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Investigation for the Process-Oriented Development of Stability Formulae for Structures made of Geotextile Sand Containers

Investigation for the Process-Oriented Development of Stability Formulae for Structures made of Geotextile Sand Containers

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I. INTRODUCTION

The hydraulic stability of geotextile sand containers (GSCs) subject to wave action has been studied within an ongoing extensive research program at Leichtweiß Institute on the use of geotextile structures for coastal structures, including artificial reefs, revetments, sea walls as well as dune reinforcement.

Although the effect of the deformations of the sand containers on the hydraulic stability is significant, no stability formula is available to account for those deformations. To achieve a better understanding of these processes and to analyze the influence of the deformation on the stability of GSC-coastal structure, large scale model tests have been performed which are being complemented by: (i) VOF-modeling (volume of fluid) to simulate the outer and inner wave-induced flow field, including the resulting loads on the containers (validation and verification provided by the experimental data) and (ii) a Finite Element and Discrete Element modeling (FEM-DEM) to simulate the deformations and displacements of the containers. The paper will primarily focus on the results from scale model tests, including: (i) wave-induced forces on the sand containers, (ii) internal movement of sand in the containers and its effect on the stability and (iii) underlying processes leading to the deformations and displacement of the containers. Based on the model test results a better understanding of the processes which affect the stability of the revetment has been achieved, including the effect of the deformations of the sand containers and their mutual interaction.

In this paper, it is shown that the deformations of the geotextile sand containers strongly influence the stability of a GSC-revetment. The final goal of the project is to develop a generic hydraulic stability formula taking into account the effect of the deformations and that can be applied to a class of protective structures such as seawalls, revetments, breakwaters as well as dune and beach reinforcement.

II. EXPERIMENTAL SET-UP AND PROCEDURE

The model tests have been performed in the wave flume of the Leichtweiss Institute for Hydraulic Engineering and Water resources (LWI). At one end waves were generated. At the other end a revetment made of geotextile sand containers was built (figure 1).

The 2m-wide flume was divided in two sections. In the first section at the glass window, PIV measurements of the wave-induced flow are performed using the large-scale PIV system proposed by Bleck and Oumeraci [1]. The main characteristics of the PIV set-up are summed up in figure 3. The general PIV characteristics consisted in a measurement area of 2 x 1 meters, ("PIV-section") lighted with halogen lamps and using seeding particles having approximately the same density as water. Using the common commercially available PIV system with laser-light only a "PIV-section" of 0.25m2 (instead of the 2m2 with white light) can be obtained.

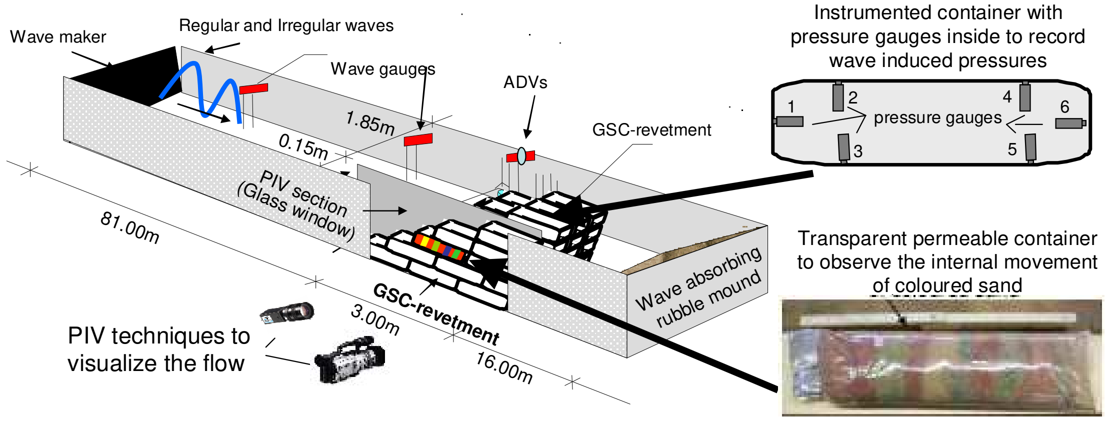

Figure 1: Experimental Set-Up

Inside the "PIV section", a single column GSC-revetment was installed (figure 2) and subjected to different wave conditions. Over the "PIV-section" two vibrating trays were constructed, from where the amount of seeding particles in the flow was controlled. To visualize the flow, the "PIV section" was illuminated using halogen lamps and the flow was recorded using a CCD-chip-camera (DMP-60-H13). This camera and the PIV section were covered with a black textile "tent" to avoid disturbance from other light (and noise) sources. After the images were recorded, the "DaVis PIV software" was used to process the velocity vectors.

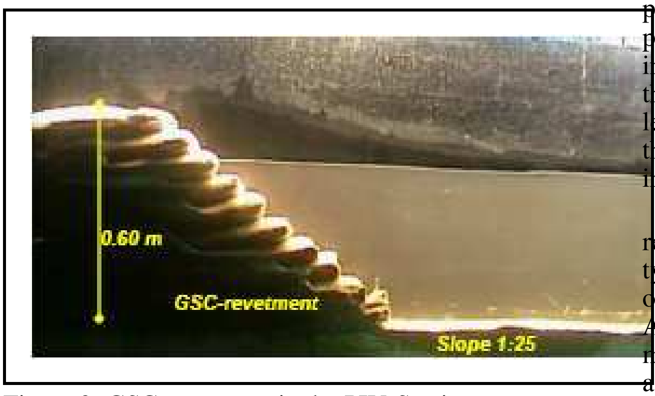

Figure 2: GSC-revetment in the PIV-Section

(a) PIV General Characteristics

- Measurement Area: 2.0 x 1.0m over a width of 0.15m (black training wall parallel to glass window)
- Seeding Particles: PA12 Mix with ρ_s=1.01t/m³, d_s=3mm(≅1.3 Pixel) and w_{S0}=4.9cm/s
- Lightening: White light (2 x 1500 W and 1 x 500 W)
- Time interval between PIV-Pictures: Δt=1/10s

(b) CCD-Camera Characteristics

Camera	The Imaging Source DMP 60H13
CCD-Chip	Sony ICX084AL: 1/3", 659x494 Pixel, Pixel size 7.4x7.4 µm
Sampling Frequency	30 Hz and 60 Hz
Scanning Mode	Interlaced or Progressive Scan
Shutter	Electronically: off ÷ 1/10,000 s
Amplification	0-25 dB
Lens	f_n = 4.8 mm k_n = 1.8-16

Figure 3: Main Characteristics of PIV-Set-Up According to Bleck and Oumeraci [1]

In addition, a permeable transparent container was filled with colored sand and placed within the revetment to investigate the sand movements inside the container. The sand movements were recorded using digital video cameras.

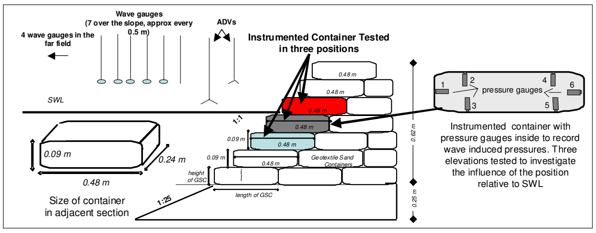

Figure 4: GSC-Revetment in the Wave-Flume (Adjacent to PIV Section)

In the other section, adjacent to the PIV section, pressure measurements on instrumented container are performed to record wave induced loads (figure 4). This instrumented container was laid at different elevations in the revetment to investigate the location of the still water level on the wave induced pressures. Then, by integrating the pressures around the containers, the total wave-induced forces and moments were derived.

Surface elevations were recorded in front of the revetment and along the flume using common resistance type wave gauges (figure 5). The gauges directly in front of the revetment were combined with pressure cells and ADV-probes (Acoustic Doppler Velocimeters) in order to measure the energy components simultaneously. In addition, ADV-probes were used to calibrate PIV-measurements. The revetment was also instrumented with four additional pressure gauges on its seaward face to record wave-induced pressure distribution. The GSC-revetment was subject to both regular and irregular wave trains with wave heights varying from 0.08 to 0.20 m and wave periods from 1.5 to 4 seconds by using three constant water depths (0.52, 0.61 and 0.70m).

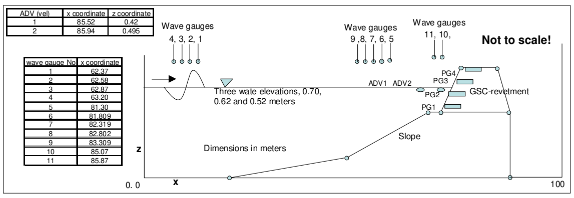

Figure 5: Location of the Measurement Devices

III. EXPERIMENTAL RESULTS

3.1 Wave Loading of Instrumented Sand Container

Among the three tested elevations of the instrumented container, the largest wave-induced pressures are recorded at the container placed just below the still water level (figure 6). For all three locations, the temporal development over each wave cycle of the pressure distribution around the container as well as the resulting wave-induced force and overturning moment have been determined, showing that the most critical situation for the hydraulic stability of the revetment clearly occurs during wave down rush (figures 6 and 7).

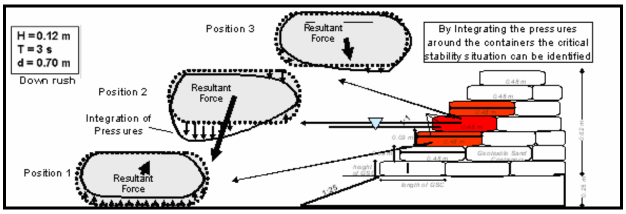

Figure 6: Wave Induced Pressures on Instrumented Sand Container

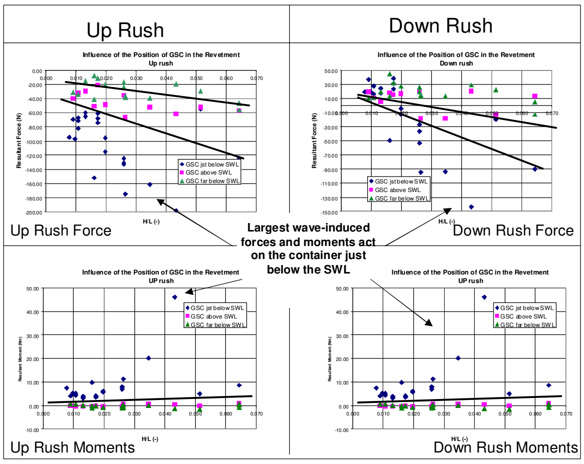

Figure 7: Total Forces and Moments Induced by Waves on the Instrumented Container at Three Tested Elevations

3.2 Wave-Induced Flow on GSC-Revetment

To get an insight into the coherent structure of the flow next to the revetment and to obtain pertinent data for validation of a VOF-model (Volume of Fluid) a PIV-technique was used.

The images obtained from the CCD camera where processed to get velocity vectors and from the images and flow vectors, global and local effects could be determined.

a) Global effects

For each model test, several waves were recorded and the velocity fields were obtained. The velocity fields as well as the visualization of the particles help to clarify the flow processes on the revetments. A better insight in these processes is achieved when the images are observed in rapid succession ("movie"). However, the photographs (figure 8) show clearly how the flow varies at every phase of the wave cycle. It was found that the flow in front of the revetment is initially orbital (induced by wave motion). During up and down rush, it was observed that the flow consists in a main flow running up/down and in local flows that are "trapped" between the containers (see next section "local effects" for details). The velocity vectors of the main flow are approximately parallel to the revetment slope. During up rush an "uplift" deformation of the containers is induced. During down rush, the velocity vectors of the main flow will increase the return of the up-lifted part to a "normal" position and will also induce a seaward force on the containers.

Under breaking waves the containers behave as flexible structures. They are uplifted and deformed at the front part by the impact of the breaking waves. The entire wave breaking process (figure 10) was recorded by PIV-techniques. However, after breaking, clear velocity vectors could be hardly obtained due to the extremely strong vortices and turbulence.

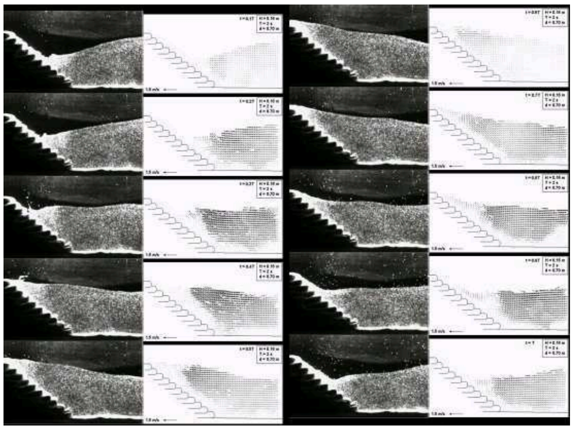

Figure 8: Flow Visualization for a Wave Cycle (H=0.16m, T= 2s) with Between Successive Images

b) Local effects

Among the local effects at the revetment vortex generation was also investigated. During wave action two different types of vortices were observed:

(i) Well structured vortices. The motion is characterized by fluid particles moving around a common centre. These vortices are generated during up and down rush and appear in the areas between containers. These vortices may affect the stability of the structure by applying a small rotational force on the container. (figure 9).

(ii) Non-structured vortices. They occur during up rush induced by higher waves (higher than 0.12m) which break before reaching the revetment (figure 11).

Figure 9: Vortices Appearance During Wave Up and Down Rush

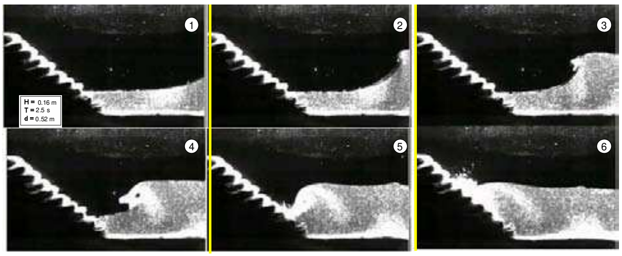

Figure 10: Breaking Waves Recorded with PIV-Techniques

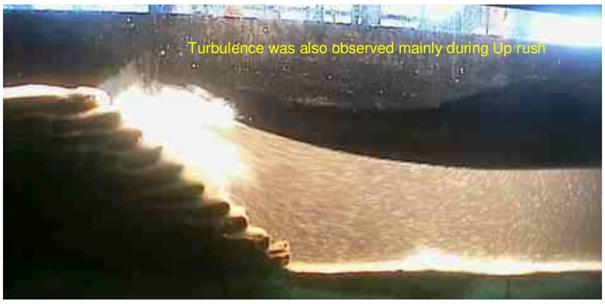

Figure 11: Turbulence During Wave Up and Down Rush of High Waves

3.3 Internal Sand Movement in the Container

The internal movement of sand inside the containers was based on the video records investigated. The observations of the colored sand in the transparent container subject to wave attack have shown that (figure 12):

a) Similar pattern of the sand motion occur for different wave conditions. As expected, noticeable movements of sand are only induced by larger incident waves.

b) The largest sand movements occur during the first 30 wave cycles which then rapidly decrease. This means that the sand fill re-accommodates due to the wave induced forces on the container.

c) During wave up rush the dominant sand movement is rather rotational and directed upward (figure 12a).

d) During wave down rush the movement is essentially translatory rotational and directed seaward (figure 12b). At this stage, a displacement of the container occurs as soon as a certain critical wave height is exceeded.

e) After some wave cycles, the sand accumulates at the seaward end of the container causing a deformation of the latter and reducing the contact areas with neighboring containers (figure 12c). These conditions prevails as long as no further horizontal displacement of the container occurs, internal movements of sand are triggered by an incremental horizontal displacement of the container. These movements of sand occur because the contact areas of the GSC with the neighboring containers are reduced. As a result, the entire process of sand movement will again repeat itself in a similar way as during the first wave cycles (figure 12d).

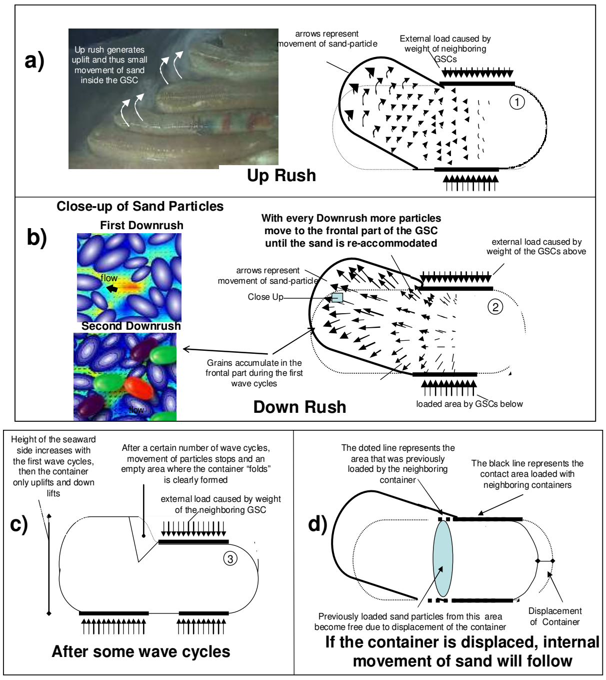

Figure 12: Internal Movement of Sand in a GSC During Wave Action

3.4 Effect of Internal Sand Movement on the Stability of the Geotextile Sand Container

During the model tests the effect of sand movement inside the container on the stability of GSC-revetments was investigated.

To understand the effect of the internal movement of the sand fill on the hydraulic stability of GSC, it is necessary to consider the force balance on the container (figure 13).

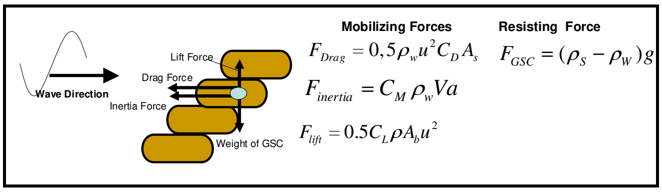

Figure 13: Force Balance on a GSC

The hydraulic loading (mobilizing forces) due to wave action on the revetment can be defined as:

Drag force: $$F_D = 0,5\rho_w u^2 C_D A_s \qquad (1)$$

Inertia force: $$F_M = \rho_w \frac{\partial u}{\partial t} C_D V_{GSC} \qquad (2)$$

Lift force: $$F_L = 0,5\rho_w u^2 C_L A_T \qquad (3)$$

where:

FD is the drag force, Fm is the inertia force, FL is the lift force, the density of water, CD, CL and CM are empirical coefficients, u the wave-induced horizontal particle velocity, $\frac{\partial u}{\partial t}$ is the associated horizontal particle acceleration, is the volume of the container, AS the projected area of the containers normal to the wave direction and AT is projected area in wave direction (figure 14).

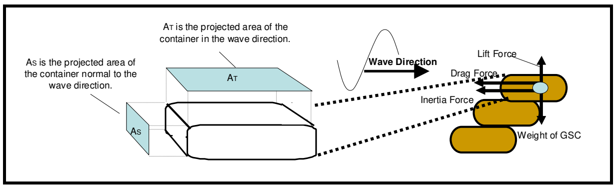

Figure 14: Definition of Projected Areas AS and AT of a GSC

The resisting force of the submerged container can be defined as:

Resisting Force: $F_{GSC} = (\rho_S - \rho_W) g V_{GSC}$ (4)

where:

ρ_s is defined as the density of sand, g is the gravity and V_{GSC} is the volume of the container.

Depending on the way the containers are placed on a coastal structure, on the geometry and on the hydrodynamic processes acting on the containers two kinds of displacements are possible. The container can either slide or overturn.

a) Sliding

The condition of stability against sliding of the container can be described as (figure 15):

$$\mu\left[F_{GSC} - F_L\right] < F_D + F_M \qquad (5)$$

where μ is the friction coefficient between containers

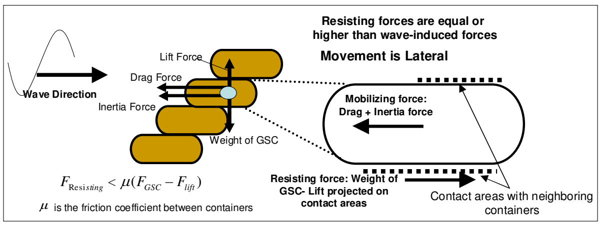

Figure 15: Stability of a GSC Against Sliding

When internal movement of sand in the container occurs, the frontal part of the container will increase while the rear part will decreased. This means that the projected areas (AS and AT) will change. If we recall equations 1 and 2, the mobilizing forces FD and FL which are a function of the projected areas will increased. Now, if the deformed container is uplifted, the contact areas with the neighboring containers are smaller than before sand movements leading to a reduction of the resisting forces. Thus, the stability of the container is reduced by the internal movement of sand (figure 16).

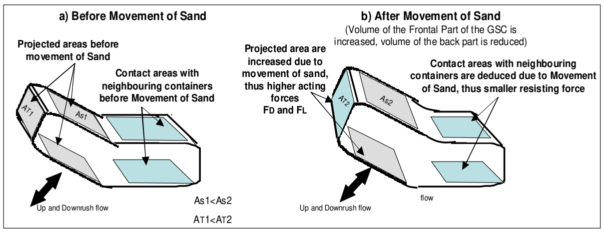

Figure 16: Effect of the Movement of Sand on the Stability of a GSC (Sliding Displacement of GSC)

b) Overturning

The condition of stability against overturning of the container can be described by the relation (figure 17):

Resisting Moments > Mobilizing Moments

$$F_{GSC} \cdot r \geq (F_D + F_M)m + F_L \cdot r \qquad (6)$$

where r is the horizontal projection of the distance between the centre of gravity of the container and the rotation point and m is the vertical projection of the distance between the centre of gravity of the container and the rotation point.

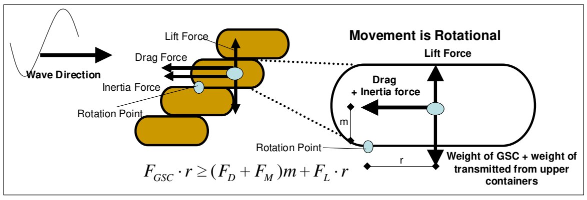

Figure 17: Stability of a GSC Against Overturning

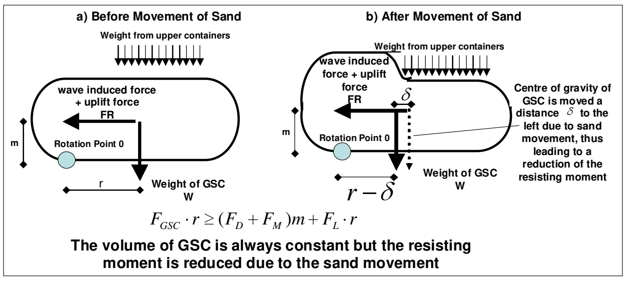

Figure 18: Effect of the Movement of Sand on the Stability of a GSC (Overturning Displacement of GSC)

When the movement of sand in the container occurs, the centre of gravity of the container will move seaward due to the fact that the frontal part of the container will be heavier (accumulation of sand in the frontal part) than before the sand movement started. This means, the resisting moment of the container decreases (due to the fact that centre of gravity has moved a distance) and thus the stability of the container is also reduced (figure 18).

3.5 Variation of the Contact Areas During Wave Action

During the model tests, the variation of the contact areas among neighboring containers was observed during wave action. It was seen that the contact areas among neighboring containers are reduced due to the uplifting of containers. Recalling that the resisting force of GSC is the weight projected on the contact area, a reduction of these contact areas will thus reduce the stability of the revetment (figure 19).

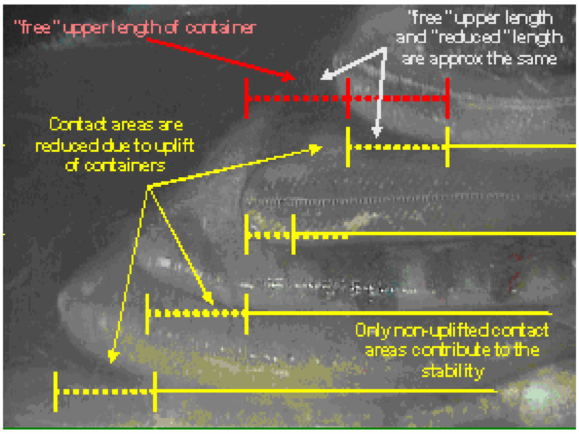

Figure 19: Variation of the Contact Areas Between Neighboring Containers

3.6 Effect of the Deformation on the Stability of a GSC-Revetment

The experimental results have shown that the deformation of the containers strongly affects the hydraulic stability of the revetment.

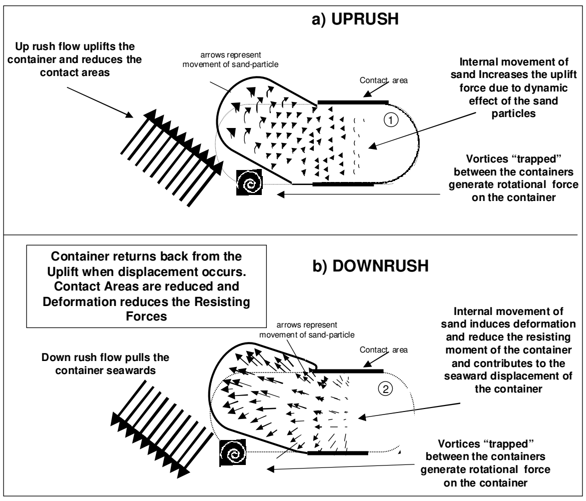

Figure 20: Influence of the Deformation on the Stability of the Container

During up rush the wave-induced flow uplifts the frontal part of the containers (figure 20a). Moreover the local vortex flow between the containers induces an overturning moment on the container. Uplift of the containers reduces the contact areas and thus the stabilizing forces.

During down rush (figure 20b), the uplifted container returns down, while its contact areas are still reduced and the internal movement of sand has reduced its contact areas and resisting moment. The return flow in front and behind the container induces seaward forces, resulting in a critical situation for the stability of the containers (figure 21).

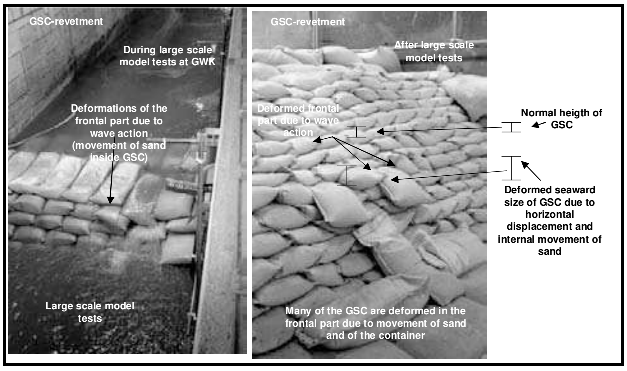

Figure 21: Displacement of Containers Observed During the Large-Scale Model Tests

3.7 Types of Displacements of a GSC in the Revetment

From the model tests two types of displacements of the slope containers were recorded:

a) When the wave height is large enough to induce displacement of the loaded container, the displacement of the container is rather rotational in the upward direction.

b) The most common displacement of a GSC occurs during down rush, when the uplifted container is released at maximum run up level. This displacement is progressive and only becomes noticeable after several wave cycles (for example, with a wave height of 0.12m and period of 3 seconds, a displacement of couple of centimeters was recorded after approx. 100 wave cycles).

IV. CONCLUDING REMARKS

Based on (i) the detailed measurements of wave-induced loads on the instrumented sand container, (ii) on the PIV-measurements of the flow field in front of the GSC-revetment, and (iii) the video observations of the internal movement of colored sand in a transparent container, a much better understanding of the processes which affect the hydraulic stability of the revetment has been achieved, including the effect of the deformation of the sand containers and their mutual interaction. With this understanding it can tentatively be concluded that:

a) The most critical location on the seaward slope with respect to the hydraulic stability is for the containers located just below the still water level;

b) The most critical phase for the stability of the revetment occurs during wave down rush;

c) The deformation of the container strongly affects the stability of GSC-revetments. Deformation reduces the resisting contact areas and thus the resisting forces on the containers;

d) The internal movement of sand inside the container induces deformation of the container and therefore substantially affects the stability of the revetment;

e) Breaking waves are not as critical as originally expected for the hydraulic stability of GSC-revetments

The experimental results will be used for the validation of a VOF-model and an FEM-DEM model, which will be run to further improve the understanding of the aforementioned processes. This improved understanding will then allow to develop HUDSON-like stability formulae that can be applied to GSC-made seawalls, revetments and reefs and scour protection systems, but additionally including the effect of the deformation of the sand containers and further related effects. This is the ultimate objective of the PhD-Thesis of the first author which is to be completed in March 2007.

ACKNOWLEDGMENT

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REFERENCES

[1] Bleck, M. and Oumeraci, H. 2004. Hydraulic Performance of Artificial Reefs: Global and Local Description, Proceedings of the 28th ICCE 2002, pp. 1778-1790, Cardiff, Wales

[2] Dean, R. G., and Dalrymple R. A. 1998 Water Wave Mechanics for Engineers and Scientists. World Scientific, Advanced Series on Ocean Engineering, Singapore.

[3] Fuerboeter, A, 1991, A.: Wave Loads on Sea Dykes. In: M.B. Abbott and W.A. Price Coastal, Estuarial and Port Engineer's.

[4] Marth R., Mueller G and Wolters G, 2005. Damages of blockwork coastal structures due to internal wave impact induced pressures, Proceedings of the International Coastal Symposium, Ireland 2005 (in print)

[5] Oumeraci H.; Hinz, 2004 M.: Geotextile sand-filled container as innovative measures for shore protection, Technical paper, Proc. EuroGeo 2004, Vol 1, p. 175-180.

[6] Oumeraci, H.: Review and Analysis of Vertical Breakwater Failures - Lessons learned. Coastal Engineering, Special Issue on "Vertical Breakwaters", Amsterdam, The Netherlands: Elsevier Science Publishers B.V., vol. 22, nos. 1/2, pp 3- 29

[7] Recio J. and Oumeraci H. 2005 Analyse der Stabilitätsgefährdenden Prozesse von Deckwerken aus Geotextilen Sandcontainer, 5.FZK Kolloquium „Seegang, Küstenschutz und Offshorebauwerke“ Hannover, pp 83-87.

[8] Recio J. and Oumeraci H. 2005b Processes Affecting the Stability of revetments made with geotextile Sand Containers. International Conference of Coastal Engineering, ICCE 2006, (Abstract submitted)

[9] Recio J. and Oumeraci H. 2005c, Experimental Results obtained from Model Tests, Wave-induced Forces, PIV visualization and Internal Movement of Sand of a Revetment made with Geotextile Sand Containers, Leichtweiß Institute for Hydraulic Engineering, Progress Report

[10] Roeckelein S., 2004. Erosion of blockwork coastal structures and rock cliffs. Master Thesis, Queen’s University Belfast/University of Kalsruhe

[11] Wouters, J. (1998) Open Taludbekledingen; stabiliteit van geosystems (Stability of Geosystems) Deftt Hydraulics Report H1930, Annex 7 (in Dutch).

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