GSCs moved < 20 % of Critical GSCs detached	> 20 % of Critical GSCs detached	> 40 % of Critical GSCs detached	> 50 % of Critical GSCs detached
* GSC Structure is tested for regular wave set of 100, and subjected to minimum value of 80 waves.					

6.3 Stability Formulae

Based on the wave analysed data and damage analysis, a relationship between stability number and surface similarity parameter was derived as follows.

$$N_s = \frac{C_1}{\xi_o^{0.9}} + C_2 \sqrt{\xi_o} \quad \text{----- (1)}$$

Where,

$$\text{Stability Number} = N_s = \frac{H_m}{\Delta l_c \sin \alpha}$$

$$\text{Surface Similarity Parameter} = \xi_o = \frac{\tan \alpha}{\sqrt{H_m/L_o}}$$

H_m = Mean wave height,

Δ = Relative density of submerge GSCs,

l_c = Length of the critical container,

α = Slope of the structure,

L_o = Deep water Wave length

C_1 and C_2 = coefficients in order to adjust for the effect of the freeboard, the sand fill ratio, the geotextile material and the inclination of GSC placement.

Identifying the “No Damage”, (Damage Category 0) and “Incipient Motion” (Damage Category 1), two stability curves were derived for each test cases, by altering the C_1 and C_2 values (equation 1) in order to suit the results

6.4 Effect of the Sand Fill Ratio

Both weight of the GSC and the buoyancy force exerted on the GSC are directly proportionate to the volume of the GSC. However, as filled material density is higher than the water, net resisting force (weight – buoyancy) is higher for the 100 % filled GSC. Therefore, friction force which assist the GSC stability is also higher for the 100 % filled case. The uplift force due to wave action will be more or less same for both GSCs with different sand fill ratio as projected area of GSC parallel to the wave direction are almost similar. However, the drag force on 100 % filled GSC will be comparatively high as in GSC with a higher sand fill ratio has comparatively higher projected area perpendicular to the wave action. Since the Inertia force is based on the surface texture and flow velocity, it will not vary with the sand fill ratio. Henceforth resisting forces against mobilising forces from waves are higher for a GSC with higher fill ratio, thus it shows higher stability.

Apart from the consideration of forces, GSCs with higher sand fill ratio are less flexible and more in round shape resulting voids in the GSC structure. Therefore, higher permeability may also result higher stability for higher sand fill ratio. Stability increment observed for higher fill ratio is shown in Figure 9 with derived stability curves.

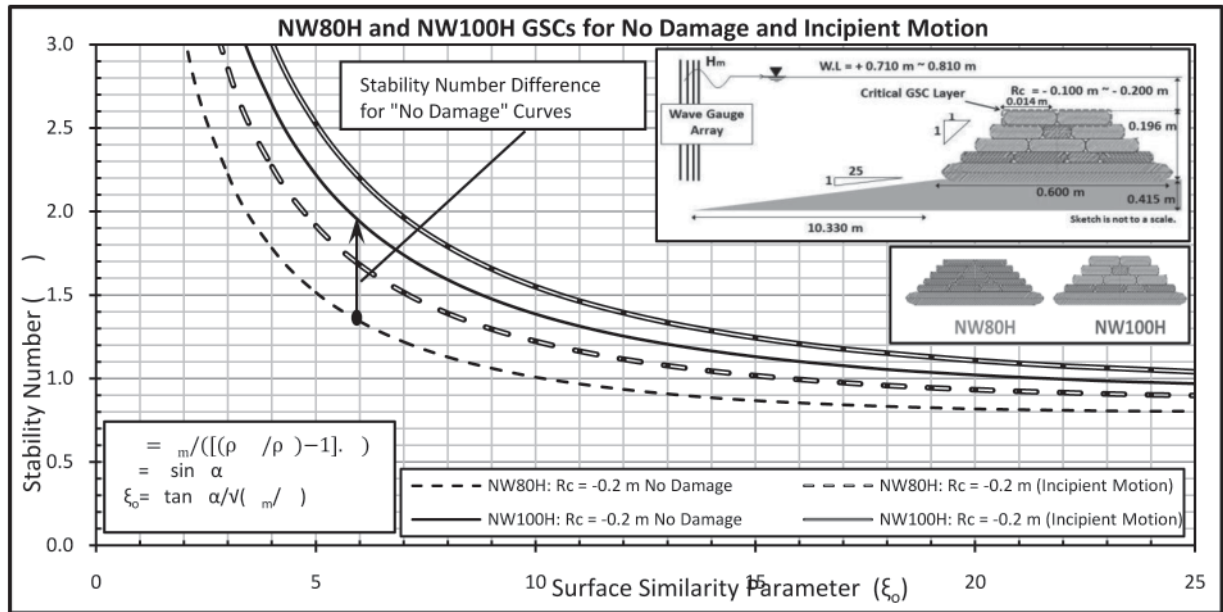


Figure 9 - Effect of the Geotextile Material - Stability Curves for NW80H and W80H

6.5 Effect of the Geotextile Material

Effect of friction of the selected geotextile material against the hydraulic stability is investigated during the study. Friction angle for woven and nonwoven were 16° - 18° and 20° - 26° respectively. Accordingly, it is expected that W80H test series indicates a lower stability number as the friction angle is comparatively lesser. However, stability decrement of W80H compared to the NW80H shown in Figure 10 does not illustrate reasonable magnitude compared to the difference in friction angle of two material types. It implies that apart from the friction, other different properties of woven and nonwoven materials and processes influence the stability of the GSC.

6.6 Effect of the Inclination in GSC placement

According to the 'No Damage' stability curves for NW80H and NW80I shown in Figure 11, small stability increment can be observed for the inclined GSCs. However, increment is trivial for the 'Incipient Motion' curve. It indicates that GSCs in both orientations, motion commence at the same wave conditions.

If failure mechanism of sliding is considered, inclined GSC shows higher stability, as if it is to be detached, GSC should initially move upwards. Nevertheless, inclined GSCs are prone to failure through overturning than horizontally placed GSCs.

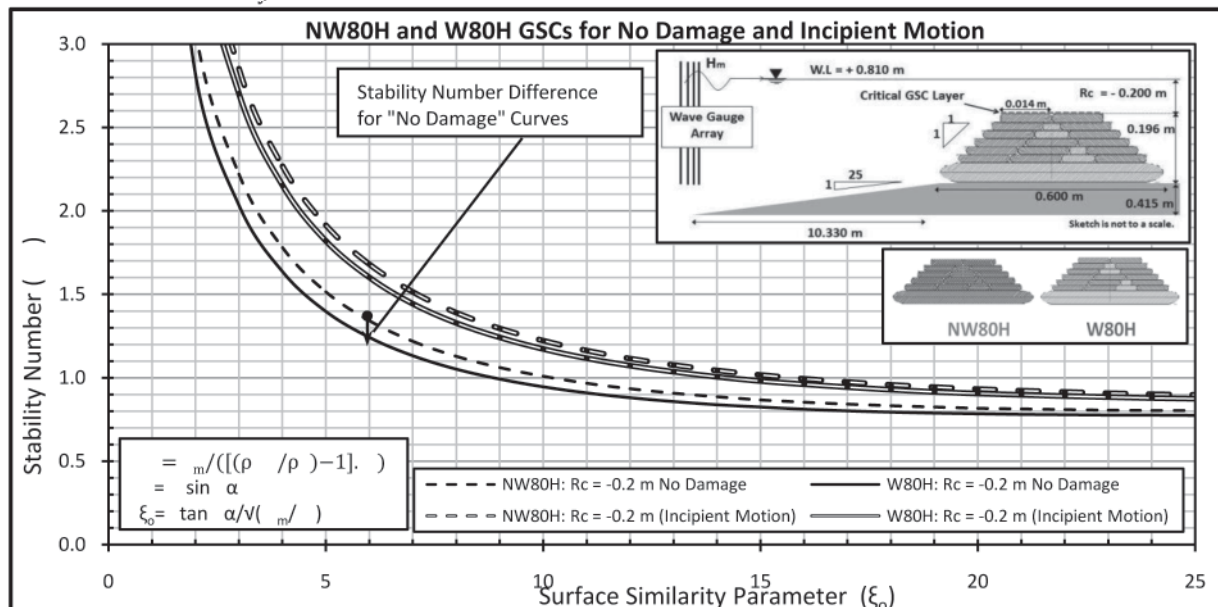


Figure 10 - Effect of the Geotextile Material - Stability Curves for NW80H and W80H

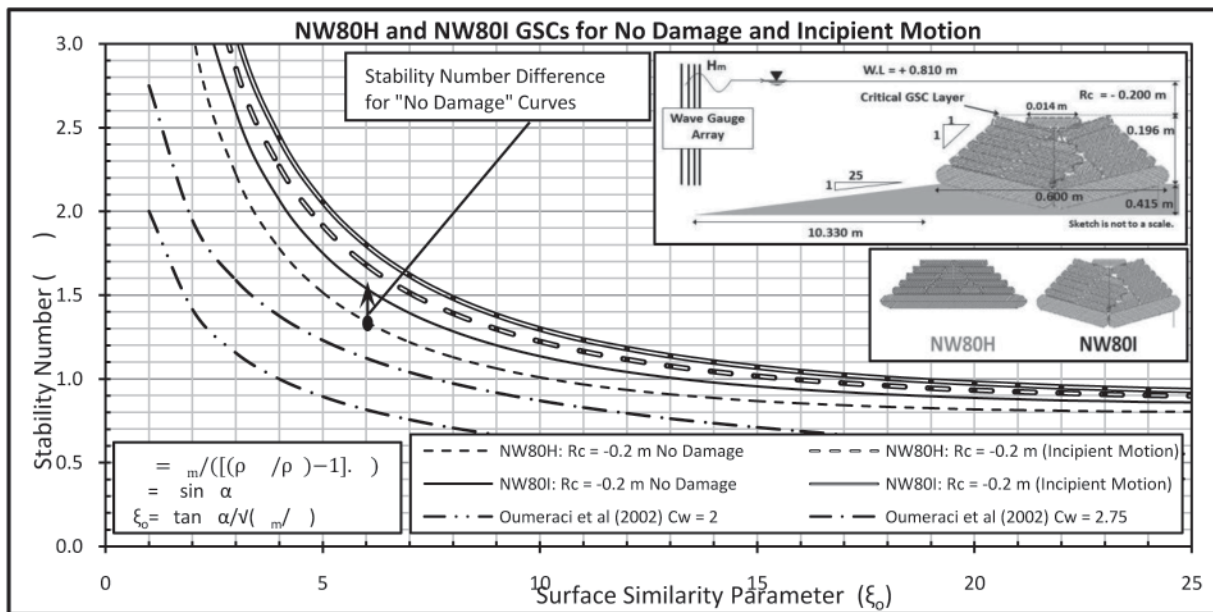


Figure 11 - Effect of the Inclination in GSC placement - Stability Curves for NW80H and NW80I

However, during the model tests, it was noted that GSCs in inclined orientation shows incipient motion for a considerable time before detachment, as GSC has to be moved upwards in order to detach from the structure. Therefore, progressive damage analysis was carried out with the purpose of investigating the effect of inclination during the period the damage progresses. Figure 12 shows the progress of the damage in horizontal and inclined GSCs with respect to number of waves during two tests with almost similar wave conditions. Progressive analysis results implies that though the 'Incipient motion' stability curves for NW80H and NW80I didn't show reasonable difference, inclined placement GSC resulted comparatively lesser damage. Moreover, incipient motion had taken place for a considerable duration before the GSC was detached.

7. Discussion

Figure 13 indicates that most influencing parameter for the stability of submerged GSC structure is the sand fill ratio and geotextile material is the least influencing parameter. Having higher sand fill ratio, GSC is more stable against sliding, overturning, uplift and drifting failure mechanisms. Apparently, higher permeability of the structure due to GSCs with higher sand fill ratio may also cause higher stability increment.

However, it implies that friction properties of the geotextile material is not significant in submerged conditions, as uplifting and drafting failure mechanisms were observed for nonwoven GSCs where friction doesn't account.

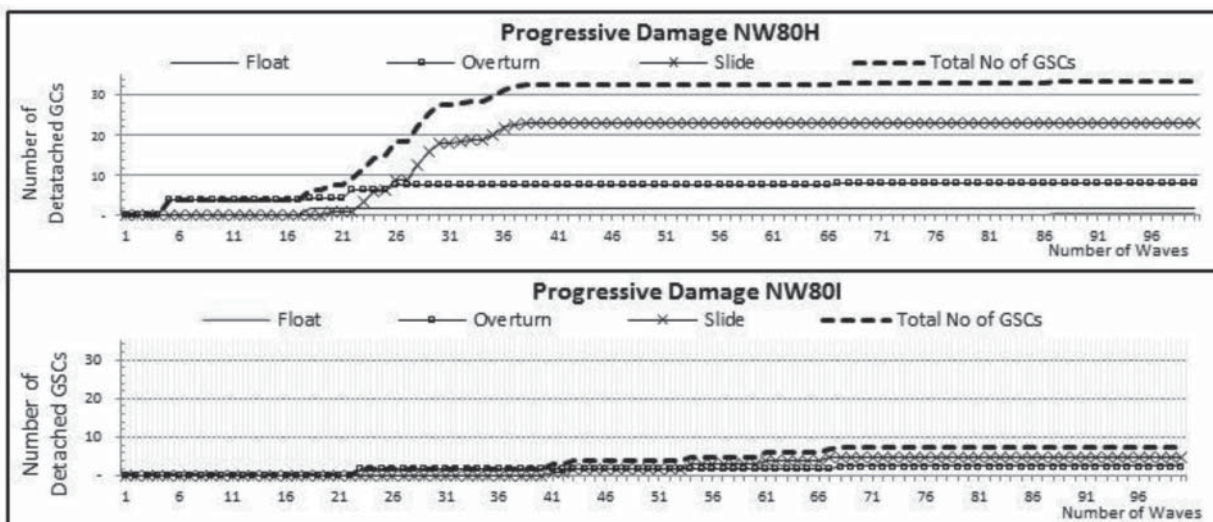
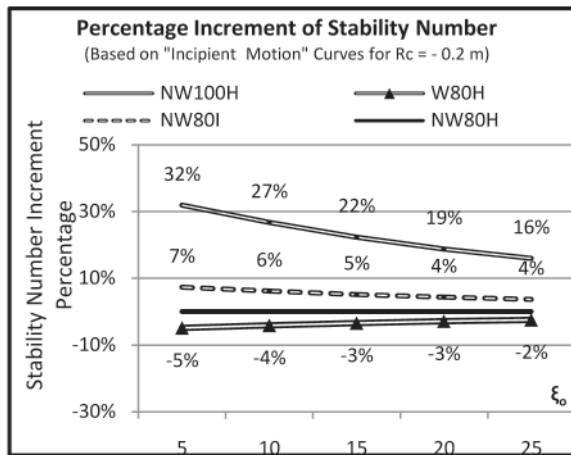


Figure 12 - Progressive Damage Analysis for NW80H and NW80I

Although the nonwoven material has a higher friction comparative to the woven material, nonwoven GSCs failed through other mechanisms rather than sliding. Further, it was observed that most of the woven GSCs failed through sliding and hardly uplift and drifting. Apart from the friction, other properties of geotextile material may effect on the stability, and that may result a small magnitude of stability decrement for the woven in comparison with nonwoven.



$$\text{Percentage Increment of Stability Number}_{(k)} = \frac{[\text{Stability Number}_{(k)} - \text{Stability Number}_{(NW80H)}] / \text{Stability Number}_{(NW80H)}}{k} \times 100\%$$

k = Test Series (Figure 1)

Figure 13 - Effect of geotextile material, fill ratio and inclination of GSC placement against hydraulic stability of submerged GSC Structure

Drag force: Due to the difference of material thickness in between nonwoven (1.2 mm) and woven (< 0.1 mm), height of the 80 % filled woven GSC was 4 mm lesser than the nonwoven GSC. As a result of the height difference, 6 layers of woven GSCs had to be used for W80H test series in order to achieve the same structure height gained for 5 layers of nonwoven GSCs during NW80H test series (Figure 1). Therefore, drag force acting on woven GSC is lesser than the nonwoven GSC, as the projected area perpendicular to wave direction in woven GSC is less. Having almost same length, width and weight with compared to nonwoven GSC, stability of the woven GSC may tend to indicate a higher value due to the fact that it undergoes less drag force.

Permeability: During the model test, it was observed that water flow through the woven material quicker than the nonwoven material. For instance, when a dry GSC is put in the water, woven GSC becomes saturated quicker

than the nonwoven GSC. Similarly, water drains off from woven GSC quickly which indicates that woven material has a comparatively higher permeability than the nonwoven material even though the permeability properties are not available from the woven manufacturer. Therefore, higher permeability might cause the woven GSC to be more stable.

Failure Mechanisms: Friction angle plays a role in stability of GSCs, if resisting force generated from the friction acts against the wave mobilising forces. For instance, sliding is the failure mechanism that would occur if friction between the surfaces is less. But for failure mechanisms such as overturn, uplift and drift, friction doesn't have unaffected. Further, failure mechanisms of uplift and drift were observed only for nonwoven GSC. Therefore, when failure mechanisms are considered, woven GSC has a higher tendency in failure through sliding.

Inclination in GSC placement shows higher influence than the material type. However, it was noted that incipient motion of both horizontal and incline placed GSCs will commence for same wave properties. Time taken for the detachment of inclined GSC was higher than the horizontal GSC. Moreover, severity of the damage was less for inclined GSCs when it was compared with horizontal GSCs for the same wave conditions.

8. Conclusions

1. The GSCs at the back row (leeward) of the crest layer in woven GSC structure have higher vulnerability in detachment compared to the nonwoven GSCs at the same position.
2. For the GSCs in submerged GSC structures, a failure mechanism of uplift and drifting was identified in addition to the overturning, and sliding. In uplift and drifting failure mechanism, friction of the GSC material does not account, but the weight of the GSC does due to the wave forces, GSC is uplifted and is floated in the water unlike in sliding failure.
3. Similar to the stability curves developed by Oumeraci et al. in 2002 for GSC revetments, a relationship between stability number and surface similarity parameter can be found for the submerged GSC structures as well. Further, it was concluded that stability curves developed as a relationship between stability number $[N_s]$ and surface similarity parameter $[\xi_0]$, should be specific for a freeboard

condition, otherwise soundness of the expression with respect to damage level is questionable

4. Among the influencing parameters, the sand fill ratio shows the highest relative importance towards the hydraulic stability of submerged GSC-structures. When the sand fill ratio is increased from 80 % to 100 % for nonwoven GSC structures with a freeboard of - 0.20 m, stability numbers were increased by 32 % ~ 16 % for the surface similarity parameters of 5 ~ 25.

5. The effect of the geotextile material towards the hydraulic stability of submerged GSC-structures is comparatively less though the difference of friction coefficient between the woven and nonwoven material were significant. The woven GSC resulted in a stability decrement of 5 % compared to the woven GSC when the surface similarity parameter was 5.

6. When the crest freeboard is - 0.20 m, inclined GSCs in submerged GSC-structures increase the hydraulic stability only by an average value of 5 % compared to horizontally placed GSC-structures.

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