Large scale physical model tests on the stability of geocontainers

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Report

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| Within geosys geocor Cluste scale. materi This ra investi geocor It appo mecha is lowa Migrat Above caused It is cor recom leads t The ap < 1.1 r | Abstract: Within the framework of the Delft Cluster project Geosystemen, WP4c: "Flexible coastal defence systems with geosystems", which is part of the workpackage 4: "Morfodynamics of the North sea and Coast", the stability of geocontainers on a slope under wave attack is studied by performing physical model tests. This is performed within the Delft Cluster project "Sustainable development of North sea and coast". The tests have been performed with dimensions on a 1:4 scale. Geocontainers are of special interest since it may be a good and in some cases a cheaper alternative for conventional materials used in breakwaters or shore protections such as rock or concrete. This report describes the tests performed in the Delta Flume of WL[Delft Hydraulics and analyses the results of this investigation. Main objective of this report is to determine the stability of the structure and the migration of sand in the geocontainers to derive recommendations for the range of applications. It appeared that besides sliding, the caterpillar mechanism of a geocontainer is a significant mechanism. This caterpillar mechanism is caused by the migration of sand in the geocontainers. The stability of the geocontainers in the performed tests is lower than the stability determined in other (smaller) scale model tests. This can be explained by the fact that the migration of the sand is better modelled in the Delta Flume than in the small scale models. Above the geocontainers that formed a berm with a width of approximately 6 m, a smooth 1:3 slope was present. This slope caused a severe wave rush-down which probably has influenced in a negative way the stability of the geocontainers. It is concluded that the stability of geocontainers is, due to the migration of sand, lower than presumed before. Therefore it is recommended to reckon with the migration of sand since this causes the caterpillar mechanism of the geocontainers, which leads to a lower stability. The application of geocontainers is limited to areas with low | | | | | | | |
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List of symbols

| Symbol | Unit | Description |
|-----------------------------------|--------------------|--|
| h m | | width of the geocontainers (parallel to the wave attack, see |
| D | 111 | also figure 20) |
| C_{u} | - | uniformity coefficient (D_{60}/D_{10}) |
| D | m | average thickness of the geocontainers |
| Δ | | sievesize of the theoretical sieve with rectangular openings |
| $D_{\rm x}$ | | where x % of the grains of the sand passes through |
| $F_{ m walls}$ | N | total force on the flume walls |
| $F_{ m bottom}$ | N | total force on the flume bottom |
| g | m/s^2 | acceleration due to gravity |
| $h_{ m c}$ | m | water leve above the crest of the geocontainers |
| $H_{ m m0}$ | m | spectral significant wave height, $H_{\rm m0} = 4\sqrt{m_0}$ |
| $H_{\rm max}$ | m | the maximum measured wave height in the wave record |
| $H_{\rm s}$ | m | significant wave height |
| k | m/s | permeability coefficient |
| Κ | | ratio of horizontal and vertical pore pressure |
| L | m | length of the geocontainer (perpendicular to wave attack) |
| m_0 | m^2 | zeroth moment of wave spectrum |
| n | - | scale |
| Ν | - | number of waves |
| | | opening size of the geotextile corresponding to the diameter |
| 0 | | of the largest particles that can pass through the geotextile. |
| <i>U</i> _n | | $O_{\rm n}$ corresponds to the $d_{\rm n}$ of the soil passing through the |
| | | geotextile. |
| P | m | crest height of the stack of geocontainers (positive above |
| Λ_c | 111 | water level) |
| $R_{ m d2\%}$ | m | wave run-down level exceeded by only 2% of the waves |
| R | | wave run-down level where influence of wave forces is |
| N influence, wave run-down | | significant |
| <i>S</i> _{0,p} | - | wave steepness based on the wave peak period |
| S(f) | m ² /Hz | variance spectral density |
| T | s | peak period, the wave period corresponding to the peak of |
| Гр | 3 | the variance spectral density |
| 11 . | | critical velocity outside the geocontainer with respect to the |
| <i>u</i> _{crit,cp} | | start of sand movement inside the geocontainer |
| | | |
| α_{cb} | - | influence factor cross-bracing mechanism |
| γ | kN/m ³ | specific weight |
| Δ | - | relative density of the geocontainers $\Delta = (\rho_{sand} - \rho_{water})/\rho_{water}$ |
| ξ_p | | breaker parameter defined as $\tan \alpha / \sqrt{s_{0,p}}$ |
| $\sigma'_{ m h}$ | N/m ² | horizontal grain stress |
| σ'_{v} | N/m ² | vertical grain stress |
| ρ | kg/m ³ | density |
| ρ_{sand} | kg/m ³ | density of saturated sand |

I Introduction

I.I General

Within the framework of the workpackage 4c: "Flexible coastal defence with geosystems", which is part of the workpackage 4: "Morfodynamics of the North Sea and coast" several problems are formulated with respect to the application and design of Geosystems. This is performed within the Delft Cluster project "Sustainable development of North sea and coastal zone". The formulated problems are:

- 1. Stability of geocontainers under wave attack and/ or currents.
- 2. Positioning accuracy of geocontainers.
- 3. Required strength of the geotextile during the placement of geocontainers.
- 4. Sustainability of geocontainers with respect to UV load, ageing process and mechanical loads.

The first subject is suitable for research in Delft Cluster 2. Taking in mind that wave loads are a larger problem with respect to the stability than currents, the former is selected for research.

The second and third topic have been investigated in Delft Cluster 1. This resulted in an improvement of knowledge. The main goal in the long run, providing a thorough insight in the risks of applying geocontainers, can be realised by backing up the research with practical experience and scale model tests. The costs of these are however too much to include in Delft Cluster 2.

UV loads and ageing processes of geotextile are subjects in the domain of the manufacturers of geotextiles.

Therefore, it is decided, in close cooperation with the Centre for Civile Engineering Research and Codes (CUR), to focus on the stability of geocontainers under wave attack.

This report describes and analyses the large scale model tests which have been executed to determine the stability of geocontainers.

The physical model tests were performed in the Delta Flume of WL|Delft Hydraulics under supervision of ir. M. Klein Breteler (Deltares) and ir. P. van Steeg (Deltares). This report is written by ir. P. van Steeg with contributions of ir. M. Klein Breteler and is reviewed by ir. A. Bezuijen (Deltares). During the whole project the CUR gave feedback on the project.

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| | | |

The geocontainers and geotextile used in this research are supplied by Ten Cate Geosynthetics. A DVD with an impression of the performed tests is enclosed with this report.

I.2 Objective

The main objective is to determine the stability of geocontainers and the migration of sand in the geocontainers during wave attack, to establish recommendations for the applicability of geocontainers.

I.3 Outline

The set-up of the physical model investigations is described in chapter 2. In chaper 3 the results of the tests are given (section 3.1) and the tests are described (section 3.2). Besides this, an analysis of the failure mechanisms is given (section 3.3), possible model effects (section 3.4) and scale effects (section 3.5) are discussed and a comparison with the results of earlier investigations is carried out (section 3.6). Conclusions and recommendations are given in chapter 4.

Allthough the tests have been carried out with geocontainers with dimensions on scale 1:4, all results and measurements are given on model scale.

2 Model set-up

2.1 General

This chapter describes the physical model tests that have been executed in the WL|Delft Hydraulic testing facility 'The Delta Flume'. This chapter describes the applied cross-sections, the lay out of the used geocontainers and the hydraulic test conditions. Besides this, the test program is given, the test facility is described and an overview of the measurements is given.

2.2 Application of geocontainers

The design of a model requires insight into a prototype. Therefore, this section gives a background on the application of geocontainers.

The application of geocontainers is described extensively in CUR (2004) and CUR (2006).

Geocontainers are built with the use of split barges. At high water the geocontainers are dumped on a stack. The stability of geocontainers is at interest at high water ($h_c/H_s = 0.5$ -1.0) as well as during low water ($h_c/H_s = 0.0.5$). h_c represents the water level above the crest of the geocontainers and H_s is the significant wave height.

Geocontainers can be used for several applications. Three possible applications for the use of geocontainers are given below.

2.2.1 Supporting berm for dikes

At a dike or dam, which is attacked by currents or waves, a supporting berm can be created by the use of geotextile containers. During construction this prevents the sand fill to wash into the sea. By applying this supporting berm, sliding down of the dike or dam is prevented and the dike or dam is protected against erosion.



Figure 1: Geocontainers used as a supporting berm for dikes (prototype)

2.2.2 Core material for breakwaters

Geotextile containers can be used for the construction of breakwaters in areas where rock material is not locally available.



Figure 2: Geocontainers used as core material for breakwaters (prototype)

2.2.3 Dams

In the cross-section of a dam, geotextile containers can be used for the outer layers. Since it is possible to build steeper slope with this technique, the amount of sand and rock required is limited.



Figure 3: Geocontainers used for the stability of dams (prototype)

2.2.4 Selection of prototype for modelling

Since it is not possible due to budget limitations to test all configurations of geocontainers, there is a need to select one specific configuration. However, it should be realised that the results of this configuration cannot automatically be ascribed to all configurations.

It is chosen to test the configuration where geocontainers are used as a supporting berm (Figure 1). This configuration is chosen since it is expected that this configuration will be applied relatively often in prototype situations. A 1:3 smooth slope was already present in the Delta Flume and is used as part of the construction. Due to the presence of this slope, this configuration is relatively easy to construct and therefore meets the budget criteria.

2.3 Test facility

The physical model tests were carried out in WL|Delft Hydraulics 'The Delta Flume'. The width of the flume is 5 m, the height 7 m and the overall length is 240 m.

Waves as described in section 2.6 were generated at the wave board. Active re-reflection compensation was used to compensate for waves that reflect from the structure. Second order steering was applied to allow for compensation of second order effects of the first higher and first lower harmonics of the waves. In this way waves are generated that resemble natural waves very closely. This system has been validated and applied in a large number of experimental investigations. An impression of the Delta Flume is given in Photo 2.5.

2.4 Cross-sections

The stability of geocontainers is of interest at high water as well as at low water. Therefore, two types of cross-sections were tested. One cross-section where the crest is placed around $0.75 H_s$ below sea-level and one cross-section where the crest is placed at the sea-level. Schematizations of the test configurations are shown in Figure 4 and Figure 5.



Figure 4: Testseries 1, high waterlevel



Figure 5: Testseries 2, low waterlevel

In both cross-sections, the structure is placed on a 1:3 slope. This slope was already present in the Delta Flume. One layer of geocontainers is placed on top of the 'filling' containers. These filling containers were placed on the 1:3 slope. Filling container C, D, E and F are attached to the smooth slope with an extra layer of geotextile which is wrapped around the containers. The outer slope of the geocontainers has a slope of 1:2.

Since the waterlevel at test series 1 is relative to the significant wave height H_s , the water level is adapted after every test. The model set up of test series 1 is shown in Photo 3.1 (Appendix C). The model set up of test series 2 is shown in Photo 3.3 (Appendix C). (The lowest geocontainer is not visible at this picture).

2.5 Geocontainers

2.5.1 Dimensions

The size of the geocontainers is chosen in such a way that the wave machine is capable of creating waves, with a sufficient height to create damage to the structure. To estimate the wave height which causes damage, an investigation to other scale model tests is executed. A summary is given in Appendix G. This study indicates that not only the average thickness D, but also the width of the geocontainers b, is important regarding the stability. Therefore the used stability number is $H_s/(\Delta \sqrt{(bD)})$ where $\Delta \approx 1$. The studied tests indicate instability for a stability number of 1.0-1.4. Given the maximum possible wave height in the Delta Flume of approximately $H_s = 1.6$ m and a ratio of b/D = 5 the size of the geocontainers is determined:

| Width of the geocontainers: | b | = 2.75 m |
|---|---|----------|
| Average thickness of the geocontainers: | D | = 0.55 m |

By determining the model dimensions the scale of the geocontainers can be determined. Since the prototype thickness of geocontainers is 1.5 - 2.2 m the scale of the model is around 1:4 (applying large geocontainers in prototype).

2.5.2 Used materials

Since the model and the prototype are not on the same scale, it is not possible to use geotextile which is used in prototype. A scale effect would be the inflexibility and the tensile stenght of the geotextile. Applying proper scaling rules would result into an impractible non-existing geotextile. (at a geometric scale of 1:4, the tensile force is 1:16). Therefore, a choice is made for a thinner geotextile which is more flexible.

The geotextile used for the model is Geolon[®] P180L and is fabricated by Ten Cate. Specifications of the geotextile used are given in Appendix D.

Requirements regarding sand tightness of the geotextile, which are based on CUR (2006) are:

• $O_{90} \leq D_{90}$ and

• $O_{90} < 1.5 D_{10} C_{\rm u}^{1/2}$

Where

- O_{90} = the opening size which corresponds to the d_{90} of the soil passing the geotextile
- D_x = Sieveseize of the theoretical sieve with rectangular openings where x % of the grains of the sand passes through
- $C_{\rm u} =$ uniformity coefficient (D_{60}/D_{10})

A sieving curve of the used sand is given in Appendix B: Figure B.2. This sieving curve is based on two samples. With $D_{90} = 0.27$ mm and $O_{90} = 0.17$ mm these requirements are met. Nevertheless, in theory approximately 27% of the grains (by weight) can pass the openings in the geotextile.

2.5.3 Construction

The geocontainers are filled with sand at the construction site. (Photo 2.1, Appendix C). The sand is compacted with the use of a compacting machine. (Photo 2.2, Appendix C). The geocontainers were closed off by using a sewing machine. (Photo 2.3, Appendix C). The sewing machines were made available by Ten Cate.

One of the requirements is that the geotextile in the model is tight around the sand since this is also the case in the prototype. This is a result of the dumping of the geocontainer since the impact on the sea bottom reshapes the geocontainer in such a way that the geotextile is expected to be tight around the body of sand. This requirement is met by using the compacting machine again after closing the geocontainers. This compacting reshaped the geocontainer in such a way that the geotextile was tight around the body of sand. In other words, spaces between the sand and the geotextiles are minimized. Reference is made to Photo 2.4 in Appendix C.

2.6 Hydraulic conditions

Several hydraulic conditions were tested at the two test series. An overview of the hydraulic conditions is given in Appendix A, Table A.1. The wave conditions are specified by a wave height, H_s (m), and a wave peak period, T_p (s). The water level is specified in metres relative to the bottom of the flume. The test duration is given as a number of waves, N (-). For all tests irregular waves (Jonswap spectrum with a peak enhancement factor of 3.3) with a wave steepness, $s_{0,p}$, of 3% were used which is characteristic for the wave conditions of a natural sea-state.

2.7 Test program

The test program consists of three sub programs:

1. Test series 1: High water level: $h_c/H_s = 0.75$; reference is made to Figure 4

- 2. Test series 2: Low water level: $h_c/H_s = 0$; reference is made to Figure 5 for an illustration of the model set-up
- 3. Test series 3. Reference is made to Figure 5 for an illustration of the model set-up. Test series 3 is comparable with Test series 2. It consists of only one test. In this test two cuts are made in the geotextile to analyse the consequences of damage to the geotextile. The locations of the cuts are indicated in Figure 6.



Figure 6: Locations of cuts applied in testseries 3 (front view)

In testseries 1 and 2 several tests are planned. A start is made with small waves. Every test the wave height will increase untill damage occurs.

2.8 Measurements

During the tests four types of measurements were carried out:

- Wave measurements
- Profile of the structure
- Registration of water velocities in the geocontainer with the use of EMF measurements
- Sand characteristics

These measurements will be described in more detail below.

2.8.1 Wave measurements

The wave characteristics were measured by means of three wave gauges in front of the structure. Each wave gauge is a pair of vertical wires which measures the surface elevation on a fixed location. To separate the incident and reflected waves a cross-correlation technique was used as described by Mansard and Funke (1980). The signals from the three wave gauges were used to determine the following wave characteristics of the incoming waves:

- the variance spectral density or the S(f) (m²/Hz)
- the peak period T_p (s), the wave period corresponding to the peak of the variance spectral density
- the wave height exceedance curves
- the significant wave height H_s (m), based on the spectrum

• the maximum measured wave height H_{max} in the wave record.

2.8.2 Profile of the structure

The profile of the structure is determined with a profiler. This profiler is a small wheel that follows the structure and can determine the profile of the structure very accurately (\sim 1mm). The profiler is used before a test serie and after each test. The profiler is used at four different lines perpendicular to the structure. The distance between each line is 1 meter. An illustration of the position of the profile lines is given in Figure 7.



Figure 7: position of profile lines (top view)

2.8.3 Registration of water movement in the sand pores with the use of EMF measurements

Sand movement in the Geocontainers is determined by measuring the water movement in the pores. To investigate whether water movement in the pores of the sand in the geocontainers occurs, 6 EMF measuring instruments are used. These instruments measure the water velocity between the pores of the sand in the geocontainers. The location of the EMF instruments in the geocontainers is shown in Appendix B, Figure B.1.

2.8.4 Sand characteristics

A penetrologger is used to investigate geotechnical aspects of the sand. A penetrologger measures the resistance of the sand while pressing a cone through the sand. During the measurements a water layer of 5 cm was on the geocontainer. An overview of the sample locations is given in Appendix A, Table A.5. For each location, three measurement are performed. The measurements of the three samples are averaged.

3 Analysis of test results

3.1 Test results

All test results are shown in tables and figures in specific appendices. An overview of the location in this report where the test results can be found is given in Table 1.

| results | specification | Table / Figure | |
|---------------------------------|------------------------|-----------------------------|--|
| | wave parameters | Appendix A: Table A.1 | |
| measured wave conditions | exceedance curves | Appendix B: Figure B.3 | |
| | energy density spectra | Appendix B: Figure B.3 | |
| | observed damage | Appendix A: Table A.1 | |
| damage | stability parameter | Appendix A: Table A.1 | |
| | displacement of GC's | Appendix A: Table A.2 / A.3 | |
| | test series 1 | Appendix B: Figure B.4 | |
| profile measurements | test series 2 | Appendix B: Figure B.5 | |
| | test series 3 | Appendix B: Figure B.6 | |
| EME measurements | description | Appendix A: Table A.4 | |
| Elvir [*] measurements | measured velocities | Appendix B: Figure B.1 | |
| papatrologger | measured values | Appendix B: Figure B.7 | |
| penetrologger | averaged values | Appendix B: Figure B.8 | |
| sieving curve sand | sieving curve | Appendix B: Figure B.2 | |

Table 1: Overview of test results

3.2 Test description

This section describes the performed tests. For all test results the following values have been used:

| width of the geocontainer: | b | = | 2.75 m |
|---------------------------------------|---|---|--------|
| average thickness of the geocontainer | D | = | 0.55 m |
| relative density of the geocontainers | Δ | = | 1.0 |

Dimensionless parameters such as $(H_s/(\Delta b), H_s/(\Delta D))$ and $H_s/(\Delta \sqrt{(bD)})$ will be given. The background of these parameters is given in section 2.5.1 and Appendix G. All values are given in model scale.

During the experiments it became clear that the sand transport in the geocontainers is decisive for the stability. Therefore it is questionable if these dimensionless parameters can be used to describe stability.

3.2.1 Test series $1: h_c/H_s = 0.75$

Test 1-1

A wave field of only 78 waves with a significant wave height of 0.89 m and a peak period of 4.33 s is applied. $(H_s/(\Delta b) = 0.32; H_s/(\Delta D) = 1.62; H_s/(\Delta \sqrt{bD})) = 0.72)$

After a few minutes it became visible that the geotexile which is wrapped around geocontainer D was not well connected to the slope which resulted into a damage of this geotextile. Therefore is was decided to abort this test and to repair the geotextile.

The EMF measurement indicate migration of sand at geocontainer 4 (see Figure 4) at a depth of 3.5 cm and 8 cm and some slight migration at geocontainer 3 at a depth of 3.5 cm. The EMF measurement at geocontainer 3 at a depth of 8 cm indicate no significant sand migration. Since the test was very short no profile measurement is carried out.

<u>Test 1-1a</u>

A wave field of 1015 waves with a significant wave height of 1.05 m and a peak period of 4.57 s is applied. $(H_s/(\Delta b) = 0.38; H_s/(\Delta D) = 1.91; H_s/(\Delta \sqrt{(bD)}) = 0.86)$

The measured displacement of geocontainer 4 is 0.10 m seawards. Geocontainer 2 and 3 moved 0.03 m seawards. The other geocontainers were not noticebly reshaped. The sand migration indicated by the EMF measurements was the same as in test 1-1.

Test 1-2

A wave field of 1015 waves with a significant wave height of 1.19 m and a peak period of 5.09 s is applied. $(H_s/(\Delta b) = 0.43; H_s/(\Delta D) = 2.16; H_s/(\Delta \sqrt{bD})) = 0.97)$

The measured displacement of geocontainer 4 is 0.67 m seawards. Geocontainer 2 and 3 moved 0.71 m.

To investigate the exact position of geocontainers 2 and 3, geocontainer 4 is removed and the surface profile of geocontainers 2 and 3 is measured with the profiler. The profile of geocontainer 2 and 3 is indicated in Appendix B, Figure B.4.

Since damage has occurred it was decided to abort other tests in testseries 1. The geocontainers which contained EMF measurements were opened to inspect the EMF measurement devices. It turned out that the measurement devices were not located at their original position and that the instruments were turned over. This indicates that severe sand transport took place. (Reference is made to Photo 3.7).

The total number of waves at test series 1 is 2108. The total displacement of geocontainer 4 is 0.77 m. The total displacement of geocontainers 2 and 3 is 0.74 m.

3.2.2 Test series 2: $h_c/H_s \approx 0$

Test 2-1

A wave field of 1014 waves with a significant wave height of 0.76 m and a peak period of 3.97 s is applied. $(H_s/(\Delta b) = 0.28; H_s/(\Delta D) = 1.38 H_s/(\Delta \sqrt{(bD)}) = 0.62)$

The measured displacement of geocontainer 8 is 0.01 m seawards. Geocontainer 7 and 5 moved respectively 0.07 m and 0.15 m towards the slope.

The EMF measurement indicate migration of sand in geocontainer 8 at a depth of 3.5 cm and 8 cm. Slight migration is measured in geocontainer 7 at a depth of 3.5 cm and 8 cm.

Test 2-2

A wave field of 973 waves with a significant wave height of 0.92 m and a peak period of 4.35 s is applied. $(H_s/(\Delta b) = 0.33; H_s/(\Delta D) = 1.67; H_s/(\Delta \sqrt{bD}) = 0.75)$

This test resulted into a seaward movement of 0.16 m of geocontainer 8. Geocontainer 7 and 5 moved respectively 0.11 m and 0.15 m seawards.

The EMF measurement located at geocontainer 7 indicates migration at a depth of 3.5 cm and slight migration at a depth of 8 cm. There was also a significant sand migration in geocontainer 8 allthough the EMF did not measure it. This is explained by the large reshaping of the geocontainer. This reshaping is shown in Appendix B, Figure B.5. It is very likely that a thicker layer of sand is covering the EMF measurement device which causes the absence of a pore flow near the measurement device.

Test 2-2a

To investigate to which extend the reshaping of test 2-2 was a time based process, test 2-2 was extended with test 2-2a which had a duration of 2084 waves. In this test, the hydraulic conditions which were used in test 2-2 were applied. $(H_s/(\Delta b) = 0.33; H_s/(\Delta D) = 1.64; H_s/(\Delta \sqrt{(bD)}) = 0.73)$

This test resulted in a seaward movement of 0.65 m of geocontainer 8. Geocontainer 7 and 5 moved respectively 0.32 m and 0.26 m seawards during test 2-2a.

The EMF at a depth of 3.5 cm in geocontainer 7 indicated migration of sand, all other EMF's indicated no movement of sand. It is very likely that the EMF's are buried under a thick layer of sand and therefore don't measure any movement.

Test 2-2b

Test 2-2 and 2-2a is extended with test 2-2b which had 2124 waves. In this test the same hydraulic conditions are applied as in test 2-1 and 2-1a. $(H_s/(\Delta b) = 0.33; H_s/(\Delta D) = 1.64; H_s/(\Delta \sqrt{bD})) = 0.73)$

Test 2-2b resulted in a seaward movement of 0.36 m of geocontainers 8. Geocontainer 7 and 5 moved respectively 0.26 m and 0.17 m seawards during test 2-2b

The EMF measurement devices at a depth of 3.5 cm in geocontainer 8 indicates migration of sand. All other EMF devices indicate no migration of sand. After test 22b it was decided to remove all the EMF measurement devices. By removing the devices it was observed that the devices were turned over and were located deeper in the sand.

The total number of waves of tests 2.2, 2.2a and 2.2b is 5181. The total seaward displacement of geocontainer 8 is 0.79m. Geocontainer 7 and 5 moved respectively 0.69 m and 0.58 m seawards.

Test 2-3

A wave field of 1011 waves with a significant wave height of 1.08 m and a peak period of 4.67 s is applied. $(H_s/(\Delta b) = 0.39; H_s/(\Delta D) = 1.96; H_s/(\Delta \sqrt{bD})) = 0.88)$

Test 2-3 resulted in a seaward movement of 0.30 m of geocontainer 8. Geocontainer 7 and 5 moved respectively 0.29 m and 0.31 m seawards. No EMF measurements were carried out.

<u>Test 2-4</u>

A wave field of 1036 waves with a significant wave height of 1.21 m and a peak period of 5.05 s is applied. $(H_s/(\Delta b) = 0.44; H_s/(\Delta D) = 2.20; H_s/(\Delta \sqrt{(bD)}) = 0.98)$ Test 2-4 resulted in a seaward movement of 0.36 m of geocontainer 8. Geocontainer 7 and 5 moved respectively 0.34 m and 0.36 m seawards. No EMF measurements were carried out.

Test 2-5

A wave field of 1038 waves with a significant wave height of 1.34 m and a peak period of 5.36 s is applied. $(H_s/(\Delta b) = 0.49; H_s/(\Delta D) = 2.68; H_s/(\Delta \sqrt{bD}) = 1.09)$

Test 2-5 resulted in a seaward movement of 0.30 m of geocontainer 8. Geocontainer 7 and 5 moved respectively 0.41 m and 0.46 m seawards. No EMF measurements were carried out.

The total displacement of geocontainer 8 is 2.13m, of geocontainer 7 is 1.65 m and of geocontainer 5 is 1.56 m. The total number of waves is 9280.

The displacement per wave of geocontainers 5, 7 and 8 as function of the stability number is shown in Figure 8. The used values for the stability number are $\Delta = 1$, b = 2.75 m and D = 0.55 m. The stability number is explained in section 2.5.1.



Figure 8: Displacement of geocontainers per wave during test series 2 as function of the stability number.

3.2.3 Test series 3: Damage

Damage is modelled by cutting the geotextile. Reference is made to section 2.7 for specifications.

Test 3-1

A wave field of approximately 1000 waves with a significant wave height of 0.91 m and a peak period of 4.35 s is applied.

 $H_{\rm s}/(\Delta B) = 0.33; \quad H_{\rm s}/(\Delta D) = 1.65; \quad H_{\rm s}/(\Delta \sqrt{(bD)}) = 0.74$

After the test it is observed that sand has washed through the cuts that were applied to the geotextiles. Reference is made to Appendix B, Figure B.5a and Figure B.5b. The reshaping of geocontainer 7 is visible in profile measurement 1 and 2. The reshaping of geocontainer 5 is visible in profile measurement 4.

3.3 Analysis of failure mechanisms

To analyse the failure mechanisms of a stack of geocontainers, a theoretical analysis is described in section 3.3.1. Since the failure mechanisms might influence each other, this is described in section 3.3.2. The failure mechanisms that are observed in the physical model tests are described in section 3.3.3.

3.3.1 Theoretical identification of failure mechanisms

The instability of the geocontainers during the tests might be the result of several mechanisms. Four mechanisms are discussed in this section:

- Sand washing out through the geotextile
- Caterpillar effect of a geocontainer due to migration of sand in the geocontainer
- Sliding of a geocontainer
- Sliding of a group of geocontainers

These mechanisms are shown in Figure 9.



Figure 9: Failure mechanisms of geocontainers

The mechanisms 'washing out of sand through the geotextile' and 'caterpillar effect of a geocontainer' are discussed below.

Sand washing out through the geotextile

Grains smaller than the openings of the geotextile might move through the geotextile and leave the geocontainer. However, movement of sand is necessary to realize this mechanism. This movement can be caused by wave attack or currents.

Another possibility is that the geotextile is damaged and a hole in the geotextile is created. This can be caused by, for example, vandalism or a screw propeller. As a result sand will wash through the hole and leave the geocontainer.

Caterpiller effect of a geocontainer

The caterpillar effect of a geocontainer can be caused by two mechanisms; surface erosion and sliding surfaces in the geocontainer.

• Surface erosion

The caterpillar effect due to surface erosion is shown in Figure 10. Sand is moving as a result of external forces such as wave action or currents. This sand movement results into reshaping of the geotextile which eventually leads to the catterpillar effect.



Figure 10: Caterpillar effect of a geocontainer due to surface erosion

• Sliding surfaces in the geocontainer

The caterpillar effect due to sliding surfaces in the geocontainer is shown in Figure 11. Sliding surface reshape the geocontainer and the caterpillar mechanism is activated.



Figure 11: Caterpillar effect of a geocontainer due to sliding surface

3.3.2 Interaction between failure mechanisms

To study possible interactions between the failure mechanisms Figure 9 is shown again in Figure 12 and interactions between failure mechanisms are indicated with arrows. For example: arrow 1 indicates the influence of mechanism A on mechanism B.



Figure 12: Possible interactions between failure mechanisms.

The number of the arrows in Figure 12 are used in Table 2. In this table the relation between the mechanisms is shown. For example, there is no influence of mechanism B on mechanism A but there is an influence of mechanism A on mechanism B.

| | Α | В | С | D |
|---|--------|---------|-------|---------|
| Α | XX | 1: yes | 3: no | 10: yes |
| В | 2: no | XX | 9: no | 7: no |
| С | 4: no | 11: yes | XX | 6: yes |
| D | 12: no | 8:no | 5: no | XX |

Table 2: Interactions between failure mechanisms. See also Figure 12

With the use of Figure 12 and Table 2 four interactions are identified. These interactions are represented by the red arrows in Figure 12 and discussed below.

1) <u>'Washing out of sand through the geotextile' influencing 'Caterpillar effect of a geocontainer'</u>

When sand is washing out through the geotextile more space is created in the geocontainer. This space gives the possibility for sand to migrate inside the geocontainer. This might result into the caterpillar effect since this effect is a result of sand migration in the geocontainer.

6) <u>'Sliding of a geocontainer' influencing 'Sliding of a group of geocontainers'</u>

In case a specific geocontainer is sliding down, this might influence the stability of a whole group of geocontainers. This is shown in Figure 13.



Figure 13: Mechanism 'Sliding of a geocontainer' influencing mechanism 'Sliding of a group of geocontainers'

10) <u>'Washing out of sand through the geotextile' influencing 'Sliding of a group of geocontainers'</u>

If several containers are loosing sand as a result of washing out of sand it is possible that the geocontainers are reshaping and that new slip circles are created. These new slip



Figure 14: Mechanism 'Migration of sand' influencing mechanism 'Sliding of a group of geocontainers'

11) 'Sliding of a geocontainer' influencing 'Caterpillar effect of a geocontainer'

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A geocontainer which is sliding might create some space for the geocontainer above it. The geocontainer above will fill up this space as shown in Figure 15. It is very likely that due to the position of the geocontainer it is not possible to perform the caterpillar motion.



Figure 15: Mechanism 'Sliding of a geocontainer' influencing the mechanism 'Caterpillar effect of a geocontainer'

3.3.3 Observed failure mechanisms and interactions

It has been shown that several mechanisms might occur en might influence each other. This section describes which mechanisms were actually observed in the scale model tests and whether these mechanisms were influencing each other.

Sand washing out through the geotextile

In the experiments it is theoretically possible to loose 27 percent of the sand due to migration of sand through the geotextile. This percentage is based on the sieving curve in Appendix B, Figure B.2 and the O_{90} of the geotextile. However, in practice it is unlikely that this will happen since larger grains will block the openings and a lot of sand is not able to reach the geotextile because of insufficient sand motion. In case of a flapping geotextile this blocking phenomenom will be minor.

To estimate how much sand is lost an estimation of volumes is carried out. Since some complicated processes such as measurement errors and the variability of sand porosity plays an important role, this analysis is described in Appendix E. According to this analysis the loss of sand is between 0 and 8 percent of the original volume.

It is emphasized that the mechanism 'disappearing of sand' in itself is not a failure mechanism but might influence strongly the mechanisms 'Caterpillar mechanism of a geocontainer' (since the sand is given more space to move) and 'Sliding of a group of geocontainers'.

Contribution of the caterpillar effect to the total displacement of geocontainers

In several tests it is observed that the geocontainers are reshaping. Reference is made to Photo 3.2 and Photo 3.4 and the profile measurements in Appendix B, Figure B.4, Figure B.5 and Figure B.6. This reshaping is ascribed to the caterpillar effect, the sliding of individual geocontainers and the sliding of a group of geocontainers.

The migration of sand in the geocontainer is demonstrated by the EMF measurements. Reference is made to Appendix A, Table A.1. The sliding of individual geocontainers and a group of geocontainers is visually observed and measured with the profiler. Reference is made to Appendix B, Figure B.4, Figure B.5 and Figure B.6.

The migration of sand might cause the caterpillar mechanism of a geocontainer. To investigate whether this mechanism is a significant failure mechanism there is a need to quantify the contribution of this mechanism to the total displacement of a geocontainer.

Use is made of the profile measurements of test 2-2a, 2-2b, 2-3, 2-4 and 2-5. These measurements are analysed in Appendix F. Based on this analysis it is concluded that the caterpillar mechanism of a geocontainer might be a significant failure mechanism regarding the stability of geocontainers. The total displacement of geocontainer 8 after test 2-2b is caused for 90 percent by the caterpillar mechanism of the geocontainer. After this test the contribution of the caterpillar mechanism to the total displacement is getting lower until 27 percent after test 2-5. There are two alternative explanations:

1) For lower wave action, the caterpillar mechanism is dominant and for higher wave action the sliding mechanism is more dominant. Lower waves do not have enough strength to start the mechanism 'sliding of a geocontainer' but are strong enough to start the mechanism 'caterpiller mechanism of a geocontainer'. However, the caterpillar effect is only substantial after a relatively long time of wave action. Therefore, when waves are inducing large enough forces to start the mechanism 'Sliding of a geocontainer', this mechanism will be dominant.

2) After initial motion the caterpillar mechanism is not possible anymore because of the shape of the geocontainers. Geocontainer 8 was partly lying in a gap between the two underlying containers. Therefore, the caterpillar effect was strongly influenced by the reshaping of the underlying containers. This is schematized in Figure 15.

There is not enough information to choose between the two.

3.4 Model effects

This section analyses potential model effects which have been observed during the tests. The following potential influences have been identified:

- Influence of side wall friction
- The caterpillar deceleration due to cross bracing of the geotextile
- The presence of the smooth slope above the geocontainers
3.4.1 Influence of side wall friction

The geocontainers were placed against the flume walls. This had a friction effect and therefore the determined stability of the geocontainers might be too high. It is difficult to quantify the friction effect since another process, which is described in the next section, might also be a reason why the sides of the geocontainers are less displaced than the middle part of the geocontainers. Reference is made to Photo 3.6. A first order approach of the influence of the flume walls is given below.

To determine the influence of the friction of the flume walls a comparison is made with the friction of the bottom, which usually is another geocontainer. Reference is made to Figure 16.



Figure 16: Schematization of friction of side walls and bottom

The grain stress at the lower part of the geocontainer is calculated with

 $\sigma_v' = (\gamma - \gamma_{water}) D = 5.5 \text{ kN/m}^2$

The total force at the bottom of the geocontainer is

 $F_{bottom} = \sigma_v L = 27.5$ kN per unit of width

The total force at two flume walls is calculated using

 $\sigma'_{h} = K \ \sigma'_{v} = 1.83 \text{ kN/m}^{2}$ $F_{walls} = 2 \ \frac{1}{2} \ \sigma_{h} \cdot D^{2} = 0.55 \text{ kN}$ per unit of width

Assuming that the friction factors are of the same magnitude the fraction $F_{\text{wall}}/F_{\text{bottom}} \approx 0.55/27.5 \approx 0.02$. Therefore it can be concluded that the influence of the flume walls is negligible regarding the stability of a geocontainer.

However, the above described theory is valid for an inflexible body. Since a geocontainer is not an inflexible body, distortions of the geocontainers caused by the influence of the walls occur. This distortion is shown in Photo 3.6.

3.4.2 Reduction of the caterpillar mechanism due to a cross bracing mechanism of the geotextile

Another possible explanation of the shape of the geocontainers after the test series as discussed in the previous section could be the influence of the 'cross bracing mechanism' of geotextile. The geotextile on the both sides of the geocontainer act as the cross-brace.



Figure 17: Schematization of a geocontainer with and without cross bracing

It should be realised that sand cannot act as a cross brace since sand cannot take tensile forces. However, geotextile on the sides of a geocontainer can take tensile forces and therefore might work as a cross brace and block the caterpillar mechanism of a geocontainer.



Figure 18: Geocontainer with geotextile which acts as a cross brace

It is obvious that the lenght of the geocontainer plays an important role regarding the influence of the cross bracing. An influence factor α_{cb} is introduced. $\alpha_{cb} = 1$ indicates no influence of cross bracing at all, an $\alpha_{cb} = 0$ indicates a total blocking of the caterpillar effect due to the cross bracing. A hypothetical relationship between the length of a geocontainer and the bracing influence factor α_{cb} is given in Figure 19.



Figure 19: Theoretical relation between the length, L, of a geocontainer and the cross bracing influence factor α_{cb}

In prototype situations the length of a geocontainer is around 20 to 35m, in the model the length is 5m. Therefore it is very likely that the cross bracing effect is too strong in the model. However, to reduce the caterpillar effect of the geocontainer it is considerable to place the geocontainers parallel to the wave attack as shown in Figure 20a. Allthough this might be a good solution to reduce the caterpillar effect, it will cause other stability difficulties which are described in Remio and Oumeraci (2006). Besides this, more Geocontainers are needed which increase the costs of the structure.



Figure 20: Position of geocontainers with respect to the wave attack

3.4.3 The presence of a conventional slope above the geocontainers

Three important elements can be distinguished in the structure:

- under water slope of geocontainers
- a wide berm with a width of $4H_s 6H_s$
- a smooth upper slope

In the first test series most wave breaking occurred above the berm. Wave impacts came down in a thick waterlayer, without directly impacting the geocontainers.

In the second test series the wave impacts imposed large forces, directly on the geocontainers. During all tests a large part of the wave energy contributed to wave run-up on the upperslope, leading to a down rush in the second part of the wave cycle.

Compared to a rock slope, or no upper slope at all, there was a relatively strong downward current during each wave run-down. These currents impose forces on geocontainer 4 (1st test series) and geocontainer 8 (2nd test series), which may have contributed to the displacement of these geocontainers. The test results will therefore be conservative (safe) for structures without such a smooth upper slope.

3.5 Comparison with earlier experimental investigations

To compare the stability of geocontainers an overview of earlier experimental investigation is given in Appendix G. The used stability number in these experiments is usually $H_{s'}(\Delta D)$ or $H_{s'}(\Delta b)$. Since both the average thickness D and the width b of geocontainer seem to have influence on the stability of the structure it is suggested to use a combined stability number $H_{s'}(\Delta \sqrt{(bD)})$. Based on the overview in Appendix G the start of damage would occur at $H_{s'}(\Delta \sqrt{(bD)}) = 1.1-1.4$.

However, the current test results indicate a lower stability number which is around 0.7 for a stack of geocontainers with the crest placed around the water level and around 0.9 for a stack of geocontainers with the crest placed 0.75 H_s below the water level. Two possible reasons for the difference between this experiment and earlier experiments are:

- 1. The scale model at the current test is much larger than the other scale model tests. The small-scale model tests are probably too small to identify the caterpillar mechanism of the geocontainer caused by the movement of sand. This is alo shown in earlier investigated experiments described in Venis (1968). In the current test it appeared that the movement of sand is a significant mechanism.
- 2. The structure in the current tests has a 1:3 smooth slope above water. The structures in the small-scale model tests are breakwaters consisting completely of geocontainers or geotubes without a 1:3 slope. The wave run-down has influenced the stability. This is shown in Photo 3.8 (Appendix C) and is discussed in section 3.4.3.

3.6 Scaling with respect to sand transport in the geocontainers

In reality the geocontainers are approximately four times larger than those in the Delta Flume. In this section this scaling issue is adressed. An important aspect of the scaling of the stability is the sand transport in the geocontainers.

To investigate the sand transport in geocontainers in a prototype situation there is a need to analyse the scaling aspects of this phenomenom. The sand transport causes the Caterpillar mechanism. A description of the Caterpillar movement is given in section 3.3.1.

In Venis (1968) it is assumed that the start of sand transport in a sandbag does not depend on the dimensions of this sandbag. In his research, Venis found a relation between the dimension of sandbags and the critical velocity. This relationship is shown in Figure 21.



Figure 21: Relation between the root of the length of a sandbag (\sqrt{L}) and the critical velocity ($u_{crit,cp}$)

For low velocities, the relationship between the root of the length of a sandbag (\sqrt{L}) and the critical velocity, u_{crit} is a straight line in Figure 21. This results from the applicability of the Froude scaling law. However, on a large scale the velocities are so large that the Froude

scaling law is not applicable, because sand transport inside the bags occurs. Venis concluded that the point at where the sand started to shift was almost independent of the model scale. This implies for the Delta flume tests that the scaling is 1:1 regarding the start of movement of sand in the geocontainers. However, some remarks have to be made regarding this conclusion.

Venis stated that sand transport in the geocontainers is independent of the size of the sandbags he used. However, this does not imply that sand transport in the geocontainers is not dependent on other apects such as the shape of the element or the used material. The main question which raises is: To which parameters is the critical velocity with respect to the caterpillar motion dependent? Or:

 $u_{\text{crit,cp}} = f(?)$

where $u_{\text{crit,cp}}$ is the critical flow velocity above the geocontainer.

Before this question can be answered a hypothesis is developed in which the sand movement is explained.

It is assumed that the sand movement is caused by a flapping geotextile. This flapping is caused by external forces such as (breaking) waves or currents which generate turbulence. This is illustrated in Figure 22.



Figure 22: Flapping geotextile causing sand transport

The intensity of the flapping of the geotextile depends on the shape of the geocontainer. If the geocontainer is strongly curved around the sand it is hardly possible for the geotextile to flap. A relatively large force is needed to lift the geotextile in Figure 23.b since the geotextile is able to give a counterforce (the stress in the geotextile). This counterforce is only possible when the geotextile is curved. A relatively small force is needed to lift the geotextile in Figure 23.a (not a curved shape).



Figure 23: The shape of the geocontainer in relation to vibration

Besides the shape of the geocontainer, the stiffness of the geotextile might play a role with respect to flapping of the geotextile. A thick geotextile which is relatively stiff will flap less. The elasticity might also play a significant role. When tension forces are exposed to the geocontainer, the geotextile will stretch and more space will be created for the sand to move. The permeability, k, of the geotextile might influence the velocity in the geocontainers. A lower permeability gives a lower velocity in the geocontainer resulting in a higher critical velocity above the geocontainer. An assumed relationship between the permeability of the geotextile and the critical velocity above the geocontainer, $u_{crit,cp}$, is given in Figure 24. It is assumed that the difference in the model and prototype with respect to the permeability does not significantly influence the critical velocity. This is indicated with the red indicators in Figure 24.



Figure 24: Assumed relation between the permeability of the geotextile and the critical velocity $u_{crit,cp}$

It is concluded that the critical velocity depends on the shape of the geocontainer and the stiffness and elasticity of the geotextile or:

 $u_{\text{crit,cp}} = f$ (shape of gc, stiffness of gt, elasticity of gt.)

The above described parameters are summarized in Table 3, Table 4 and Table 5. The last column shows which influence the parameters have on the critical velocity. From these

tables it can be derived that a high critical velocity (thus a more stable geocontainer) can be obtained when the geocontainer is strongly curved (like Geotubes) and when a stiff geotextile with a low elasticity is applied.

| shape of gc | <i>u</i> _{crit,cp} |
|-----------------|-----------------------------|
| not curved | low |
| strongly curved | high |

Table 3: Influence of the shape of the geocontainer with respect to the critical velocity $u_{\text{crit,cp}}$

| stiffness of gt | <i>u</i> _{crit,cp} |
|-----------------|-----------------------------|
| not stiff | low |
| stiff | high |

Table 4: Influence of the stiffness of the geocontainer with respect to the critical velocity $u_{crit,cp}$

| elasticity of gt | u _{crit,cp} |
|------------------|----------------------|
| elastic | low |
| not elastic | high |
| | |

Table 5: Influence of the elasticity of the geotextile with respect to the critical velocity $u_{crit,cp}$

The shape of the geocontainers in this physical model test is less curved than the shape in a prototype. This can be explained due to the fact that a compacting machine is used. Reference is made to section 2.5.3 and Photo 2.2 (Appendix C).

It is assumed that the relative stiffness (relative with respect to a scaled wave height) of the geotextile is lower for a prototype situation. Allthough the tension forces are higher in prototype situation, the relative elasticity is probably lower in prototype situations. It is a difficult task to quantify the influence of the above described parameters. Therefore it is unknown which parameters are dominating.

It is very likely that the above described processes only show marginally differences between the model and the prototype situation with respect to the critical velocity. Therefore it seems that the critical velocity (and thus the critical wave height) is equal to the prototype (scale 1:1). According to figure 8 (page 18), the movement of geocontainers starts at test 2.1. The significant wave height in this test serie is 0.76 m. Therefore it is concluded that a geocontainer which is placed at the water level becomes unstable when a significant wave height of 0.76 m occurs, independent of the scale (large scale model or prototype).

3.7 Stability of geocontainers as function of the depth.

The hydraulic forces exerted by the waves decrease with depth under water. Therefore geocontainers are more stable when placed deep under water since wave forces and wave run-down velocities are lower. We are looking for the depth at which the hydraulic loads are so small that geocontainers can be applied without the risk of sand motion or instability.

To quantify this influence use will be made of existing theories of submerged breakwaters. These kind of breakwaters have a crest which is placed below sea-level. Several theories do exist. The commonly used emperical relationships, Vidal et. al (1995), Burger (1995) and Kramer and Burcharth (2004) are summarized in Figure 25. The hypothesis is that the

hydraulic load can be expressed as the stone diameter which is necessary for a stable crest of a submerged breakwater. The bigger the required stone size, the larger the hydraulic loads.



Figure 25: Influence of the relative crest height, R_c / D_{n50} , with respect to the relative wave height, $H_s / (\Delta D_{n50})$ CUR / CIRIA (2007)

In Figure 25 it can be seen that applying a lower relative crest height, R_c/D_{n50} , leads to higher acceptable relative significant wave heights $H_s/(\Delta D_{n50})$. To 'translate' this graph to the stability of geocontainers the following calculations are made:

Suppose that a rock armour is used instead of geocontainers. The required rock size at the waterlevel can be calculated in various ways. 'Reading' Figure 25 at $R_c/D_{n50} = 0$ gives a $H_s/(\Delta D_{n50})$ of around 1.5. With $H_s = 0.76$ m (This is the significant wave height at which the geocontainers started to move as a results of the Caterpillar mechanism) and $\Delta = 1.65$ (the relative density for armour stone), the required nominal diameter for the rock armour, D_{n50} , is around 0.30 m. This is the same stone size as required on a slope as can be calculated using the stability formula of van Gent et. al. (2003).

Suppose that the rock armour with a diameter of $D_{n50} = 0.30$ m will be placed 0.75 m below sea level (This is the case for test series 1 in the physical model tests). The maximum allowed significant wave height, H_s , can be derived with the use of Figure 25:

 $R_c/D_{n50} = -0.75 \text{ m} / 0.30 \text{ m} = -2.5$. Using Figure 25 a value of 2.3 is found for $H_s/(\Delta D_{n50})$. From this value it is calculated that the maximum allowed significant wave height is 1.14 m. This calculated value shows a good agreement with the observations in test serie 1. (At test 1-2 the geocontainer was significantly displaced when using a significant wave height, H_s , of 1.19 m).

This agreement gives confidence with respect to the hypothesis that the stone size is a good measure for the hydraulic load.

Unfortunately, Figure 25 does not give information for very low crest breakwaters. Therefore, extrapolation is required. Results from extrapolation of emperical relations should be considered with great care. Allthough the relationship shown in Figure 25 is parabolic, a lineair fit is applied to guarantee conservative results.

 $(\mathbf{x},\mathbf{y}) = (R_c / D_{n50}, H_s / (\Delta D_{n50})) = (0, 1.5)$ (x,y) = (R_c / D_{n50}, H_s / (\Delta D_{n50})) = (-2.5, 2.3) With $\Delta = 1.65$ and $D_{n50} = 0.30$ m gives the following relationship between H_s and R_c :

 $H_{\rm s}$ = -0.53 $R_{\rm c}$ + 0.76

Or

 $R_{\rm c} = -1.89 \ H_{\rm s} + 1.43.$

This relation is plotted in Figure 26. It means that the structure is stable if $R_c < -1.89 H_s + 1.43$, which is approximately the same as the crest to be below 1.5 H_s below SWL. For such low crested structures it is known that waves will not break above it, but behind it or not at all.



Figure 26: Relation between H_s and R_c

3.7.1 Influence of wave run-down

If not a submerged structure, but a submerged berm in front of a slope is considered, also run-down from the slope can induce significant hydraulic loads. Reference is made to Figure 27.



Figure 27: A slope with a berm of geocontainers

The wave run-down level is an indication for the depth on which large hydraulic loads will take place.

The wave run-down on straight smooth slopes is defined in the Rock Manual (2007) as: $R_{d\,2\%} = 0.33\xi_p H_s$ where $R_{d2\%}$ is defined as the run-down level which is exceeded by only 2% of the waves. ξ_p is the breaker parameter defined as $\tan \alpha / \sqrt{s_0}$ where α is the slope angle and s_0 is the wave steepness based on the peak period. The wave run-down level is defined vertically relative to SWL.

The main hydraulic loads will also be somewhat deeper then this run-down level. This is estimated to be up to 1.2-1.5 times the wave run-down:

 $R_{d2\%} = 1.5 \ 0.33 \xi_p H_s$

This relation depends on the surf similarity parameter ξ_p . Assuming waves with a steepness, s_p , of about 3% and a slope with tan $\alpha = 1:2$, the wave run-down level is defined as:

 $R_{\text{influence,waverun-down}} \approx 1.5 H_s$

From this analysis it is concluded that the crest of the stack of geocontainers should be below SWL - $1.5 H_s$. This is in agreement with the conclusion in the previous section.

3.7.2 Recommended design formulae

It is stressed that the formula described in the previous section can only be used as a first order estimate. It is strongly recommended to perform physical model tests before applying this in a prototype situation.

To get a better insight into the loads (wave forces and velocity) it is recommended to perform a numerical study to the loads as a function of the depth.

To be on the safe side, with the information now available, one can consider to apply geocontainers only if the crest of the stack of geocontainers is below SWL – $2 H_s$.

3.8 Implications of the results

3.8.1 Implications with respect to the practical applicability of geocontainers

From the results and analysis described in this report some conclusions can be made with respect to the applicability of geocontainers.

In section 3.3.1 it is described that due to the Caterpillar mechanism geocontainers become unstable when located in a wave breaking zone. Therefore it seems unlogical to place the geocontainers in this zone. In section 3.7.2 it is described that geocontainers can be used at around 2 H_s below sea water level and deeper. Besides this, the geocontainers can also be used in the wave zone when placing a layer of rock armour on top of the geocontainers.

3.8.2 Implications with respect to further research

Small and large scale physical model tests have been performed regarding the stability of geocontainers. However, one should realise that every situation is unique with respect to the design, the used materials and the external loads. Therefore, the stability criteria can only be used as a first order approximation. It is therefore recommended to perform physical model tests to optimize the design for a specific situation.

To gather more insight in a generic way of geosystems physical model studies and a pilot study are described in the following sections.

Physical model study

It is assumed that the Caterpillar mechanism will be less when applying geotubes. The filling degree in geotubes is higher and therefore less flapping of the geotextile is expected. This flapping probably causes the sand transport inside the geotextile element and thus the Caterpillar mechanism. This is described in section 3.5.

Therefore it is recommended to study the Caterpillar mechanism of geotubes on a large scale.

Pilot study

A lot of theoretical and physical model studies regarding the application of geocontainers have been performed to study the various aspects of implementation of geocontainers. These studies helped a lot to reduce uncertainties such as placing uncertainty or the stability of geocontainers during wave attack. (Klein Breteler, 1994 and Delft Cluster 1, 2003). A good overview of the use and application of geocontainers is given in CUR (2004) and CUR (2006). It is now assumed that the most critical aspects of the application of geocontainers have been studied or tested in a physical model. We have now reached the point at which we need a pilot project to make the final step ahead.

Before a pilot study will be performed there is a need to acknowledge the application of geocontainers as a potential attractive alternative for conventional methods.

The pilot study contains four phases; selecting a pilot area, the construction phase, monitoring and evaluation of the pilot project (see Figure 29).

A location where a pilot study with geocontainers could be applied should be selected. An interesting location in the Netherlands is Maasvlakte 2. Maasvlakte 2 will be created directly to the west of the current port of Rotterdam and will shortly cover 1000 hectares net of industrial sites, located directly on deep water. An impression of Maasvlakte 2 is shown in Figure 28.



Figure 28: An impression of future Maasvlakte 2

Based on the selected area a comparison should be made between an alternative with geocontainers and other conventional alternatives. Several aspects such as costs, construction, maintenance, required space and environmental issues can be included in this comparison. An example of such a comparison is given in CUR (2004) where geotubes are compared with conventional methods. This comparison is performed with the use of a Multi Criteria Analysis (MCA). The advantage of this (relatively low-cost) analysis is that it will probably give a lot of practical information regarding the attractiveness of the application of geocontainers. Assuming that the results of the comparison indicate that geocontainers are more attractive or comparable to conventional methods, it can be decided to apply geocontainers and start the pilot project.

It is recommended to perform the pilot study at only a small section (around 100m) of the project. In this way, financial and technical consequences are minimized but a lot of experience will be gathered. During the process of design, construction and the lifetime of the structure monitoring is required. Especially the exact position of the geocontainers is important. One could also consider to construct more than one alternative designs with geocontainers.

After the pilot project there is a need to evaluate this case study. This can be done by interviewing the participants of the project, evaluating the monitoring and reviewing the earlier stated criteria. Based on this evaluation new experience is gathered which can be used to give design recommendations.

The above described process is summarized in the flow diagram below.



Figure 29: Flow diagram pilot project with geocontainers

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Based on the investigations and some theoretical considerations described in this report the following conclusions and recommendations are made:

Conclusions

• Physical model tests where a stack of geocontainers is placed on a 1:3 smooth slope have been executed. The tests had the following specifications:

| _ | scale of the geocontainer dim | = | 1:4 | |
|---|-------------------------------|-------------------------|-----|----------|
| _ | slope | = | 1:3 | |
| _ | slope geocontainers | | = | 1:2 |
| _ | wave steepness | <i>S</i> _{0,p} | = | 3 % |
| _ | porosity geotextile | O_{90} | = | 0.170 mm |
| _ | sand specifications | D_{90} | = | 0.270 mm |
| _ | specifications geocontainer | | | |
| | width | b | = | 2.75 m |
| | length | L | = | 5.00 m |
| | average thickness | D | = | 0.55 m |
| _ | water level above crest | | | |
| | • test series 1: | $h_{\rm c}/H_{ m s}$ | = | 0.75 |
| | test series 2: | $h_{\rm c}/H_{ m s}$ | = | 0 |
| | test series 3: | $h_{\rm c}/H_{ m s}$ | = | 0 |
| | | | | |

- The decisive failure mechanism in this test set up is the Caterpillar mechanism which is caused by sand movement inside the geocontainers. Long time series are required to identify this process. ($N \approx 5000$ waves) such as carried out in this project.
- The conditions at start of damage of the stack of geocontainers was
 - $H_{\rm s} \approx 0.76$ m for a stack of geocontainers with the crest at the water level
 - $H_{\rm s} \approx 1.15$ m for a stack of geocontainers with the crest at 0.75 $H_{\rm s}$ under the water level
- It is very likely that the sand movement inside the geocontainer is not dependent on the size of the geocontainers (assuming not very small experimental set-ups). This implies that the scaling with respect to Caterpillar mechanism is 1:1. In other words; in a prototype situation start of displacement would occur at the same wave heights as in the large scale experimental set-up in the Delta flume.
- The stability of the geocontainers in the current scale model tests is significantly lower than the stability of geocontainers in earlier (small) scale model tests. The difference in the stability is explained due to the following two aspects:
 - The migration of sand caused a caterpillar mechanism of the geocontainer which contributed significantly to the instability of the geocontainers.

- The presence of a 1:3 smooth slope above the geocontainers caused a wave rundown which might have effected the stability of the geocontainers.
- It is observed that the small grains in the sand washed through the geotextile. The amount of sand which washed through the geotextile is between 0% and 8% of the original volume of the geocontainer. Due to the disappearence of this sand, more space is created for the sand which contributed to the caterpillar mechanism.
- From a theoretical analysis it is derived that the geotextile on the sides of the geocontainer might act as a cross brace and therefore decrease the caterpillar mechanism.
- The penetrologger measurements indicate that the porosity of the sand in the geocontainers is higher after wave attack.

Recommendations

- It is recommended to avoid the use of geocontainers in the zone where waves break (between SWL and 2 H_s below SWL). Below this level geocontainers are not affected by wave impacts or wave run-down and can therefore be applied.
- It is recommended to study the influence of the presence of a slope above the geocontainers since the wave run-down might have influenced the stability of the geocontainers. This can be done by performing the tests without the presence of a slope.
- Since migration of sand in the geocontainers causes the caterpillar mechanism, it has a significant influence on the stability of the geocontainers. Therefore it is recommended to study a method to stop the migration of this sand.
- It is assumed that wave loads are a larger problem with respect to stability than currents. However, it is unknown what the influence of currents is on the migration of sand in the geocontainers. Therefore it is recommended to study whether a current might influence the stability of a geocontainer considering the migration of sand in this geocontainer.
- It is very likely that geotubes are less sensitive to sand transport inside the geotextile element. Therefore it is very likely that geotubes are more stable than geocontainers. Large scale physical model tests are recommended to study the stability of geotubes.

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A Tables

| test | water level | H _s | T _{pd} | s _{0,p} | H _{max} | N | $\sum N$ | $rac{H_s}{\Delta\sqrt{bD}}$ | observed damage |
|-------|----------------|----------------|-----------------|------------------|------------------|------|----------|------------------------------|------------------|
| | (m) | (m) | (s) | (-) | (m) | (-) | (-) | (-) | |
| t1-1 | 3.90 | 0.89 | 4.33 | 0.030 | 1.38 | 78 | 78 | 0.72 | - |
| t1-1a | 3.90 | 1.05 | 4.57 | 0.032 | 1.66 | 1015 | 1093 | 0.86 | little reshaping |
| t1-2 | 4.05 | 1.19 | 5.09 | 0.029 | 1.72 | 1015 | 2108 | 0.97 | damage |
| t2-1 | 4.25 | 0.76 | 3.97 | 0.031 | 1.29 | 1014 | 1014 | 0.62 | no reshaping |
| t2-2 | 4.25 | 0.92 | 4.35 | 0.031 | 1.41 | 973 | 1987 | 0.75 | little reshaping |
| t2-2a | 4.25 | 0.90 | 4.32 | 0.031 | 1.78 | 2084 | 4071 | 0.73 | large reshaping |
| t2-2b | 4.25 | 0.90 | 4.32 | 0.031 | 1.60 | 2124 | 6195 | 0.73 | damage |
| t2-3 | 4.25 | 1.09 | 4.63 | 0.033 | 1.65 | 407 | 6602 | 0.89 | damage |
| t2-3a | 4.25 | 1.07 | 4.71 | 0.031 | 1.60 | 604 | 7206 | 0.87 | damage |
| t2-4 | 4.25 | 1.21 | 5.05 | 0.030 | 1.87 | 1036 | 8242 | 0.98 | damage |
| t2-5 | 4.25 | 1.34 | 5.36 | 0.030 | 1.92 | 1038 | 9280 | 1.09 | damage |
| t30 | 4.25 | 0.91 | 4.35 | 0.031 | 1.52 | 965 | 965 | 0.74 | - |

Table A.1: Measured incoming wave parameters, stability number and observed damage

| After test | stab. nr. (-) | N (-) | sum(N) (-) | displacement (m) | | cum. di | isplacement (m) |
|---------------|------------------|----------|---------------|---------------------|--------|---------|--------------------|
| | | | | GC4 | GC 2/3 | GC4 | GC 2/3 |
| 1.1 | 0.86 | 1093 | 1093 | 0.10 | 0.03 | 0.10 | 0.03 |
| 1.2 | 0.97 | 1015 | 2108 | 0.67 | 0.71 | 0.77 | 0.74 |

Table A.2: Displacement of geocontainers in test series 1

| After | stab. nr. | N | sum(N) | di | displacement | | | displace | ment |
|-------|-----------|------|--------|------|--------------|-------|------|----------|-------|
| test | (-) | (-) | (-) | | (m) | | | (m) | - |
| | | | | GC 8 | GC 7 | GC 5 | GC 8 | GC 7 | GC 5 |
| 2.1 | 0.62 | 1014 | 1014 | 0.01 | -0.09 | -0.15 | 0.01 | -0.09 | -0.15 |
| 2.2 | 0.75 | 973 | 1987 | 0.16 | 0.11 | 0.15 | 0.17 | 0.02 | 0.00 |
| 2.2a | 0.73 | 2084 | 4071 | 0.65 | 0.32 | 0.26 | 0.82 | 0.34 | 0.26 |
| 2.2b | 0.73 | 2124 | 6195 | 0.36 | 0.26 | 0.17 | 1.18 | 0.61 | 0.44 |
| 2.3 | 0.88 | 1011 | 7206 | 0.30 | 0.29 | 0.31 | 1.47 | 0.90 | 0.75 |
| 2.4 | 0.98 | 1036 | 8242 | 0.36 | 0.34 | 0.36 | 1.83 | 1.24 | 1.10 |
| 2.5 | 1.09 | 1038 | 9280 | 0.30 | 0.41 | 0.46 | 2.13 | 1.65 | 1.56 |

Table A.3: Displacement of geocontainers in test series 1

| | lowest co | ntainer | highest co | ontainer |
|------|-------------|-----------|-------------|-----------|
| | depth=3.5cm | depth=8cm | depth=3.5cm | depth=8cm |
| 1-1 | slight | none | migration | migration |
| 1-1a | slight | none | migration | migration |
| 1-2 | none | none | migration | migration |
| 2-1 | slight | slight | migration | none |
| 2-2 | migration | slight | none | none |
| 2-2a | migration | none | none | none |
| 2-2b | none | none | migration | none |
| 2-3 | N.A. | N.A. | N.A. | N.A. |
| 2-4 | N.A. | N.A. | N.A. | N.A. |
| 2-5 | N.A. | N.A. | N.A. | N.A. |

Table A.4: Observed migration of sand based on EMF measurements

| name | time | location |
|-----------|--------------------|----------------|
| Plot x002 | Before testserie 1 | Geocontainer 3 |
| Plot x003 | Before testserie 1 | Geocontainer 4 |
| Plot x004 | After testserie 1 | Geocontainer 4 |
| Plot x005 | After testserie 1 | Geocontainer 4 |
| Plotx006 | Before testserie 2 | Geocontainer 7 |
| Plotx007 | Before testserie 2 | Geocontainer 8 |
| Plotx008 | After testserie 2 | Geocontainer 8 |

Table A.5: Time and location of penetrologger measurements

B Figures




























































C Photos



WL | Delft Hydraulics

H4595

photo 2.3: Use of the sewing machine



photo 2.4: Compacting of sand with the use of compacting machine after closing the geocontainer









| Overview structure before testserie 2 | | | | | | | |
|---------------------------------------|---------|-----------|--|--|--|--|--|
| <text></text> | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | DC Geoc | ontainers | | | | | |
| WL Delft Hydraulics | H4595 | photo 3.3 | | | | | |





photo 3.6: Influence of flume wall and cross bracing mechanism







D Specifications Geolon PE 180L

May 2008

PRODUCT GEGEVENS

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|---------------------------------------|------------------------|--------------------------------|--------------------------------|---------------------------------|------------------|
| CONSTRUCTIE | | | | | STANDAARD |
| Constructietype | | weefsel | weefsel | weefsel | |
| Garentype kettingrichting | | monofii. | monofil. | monofil. | |
| Klour | | Danuje | monom. | monom. | |
| Rieul | | Zwart | Zwan | Zwait | |
| MECHANISCHE EIGENSCHAPPEN | | | | | |
| Kettingrichting: | | 40 | 40 | 07 | |
| Nominale treksterkte | KN/M | 40 | 40 | 3/ | EN-ISO 10319 |
| Rek bij nominale treksterkte | % | 24 | 25 | 32 | EN-ISO 10319 |
| Inslagrichting: | | | | | |
| Nominale treksterkte | kN/m | 50 | 35 | 32 | EN-ISO 10319 |
| Rek bij nominale treksterkte | % | 24 | 25 | 25 | EN-ISO 10319 |
| Statische doornonssterkte (CBR): | | | | | |
| Doorponskracht | kN | 5 | 5 | 3.5 | EN-ISO 12236 |
| Verplaatsing bij doorponsen | mm | 50 | 50 | 45 | EN-ISO 12236 |
| Kegelvalproef | mm | 9 | 12 | 12 | EN 918 |
| Nominale treksterkte lussen | kN | 1,5 | 1,5 | 1,5 | Ten Cate Nicolon |
| HYDRAULISCHE EN FILTER EIGENS | CHAPPEN | | | | |
| Waterdoorlatendheid | | | | | |
| bij ∆h = 100 mm | liter/m ² s | 40 | 500 | 500 | NEN 5167 |
| Waterkolom bij v = 10 mm/s | mm | 10 | 7 | 7 | NEN 5167 |
| Permittiviteit ¥s | 1/s | 1 | 1,5 | 1,5 | NEN 5167 |
| Water permeability | m/s | 0,025 | 0,300 | 0,350 | EN-ISO 11058 |
| Poriegrootte O ₉₀ | micron | 180 | 525 | 1000 | NEN 5168 |
| Karakteristieke openingsmaat O_{90} | micron | 170 | 350 | 600 | EN-ISO 12956 |
| DUURZAAMHEID | | | | | |
| U.Vbestendigheid: | | | | | |
| Xenon test (50 MJ/m ²) | U.T.S. | >90% | >90% | >90% | ENV 12224 |
| Classificatie | klasse | D | D | D | ISO 4892-2 |
| Thermo-oxidatieve | | | | | |
| bestendigheid | klasse | В | В | В | NEN 5132 |
| FYSIEKE EIGENSCHAPPEN | | | | | |
| Gewicht per eenheid (berekend) | g/m² | 250 | 195 | 200 | EN 965 |
| Dikte (2kN/m ² druk) | mm | 0,6 | 0,7 | 0,8 | EN 964-1 |
| Lussenrooster | m | 0,5 x 0,5 | 0,5 x 0,5 | 1,0 x 0,5 | |
| Rolbreedte | m | 5,05 | 5,05 | 5,05 | |
| Rollengte | m | 200 | 200 | 200 | |
| Roldiameter | m | 0,45 | 0,36 | 0,36 | |
| Rolgewicht | kg | 265 | 210 | 215 | |
| Ten Cate Nicolon code | | 392 | 373 | 447 | |

De technische gegevens werden verkregen door interne en externe testprocedures. Bovengenoemde geotextielen kunnen geassembleerd worden tot geprefabriceerde panelen.

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E Analysis "losing sand"

E Analysis "losing sand"

E.I Introduction

In this experiment it is theoretically possible to loose 27 percent of the sand due to migration of sand through the geotextile. This percentage is based on the sieving curve in appendix B, figure B.2 and the O_{90} of the geotextile. However, in practice it is unlikely that this will happen since not all the sand in the geocontainer is moving.

To estimate how much sand is lost an estimation of volumes is carried out in this appendix.

E.2 Analysis

| sample | volume under profile (m ³ /m) | netto volume (m ³ /m) | |
|-----------------|---|-------------------------------------|--|
| before test 2-1 | 65.9 | 17.7 | |
| after test 2-5 | 66.3 | 18.1 | |

Using the profile measurements an estimation of volumes before test 21 and after test 25 is made. The test results are shown in Table E.1

Table E.1: measured volume of sand before and after test series 2

Surprisingly, the volume after the test became larger than the volume before the test. This can be explained by the influence of the porosity of the sand. To illustrate this a calculation is given below.

The netto volume of compacted sand before the test is determined using the profiler: $V_{\text{soil}}\,{=}\,17.7~m^3\!/m$

First, the volume of grains, V_g will be determined. This volume depends on the porosity of the sand. It is assumed that the porosity of the sand before the test: n=0.35 The volume of grains before the test series can be calculated using:

$$(1 - n_{compact}) \xrightarrow{V_{grain}} \rightarrow V_{grain} = (1 - n_{compact}) V_{soil} = (1 - 0.35)17.7 \text{ m}^2 = 11.5 \text{ m}^3/\text{m}$$

It is assumed that the porosity after the test is n = 0.40. Suppose that no sand is lost. The total volume of soil that would be measured is then:

$$V_{soil} = \frac{V_{grain}}{(1-n)} = \frac{11.5 \, {}^{m^3/m}}{1 + 0.40} \quad 19.2 \, {}^{m^3/m}$$

This means that *if* no sand is lost <u>and</u> the porosity *n* is changed from 0.35 to 0.4, that the difference is measured volume is $19.2 \text{ m}^3/\text{m} - 17.7 \text{ m}^3/\text{m} = 1.5 \text{ m}^3/\text{m}$

From the pentrologger test it can be derived that the porosity was higher after the tests than before. However, it is not possible to derive a value for the porosity. Therefore, the rule of thumb values which are used in the calculation will be used to determine boundary errors.

Besides an influence of the porosity of the sand, there is also a measurement error. This error is explained in Figure E.1. In this figure it can be seen that the profile measurement is overestimating the profile volume since it does not follow the shape of the geocontainer entirely. The measurement error for test t2-5 is estimated at $0.25m^3/m$



FigureE.1:Estimated measurement error for test t25

Combining the porosity error and the measurement error gives the possibility to estimate the amount of sand which is lost during test series 2. An overview of the separate contributions is given in Table E.2.

| sample | netto volume (m ³ /m) |
|-----------------------|-------------------------------------|
| before t2-1 | 17.7 |
| after t2-5 | 18.1 |
| profiler error | -0.25 |
| max porosity error | -1.5 |
| Net volume after t2-5 | 16.35 |
| max loss of sand | 1.35 (8%) |

Table E.2: Overview of sand losses

A total loss of sand is maximum $1.4m^2$ which is 8% of the initial volume. It should however be realised that this is a maximum loss and that the actual loss is probably lower.

E.3 Conclusion

It is visually observed that sand is being washed through the geotextile. Due to the unknown porosity of the sand it is not possible to determine accurately how much sand is lost. Based on some estimations it is concluded that the amount of lost sand is between 0 and 8 percent of the original volume. This is significantly lower than the theoretical value of 27% based on the sieving curve.

F Analysis "Caterpillar effect of a geocontainer

F Analysis "Caterpillar effect of a geocontainer"

F.I General

To identify the failure mechanism "Caterpillar mechanism of a geocontainer" there is a need to isolate this process. This will be done in a theoretical way. The test results of t2-2a, t2-2b, t2-3, t2-4 and t2-5 will be used as input values for this theory.

F.2 Theory

It is assumed that only two failure mechanisms exist: "sliding" and "caterpillar mechanism". The goal of this section is to identify a theoretical ratio between the failure mechanisms 'caterpillar mechanism' and 'sliding'. Both mechanisms and a combination of these mechanisms are schematized in Figure F.1.

Suppose that only the mechanism 'sliding' will occur. The geocontainer has slided a certain distance which is identified with 'a'. A marker ('o') on the geocontainer has made a displacement which is identified with b. In case only sliding occurs, the displacement of the marker equals the displacement of the geocontainer or a=b.

In case the only mechanisme is moving as a result of the caterpillar mechanism, the displacement of the marker is twice as larger as the displacement of the geocontainer as a whole. Therefore the following relationship is valid: 2a=b

A combination of the caterpillar mechanism and sliding is also possible. Suppose this occurs with a ratio of 1:1. The displacement of the marker is 1.5 times the displacement of the geocontainer or 3a=2b.

The ratio of the caterpillar effect can be calculated with the following relationship:

$$fraction = \frac{b-a}{a}$$

Only sliding:fraction = 0Only caterpillar mechanism:rollfraction = 1

However, it should be realised that the above described theory assumes no reshaping of the geocontainers such as stretching of the geotextile or flattening of the geocontainer. Therefore, the above described theory should be applied with great care.



Figure F.1: Schematization of caterpillar effect and sliding of a geocontainer

F.3 Determination of the caterpillar mechanism ratio

For test t2-2a, t2-2b, t2-3, t2-4 and t2-5 the rollratio is determined using the above described theory. It should be realized that the outcomes should be treated with great care since reshaping of the geocontainers is observed.

The values of 'a' is determined by using the average movement of the front and the back of a geocontainer.

To determine the value of 'b' use is made of two markers on the geotextile which are clearly visible in the profile measurements. The results of the measurements are shown in Table F.1.

| test | displacement Marker b1 | displacement Marker b2 | average displacement markers (b) | average displacement of GC8 (a) | caterpillar coefficient |
|-------|---------------------------|---------------------------|--|---------------------------------------|----------------------------|
| | (m) | (m) | (m) | (m) | (-) |
| t2-1 | - | - | - | - | - |
| t2-2 | - | - | - | - | - |
| t2-2a | 1.60 | 1.52 | 1.56 | 0.82 | 0.90 |
| t2-2b | 1.97 | 1.92 | 1.95 | 1.18 | 0.65 |
| t2-3 | 2.39 | 2.31 | 2.35 | 1.47 | 0.60 |
| t2-4 | 2.67 | 2.64 | 2.66 | 1.83 | 0.45 |
| t2-5 | 2.69 | 2.70 | 2.70 | 2.13 | 0.27 |

Table F.1: Values of displacement

Table F.1 shows clearly that the fraction of the caterpillar effect decreases during the test series. In test 22a the caterpillar fraction 0.90, indicating that the caterpillar mechanism is the most significant mechanism for this specific test. The caterpillar fraction of the geocontainers after test 22b is 0.65 which indicates that the caterpillar mechanism becomes less. This could be explained by the fact that the geocontainer is settled into a specific shape and therefore it is more difficult for the geocontainer to role over. The caterpillar fraction decreases to 0.27 in test t25. This is possibly caused by the larger wave attack which forces the containers to slide. This sliding is the dominant mechanism in the last tests.

G Summary of earlier investigations

G Summary of earlier investigations

Several experiments have been carried out to investigate the stability of geocontainers and geotubes. A summary of these investigations is given below.

In this overall view stability is described by:

$$\frac{H_s}{\Delta D}$$
 or $\frac{H_s}{\Delta b}$

where H_s = significant wave height, Δ = relative mass density (about 1.0), D = height and

b = width of the geotube or geocontainer.

Klein Breteler et al., 1994

- Geocontainers with cross-section 0.19x0.11 m² on a steep slope of 1:1. Start of damage at $H_s/(\Delta D) = 1.4$ and $H_s/(\Delta b) = 0.82$.
- Geocontainers with cross-section 0.42x0.09 m² on a steep slope of 1:1. Start of damage at $H_s/(\Delta D) = 2.3$ and $H_s/(\Delta b) = 0.50$.

Delft Cluster 1, 2003

- Geocontainers with cross-section $0.37 \times 0.06 \text{ m}^2$ on a slope of 1:3 and 0.4H_s below swl. No damage at $\text{H}_s/(\Delta D) = 3.5$ and $\text{H}_s/(\Delta b) = 0.56$.
- Geocontainers with cross-section $0.37 \times 0.06 \text{ m}^2$ on a slope of 1:3 with the crest at swl. No damage at $H_s/(\Delta D) = 2.8$ and $H_s/(\Delta b) = 0.46$.
- Geocontainers with cross-section $0.32 \times 0.095 \text{ m}^2$ on a steep slope of 1:1.7 and 0.4H_{s} below swl. No damage at $\text{H}_{\text{s}}/(\Delta D) = 2.2$ and $\text{H}_{\text{s}}/(\Delta b) = 0.64$.
- Geocontainers with cross-section $0.32 \times 0.095 \text{ m}^2$ on a steep slope of 1:1.7 and crest at swl. No damage at $H_s/(\Delta D) = 2.3$ and $H_s/(\Delta b) = 0.66$.

Recio and Oumeraci, 2006

• Geocontainers perpendicular to the longitudinal direction of the structure of $0.09 \times 0.48 \times 0.24 \text{ m}^3$ on a steep slope of 1:1. Start of damage at $H_s/(\Delta D) = 2.0$ and $H_s/(\Delta b) = 0.75$.