GC mattress construction tests

Testing an execution method for free span remediation

BSc Thesis
Main report

G.S. Hagenaars
C.A.M. van de Vries

Delft University of Technology
Faculty of Civil Engineering and Geosciences

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This thesis includes this main report and a separate appendices report. The appendices report will give more detailed information based on the chapters of the main report. In each chapter, the referred appendix is given.

Authors
Gerben Hagenaars
BSc student at the TU Delft, Faculty of Civil Engineering and Geosciences
Student number: 4100255
Email: g.s.hagenaars@student.tudelft.nl

Cindy van de Vries
BSc student at the TU Delft, Faculty of Civil Engineering and Geosciences
Student number: 4076141
Email: c.a.m.vandevries@student.tudelft.nl

Mentor
J.P. van den Bos
H.J. Verhagen

The data of the experiments can be found online via the link: Please read the archive guide first to understand the folder setup of the archive.

Delft University of Technology

Faculty of Civil Engineering and Geosciences
Department of Hydraulic Engineering
Stevinweg 1
2628 CN Delft
Phone: +31 (0)15 27 85 440

GeoHooks BV

Waalhaven Oostzijde 85
3087 BM, Rotterdam
info@geohooks.nl

Foreword

This report is written in the context of the BSc thesis of the faculty of Civil Engineering and Geosciences. This thesis is the last project for the BSc phase of the curriculum.

In this report, the results gain from the experiments done within this project will be elaborated.

Especially those who want to learn more about the execution method with a clamshell to construct the mattress out of GC's can find more information in this report. Besides that, this report is also suitable for those who want to do experiments with GC's in the coming future and who want to learn more about the approach and the handling of GC experiments.

We would like to thank GeoHooks and Boskalis to provide us with the necessary equipment. Special attention goes to Dirk Boogaard for providing the (handmade) clamshell and the pipeline. For the assistance in the preparation and execution phase of the experiments we would like to thank Tom Wilms.

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Gerben Hagenaars
Cindy van de Vries

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Summary

In the Waddensea there is a known problem with a pipeline. This pipeline has been exposed to a free span in certain areas which can be harmful. The currents around it can start the pipeline to vibrate and eventually it can break because of fatigue. To prevent this from happening and to stop the erosion a solution must be found. Normally a solution with gravel is implemented, but of several negative side effects of this protection layer, a new solution was invented.


Figure 1 GC element

In this solution the protection method consists of a mattress on the bed made out of a large amount of small elements called Ground consolidators (GC's). An GC is a biodegradable element that looks like a hollow cube with only seven ribs. The shape can be seen in Figure 1. These elements will interlock with one another and with so many placed in the water a mattress will form. This mattress can break the currents, so the current in between the mattress has a very low velocity. Another positive effect of the breaking is that sedimentation will take place inside the mattress, which will cause extra protection by a smoothly formed sand layer. Because of the expected evenness of this sand layer, no erosion will occur at the edges of the mattress. Because this is a new invention a method for constructing this mattress must be created. The search for such a method is the main focus of this report.

The main question for this report therefore holds:
What is the best construction method in relation to dropping several batches in the water in such a way that they form a stable mattress on the seabed?

To create a mattress large amounts of batches must be placed after another. This is done by lowering a clamshell into the water and dropping a batch with an optimal amount of GC's in the water and then placing the next batch in a strategically position after the first one, and so on.

In order to analyse how a mattress would behave, the behaviour of individual batches must be observed. Therefore the first experiment, called "Constructing in currents", individual batches were dropped into the water. The first experiment had many variables that needed to be analysed. The variables were the optimal amount of GC's in the clamshell, the opening speed of the clamshell and the upper boundary of current velocity in which dropping the GC's was still possible. These tests were done in the dry, in still water and with a current. Also an analysis was made to find out whether the batches would have the desired layer height, spreading and density.
The outcome of this experiment was that the optimal amount of GC's in the clamshell was 60, because the higher the density in the clamshell the higher the density of the batch fallen on the bed. More than 60 however was not possible because the elements would float out of the clamshell or otherwise wouldn't drop when opening the clamshell because they got stuck on the edges. The clamshell had to be opened slowly when placing in currents, because the current would influence the GC's while opening. When opened slowly the GC's roll into each other which resulted in a higher density and a better interlocking behaviour. And last of all, the velocity of the current when dropping the batches shouldn't be higher than 0.25 m/s, this is scaled to the Waddensea a velocity of 0.71 m/s.

With the outcome of the first experiment the second experiment "Making a mattress" was set up to see what interlocking effect could be observed between several batches. Several situations with two and three batches were set up to see if those batches would indeed interlock with each other. For the distinction of the batches the batches were painted in different colours. The batches would be pulled out with a hook and the strings coming out of the water would be analysed to see which

amount of the string had which colour. Also in these experiments the volume properties were analysed.
From these experiments it can be concluded that batches interlock very well with each other when placed in stretching bond. There must be some overlay from the batches to create the interlocking process. It was also found that the batches had to be placed first downstream and then upstream so the second batch could just roll into the first batch.

For the third experiment, “Instance of instability” the best situations from experiment 1 and 2 were put to the test. This experiment was done to check if the batches could indeed withstand high velocities at sea. A few tests with one batch and a few with three batches were performed. The velocity of the current was increased and with footage of the cameras it could be analysed what happened during the increasing.
From these tests it was very clear that a mattress needs several batches to find stability. One batch could find stability by its surrounding batch, when one batch alone would roll away like a ball. Before the batches would become completely instable the batches compressed and therefore the density increased. One batch could hold a velocity up to 0.36 m/s and three batches could hold up to 0.49 m/s (scaled to the Waddensea this would be velocities of 1.02 m/s respectively 1.38 m/s). At spring tide, the conditions at sea are up to 1.1 m/s. Therefore, a single batch will float away during spring tide.

With all the information gathered from the previous tests a setup for experiment 4 “Placing around a pipeline” could be created. For this experiment a scaled pipeline was made which could be placed on the sand bed but also be recreated to make a free span. With building insights learnt before, a mattress with six batches could be created around the pipeline. Several situations were tested without a free span and several with a free span.
From these tests some remarkable conclusions could be drawn. The situation without the free span had some situations tested where the batches would be placed on top of the pipeline. This is not at all recommended, because the smooth surface of the pipeline and the high velocities around the pipeline influence the batches in a negative way which makes the mattress float away at a lower current velocity. Another conclusion is that without a free span the mattress would have a stable point to hold on to. The velocity could go up to 0.58 m/s (scaled to the Waddensea this is 1.64 m/s). The velocity at the point of instability was a lot lower in the situation with a free span. This was because the free span would be of some support, but only when the mattress is high enough to reach the top of the pipeline. When this occurred, the mattress could get supported by the pipeline at the top layer. At some spots were the mattress was too low, some smaller strings would just roll through the free span which caused the mattress to start moving and which resulted in a lower moment of instability.

From the experiments that are done, the overall conclusion is that placing a mattress of GC’s for protection of a pipeline is possible. Some things need to be taken into account like the optimal variables found in experiment 1. The amount of GC’s in the clamshell should be maximized (in this experiment is this optimum lies around 60 GC’s). Also it is advised to always open the clamshell slowly and to never drop GC’s when the current is too high. The GC’s will simply drift away and it’s not possible to get a stable mattress on the bed. In the Waddensea the spring tide has a velocity of 1.1 m/s. From the results of experiment 4 it can be concluded that the mattress will always be stable because the velocities at the moment of instability were always lower than the spring tide. Also always start downstream when building the mattress and from then on drop batches on the upstream side against the previous batches. Also an overlay between batches is always necessary otherwise different batches won’t interlock. Use the stability of the pipeline to hold the mattress in place.

1. Introduction


Figure 2 Basic shape GC element

Nowadays it is common to use a layer of gravel or sand under water for protection of sea beds, slopes and pipelines. This protection method has many advantages because it is an efficient way to protect the bed because of its high density and the availability around the globe. There are also some disadvantages. The protection layer forms a massive body compared to the surrounding area. On the sides of this protection layer erosion of the underlying sand occurs because of high water velocities and turbulence. The protection layer is therefore a solution with a limited lifetime. Eventually it will dissolve and the protection will be gone or, because of the erosion, the problem will be relocated to another location along the pipeline.
At this moment an important pipeline, located in the Waddensea suffers from a free span. Because of this free span, the pipeline is exposed to forces that can be harmful in the future. The current movements around all sides of the pipeline will cause the pipeline to start moving and vibrating. This will introduce a new stress condition within the material and can cause fatigue to the pipeline.

To deal with the disadvantages of the common protection layer and to protect the pipeline at the Waddensea, another protection method is conceived with the use of Ground Consolidators (GC's). The GC is an innovative product that was can be used within a wide scope of Civil Engineering applications. A GC is a small element (with outer dimensions of 0.4 x 0.4 x 0.4 m^3) which follows the form of a hollow cube with only seven ribs, see Figure 2.
Because of the design and the ratio between the open volume and the rib thickness, the GC's can easily interlock with one another. This results in a complex matrix made out of GC's that hold each other into place. Within this matrix, small volumes exists in between the GC's.

This proposed construction method for the protection of pipelines exists out of a large number of GC's that form a mattress on the seabed after interlocking with one another. Because of the open structure within the mattress, water can flow through, but the current velocity will decrease. This decrease in velocity causes the sea sand the flow through and settle down. After some time a layer of sand will lie in between and over the GC's, guarantying the stability and the protection of the area or the coverage of the pipeline. Another advantage of the reduction in velocity is that the pipeline will have less current around its edges, resulting in a smaller chance of fatigue.
Previous experiments and projects show that the GC's in fact attract sand and reduces the current velocity. It is therefore proposed to protect the Waddensea pipeline with a mattress of GC's, constructed out of several smaller batches.

The main objective of this project is to evaluate the execution method by creating a scaled mattress in current conditions under water. The main question of this project is:

What is the best construction method in relation to dropping several batches in the water in such a way that they form a stable mattress on the seabed?

To formulate an answer to this question, several experiment were performed. First, the knowledge from previous experiments is summarized in chapter 2. Then the general experiment setup will be explained. After that the behaviour of a single batch under water is examined and the results are given in chapter 4. The construction of a mattress out of 2 and 3 batches is tested in experiment 2 (chapter 5). The instability mechanism and the construction around a pipeline is examined in experiments 3 and 4 and can be found in chapter 6 and 7. The main question will be answered in the conclusion (chapter 8), followed by some recommendations for future experiments in chapter 9.

2. Results literature study

This chapters handles the results of the literature study. A more detailed elaboration can be found in appendix A.

2.1 Hydraulic aspects of Anome Ground Consolidator

In this experiment the main instability of a package of GC's was found. The toe of the package starts moving and rolls over the entire mattress causing the mattress to collapse.
With the use of colours, the reduction of the current velocity within the package of GC's was observed. The color within the package had a long residence time compared to the color outside the package. This statement is used to conclude that a whole matrix of GC's in fact reduces the velocity of the current. Besides the usages of a package of GC's for bed protection, the usability for the package on slope stability is also tested. (H.J. Verhagen et al., 2006)

2.2 Possible execution methods

The report "Haken of Kraken", deals with the results of the experiments done to evaluate the best execution method for the construction of a mattress. Three methods were examined, which resulted in a feasibility map for execution methods. For this project, based on the results of this report, the execution method with a rotating pipe mounted on a regular crane is the most feasible option. This rotation pipe can drop the GC elements as a string on the sea bed to construct the mattress.

Because of the investment costs of this method, another method is proposed by Geohooks for the usage in this pilot pipeline project. This method will make use of a regular clamshell (optimized for the handling of GC's) that drop the GC's in batches on the seabed. (Geluk et al., 2013)

2.3 Method statement remediation of free spans

The proposed construction method for the mattress near the pipeline is stated in this document. At the Waddensea, an important pipeline suffers from the free spans along the sea bed. To protect the pipeline against the increased forces (and against problems due to fatigue), the supports will be lowered so that the pipeline moves towards the sea bed. To prevent the free span from expanding and to protect the pipeline against the current velocity around it's edges, a mattress made out of GC's will be constructed around the pipeline. This mattress will be situated around the pipeline on both sides.
At the locations of the free span, a maximum current velocity of 1.1 m/s may occur during spring tide. At high waters, the current velocity decreases to 0.2 m/s. (Witteveen+Bos, 2013).

2.4 Results GC drop tests

This document includes the results of the GC drop tests performed at the wharf of Van Vliet. In this experiment, the execution method that holds dropping GC's in batches with a clamshell was tested in the dry with GC's that had outer dimensions of 0.4 x 0.4 x 0.4 m^3. Based on the experiment results, the unevenness of the clamshell had a big effect on the dropping of the batch. When opened fast, the spreading of the batch increases. An explanation could be that the GC's are swung to the corners more with a high opening speed. Another result of this experiment is that the filling method in fact has a big influence on the batch parameters. When the GC's are placed inside the clamshell in stacked orientation, the interlocking decreases.

This experiment will be used as a reference experiment to evaluate differences between the results with real size GC's and scaled GC's. (Witteveen+Bos, 2013).

3. Design experiments

For the experiments at the laboratory for fluid mechanics at the TU Delft, the situation in the Waddensea is recreated in a scaled version. To do this certain materials and equipment needs to be scaled to the experiment size as well.

3.1 Characteristics GC's

The GC's used in the experiments are scaled with a factor 1:8. The real GC's are 0.4 x 0.4 x 0.4 m^3 and therefore the scaled GC's have outer dimensions of 0.05 x 0.05 x 0.05 m^3. The GC's are made out of a biodegradable material and are injection moulded. For more information about the GC's see appendix K. In Figure 2, a scaled GC is shown.

3.2 Characteristics clamshell

For the dropping of the GC's into water, a hydraulic clamshell is used. For the experiments a simple clamshell from Plexiglas and wood was realized, without the hydraulic system for the opening mechanism. That doesn't affect the manner of dropping the GC's. The clamshell is improved with solutions for the problems found in the experiments earlier done by Van Vliet in Amsterdam. The clamshell had smooth containers so the GC's didn't hang on to ribs or anything. For more information about the clamshell see Appendix K.

3.3 Setup flume

The experiment setup has to meet the condition of the real situation in the Waddensea. This means there must be a layer of sand on the bottom, the currents must be recreated, the pipeline must be scaled and be placed with a free span in the flume and the clamshell must be placed hanging above the sand bed with the scaled dropping height of the real situation.

For the experiments the long research flume of the laboratory for fluid mechanics at the TU Delft was used. In this flume a sand bed of 0.04m thickness was realised. On the flume a system for holding the clamshell into place was setup. On this system a camera was attached to film the situation from above. From the front side of the flume a camera was positioned to film the side of experiment. Also a waterproof camera was set up in the flume looking in the direction of the current towards the experiment. The system for the clamshell and the cameras were improved during the experiments. Also for the last a scaled pipeline was placed in the flume and mounted on the sand bed. In Figure 3 the setup of the flume at the first experiment is shown.

Figure 3 Experiment setup flume

For measuring the layer height and other volume properties lines and grids were placed on the side of the flume. For taking the GC's out of the flume a special hook was made so the batches could be picked out of the water. Per experiment the setup was changed and improved according to the needs of that experiment. For more information about each experiment see Appendices B, D, F and G.

4. Results constructing in currents, experiment 1

The results of experiment 1 "Constructing in currents" are described below. For all the information, calculations and analyses, see Appendix B and C.

4.1 Experiment setup

The setup for this first experiment was the base for every experiment that followed. The flume, as described in chapter 5.2 was used to set up this experiment. For this experiment batches consisting out of 1, 30, 40, 60, 70 and 75 GC's were tested. After the right amount of GC's was placed in the clamshell, it was hung into place above the sand bed. The falling height was constant at 0.25 m. From that moment the cameras started recording. The clamshell will open with the correct opening speed (slow or fast). Everything needed for the analyses is measured. This includes layer heights and falling heights. The rest of the values are calculated later by using pictures and video footage made during the experiment. In this computer analysis the batch center positions, the spreading and the falling speed are calculated. For more information about the setup of experiment 1, see Appendix B and C.

4.2 Objective

The objective of this experiment is to evaluate the measurements of the previous "full scale placement test in the dry" (Van Vliet, Amsterdam, 3-9-2013). This experiment expands the previous experiment by examining the behaviour of a batch of GC's under water and with a current.

4.3 Hypotheses

1. Based on the results of the reference experiment and the changes made on the scaled clamshell the batch of GC's will interlock even more.
2. The batch will spread more if the clamshell is opened fast because the elements will swing to the outside of the containers.
3. Because of the current the loose elements will float away before the batch hit the bed, so a large spreading will occur.
4. Because of the importance of the filling method of the clamshell for the final shape of the batch, the behaviour found in this experiment is very similar to the behaviour in the reference test. But because of the current, the spreading in groups and loose elements will increase.

4.4 Results

Based on the experiment data, the following shows a summary of the results found in this experiment. The results can be found more detailed in appendix C.

Desired opening speed

One of the conclusions state that the opening speed of the clamshell has in fact influence on the spreading and the layer height of the batch. When opened slowly the batch will have a better spreading and therefore a higher density. Also with a slowly opened clamshell there will be less loose GC's on the bed, so the interlocking behaviour has in fact increased.

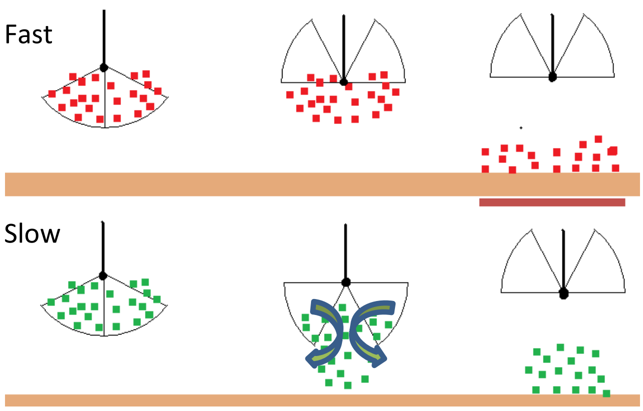


Figure 4 Observed rolling effect GC's during opening

From observations the differences could be explained by observing the opening width of the clamshell over time. In still conditions, due to the intertia caused by the buoyancy, the GC's will start falling all together after the clamshell is fully opened. Because the clamshell is opened fast, there is no rolling over effect and the GC's fall just as they were positioned during

loading.
When the clamshell is opened slowely, there is a point where the clamshell opens wide enough to help the first GC's rolling out of the clamshell. Because this gap width increases slowly, the GC's will start rolling over each other and interlock during their way out of the clamshell. This effect is schematicly displayed in Figure 4.

Desired amount of GC's in the clamshell and filling method

From the results of experiment 1 it can also be concluded that the desired amount of GC's in the clamshell is 60. Different amount of GC's were tested and it could be concluded that the more GC's in the clamshell the better the density of the batch on the sand bed becomes. But when working with more than 60 GC's, they wouldn't fall out the clamshell properly. Some strings got stuck on the edges of the clamshell. With about 75 GC's in the clamshell, the loose GC's on top would float out of the clamshell because of the current before the clamshell was even placed.
For filling the clamshell a special method was developed. In this method one after another is placed in the clamshell turning each GC 90 degrees in respect to the previous. This method is similar to the used experiment at Van Vliet.

Orientation clamshell

It was also tested if it matters if the clamshell is placed in line with or perpendicular to the current direction. Because the values of the volume properties by each of these tests weren't very different from each other the orientation of the clamshell was kept at in line with the current direction. In this way for later experiments the clamshell could be moved along the width of the flume so more than one batch could fit in the flume. Figure 5 shows the orientation of the clamshell.

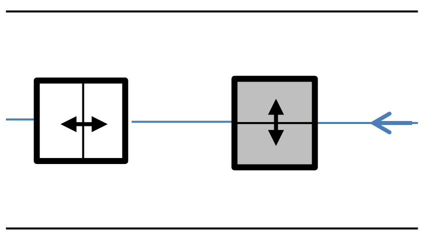


Figure 5 Orientation clamshell

Falling position batch

The velocity of the current has a very clear effect on the falling position. At a higher velocity there is a bigger chance that the elements will be in one of the two lowest groups. This means that at a higher velocity the elements won't interlock to one big batch on the sand bed. Therefore it is important that when building the mattress the velocity of the current isn't that high, so that the elements have a chance to interlock to one batch.

4.5 Conclusion

Below the hypotheses are discussed.

1. It is hard to compare the experiments with the tests in Amsterdam, because a different clamshell was used and the behaviour of a batch under water is different from the situation in the dry. For the situation with 60 GC's, slow opening speed of the clamshell and a velocity of the current of 0.25 m/s it is clear that the interlocking is very high.
2. When opening the clamshell slowly the elements would roll over each other and form a firm batch before falling out of the clamshell. The interlocking increases because of this rolling over effect.
3. With a velocity of about 1 m/s at sea (0.35 m/s in the flume) the GC's would in fact drift away before forming a batch. At a current velocity of 0.7 m/s (0.25 m/s in the flume), even the loose elements would stay in place when dropped in the current. The upper boundary for the construction of the mattress lies in between these points. The floating of the loose elements depends on the current velocity during construction.
4. The behaviour of the batch is similar to the reference experiment due to the importance of the filling method. But because of the current, there will be an increase of the spreading in groups and loose elements.

The conclusion for this experiment is that the upper boundary for constructing in currents has a current velocity of 0.25 m/s, a GC amount of 60 and an slow opening speed of the clamshell. It is also advised to construct the mattress when some current is present, so not in still waters. This is because the current has a positive influence on the interlocking behaviour.

Realized volume properties

The situation recommended by the results from experiment 1, was placing a batch with 60 GC's with a slow opening speed of the clamshell. The properties of this situation are listed in Table 1.

	Layer height (cm)	Spreading (cm^2)	Density (GC/cm^3)	Falling time (s)
Dry, slow, 60 GC's	8.93	2005	0.00381	0.52
Still, slow, 60 GC's	8.54	836	0.00862	1.10
0.25m/s, slow, 60 GC's	9.04	956	0.00723	1.47

Table 1 Realized properties with slow opening and 60 GC's

To check if the outcome of table 1 is realistic, the density will be compared to the theoretical density.

The compaction factor of the mattress will be around 1.8, so the desired density of the GC's with ribs of 0.4 m will be around 28.1 GC/m^3 (2.5 GC's per axis, a compaction factor of 1.8, this results in $(2.5)^3 \times 1.8 = 28.1\ GC/m^3$). This compaction factor of 1.8 holds a desired density of 20 x 20 x 20 x 1.8 = 14400 GC/m^3 for the mattress in this experiment (based on the scaled GC's with ribs of 0.05 m, because per meter there will fit: 1 / 0.05 = 20 GC). This means a required density of 0.0144 GC/cm^3.

The results show that the measured density is in all cases far less than the required density of 0.0144 GC/cm^3. This is most likely because of the measuring method for the spreading (area covered by GC's) of the batch. When a batch of only 60 GC's reaches the bed, some loose elements will roll apart from the central heap. Even though the gab in between the central heap and these loose elements is ignored, the loose (single) element has a relatively large contribution to the total covered area, (approximately its rib print), while it only counts as one element for the density. In other words for the loose elements, the compaction factor will be equal to 1. This is far less than the desired compaction factor of 1.8, therefor the average will be pulled down by each loose element. This effect will cause the density to become lower than the required density. When testing with more batches, the loose elements will interlock in the next batch, so this effect will be reduced.

5. Results making a mattress, experiment 2

The results of experiment 2 “Making a mattress” are described below. For all the information, calculations and analyses, see Appendix D and E.

5.1 Experiment setup

Experiment 2 was based on the setup from experiment 1. The flume was used as described in chapter 2.2. This experiment was divided into two parts: the first part where a mattress was built out of two batches and the second part where three batches were used. As in experiment 1, the GC’s are put into the clamshell. When all the cameras are turned on, the clamshell will be lowered into the water and the GC’s will be dropped. For the second or the third batch the position of the clamshell needs to be adjusted. When this is done all the above will be performed again for the second and third batch. Afterwards the same measurements and analyses were made as for experiment 1. For more information about the setup of experiment 2 see Appendix D.

5.2 Objective

The objective of this experiment is to use the results of experiment 1 “unloading in currents” to look further and determine how to create a mattress of GC’s on the seabed.

5.3 Hypotheses

1. The batches must be placed downstream first and then upstream so the latter batch can roll into the first batch.
2. The different batches will interlock with each other as good as the internal interlocking of the batch.
3. Loose elements will be interlocked eventually when other batches are placed.

5.4 Results

Based on the experiment data, the following shows a summary of the results found in this experiment. The results can be found more detailed in appendix E.

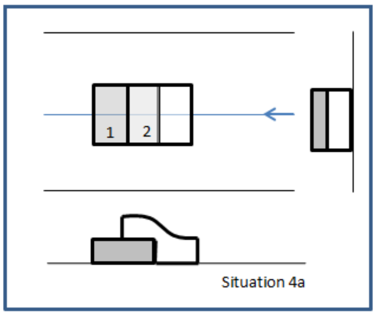


Figure 6 Best situation with two batches in line with current direction

Situation in line with current direction

Two batches

For the situation in line with the current the conclusion is that batches of GC’s must be placed first downstream and than the second batch in stretching bond (Dutch: “halfsteensverband” on top of the first one. In this way the second batch uses the influence of the current to roll its GC’s into the first batch. And with the stretching bond method the interlocking between the two batches is gauranteed. When dropping the batches next to each other almost no GC’s will interlock on the interfaces because of the positioniong deviations. In Figure 6 the best situation is shown.

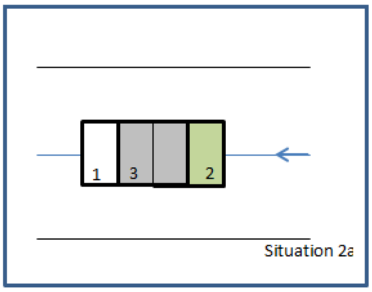


Figure 7 Best situation with three batches in line with current direction

Three batches

With three batches actually the same thing as with two batches occurred. Building must be done from downstream to upstream and with a streching bond method to gaurantee the interlocking. This can be seen in Figure 7. As told before, placing two batches next to eachother will result in no interlocking on the interfaces. Therefore the third batch is placed on top so the three batches will form a firm mattress. Because the third batch must be placed on top after the bottom layer is created, this third clamshell needs to drop exactly on top of the bottom layer, the falling height of this third clamshell must be adjusted to make a falling height of 0.25 m possible. This means that the third batch will be held about a layer height higher before dropping compared to the batches 1 and 2.

Situation perpendicular to current direction

Two batches

For this situation the conclusion for two batches is that also the batches should be placed in stretching bond regarding each other. When dropping next to each other, no interlocking occurs. The batches must overlap for interlocking to occur. Figure 8 shows this best situation.

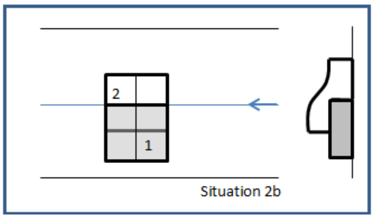


Figure 8 Best situation with two batches perpendicular to the current direction

Three batches

This situation is almost the same as the situation with two batches and the situation in line with the current direction. The batches should be placed first next to each other with a batch on top to guarantee the interlocking. Figure 9 shows this situation.

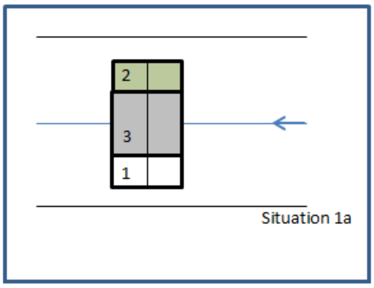


Figure 9 Best situation with three batches

5.5 Conclusion

The most important conclusion that can be drawn from these experiments is that batches should always be placed in stretching bond. It is also clear that when placing more batches of GC's, a larger surface is being covered. With a larger surface the chance of pores increases which are counted with the spreading of the batch. Therefore the density is lower than when less batches are used.

Below the hypotheses are discussed:

1. The specific order of placement is proven in quite a few conclusions to be true. As is foretold in the hypothesis this indeed will happen. When placing the first batch downstream, the second will indeed roll into the first batch and they will interlock very well. When doing this the other way around the two batches wouldn't make contact with each other and almost none interlocking would occur.
2. The difference between the quality of inside interlocking and interlocking between the batches depends on the situation. It is not easy to say that they will interlock as good as the internal interlocking of a batch, but the interlocking is high enough to create a desired density and therefore it can be said the interlocking is approximately as good as the internal interlocking.
3. The interlocking of loose elements into the next batch cannot be statistically proven with these experiments, because no interlocking was tested before the second or third batch would fall into the first batch and therefore fall into the loose elements.

Realized volume properties

In Table 2 below the average volume properties of the best situations described above.

	Layer height (cm)	Spreading (cm^2)	Density (GC/cm^3)
Two batches in line	8.19	1,402	0.0053
Two batches perpendicular	9.63	1,816	0.0027
Three batches in line	13.6	2,183	0.0021
Three batches perpendicular	12.9	2,016	0.0023

Table 2 Properties best situations

6. Results instance of instability, experiment 3

The results of experiment 3 “Instance of instability” are described below. For all the information, calculations and analyses, see Appendix F and G.

6.1 Experiment setup

Experiment 3 was based on the setup of experiment 1. The flume was used, as described in chapter 2.2. For this experiment the best situations from experiment 1 and 2 are tested for stability. Three experiments were done per situation. First a situation with one batch was tested.
After that the best situations from experiment 2 with three batches were tested. First these three batches were positioned in line with the current direction in two testes, then once perpendicular to the current direction. For more information about the setup of this experiment see Appendix F.

6.2 Objective

The objective of this experiment is to find the moment of instability and the failure mechanism of a mattress of GC’s that is constructed in a specific order, and at which velocity of the current the mattress becomes instable.

6.3 Hypotheses

Before starting these experiments some hypotheses were stated:

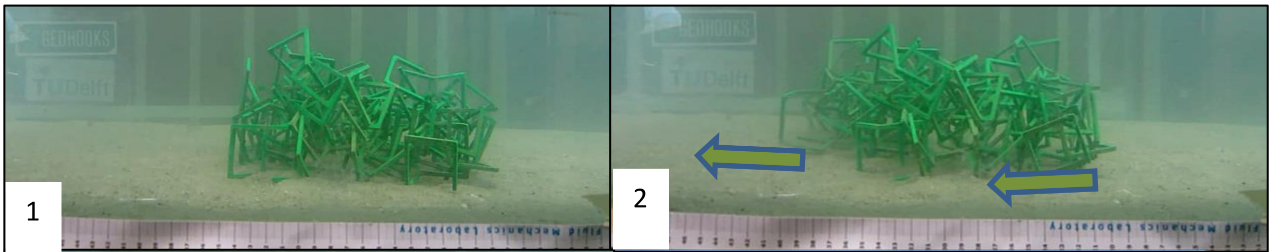
1. If a mattress is constructed out of several batches, it will wash away by a higher velocity than a mattress constructed out of a single batch.
2. The mattress will first become instable at its toe (the base of the mattress, which is closest to the sand bed), and will roll over. This will lead to the failure mechanism.
3. If a mattress consists out of one or more peaks, it will become instable at a lower current.

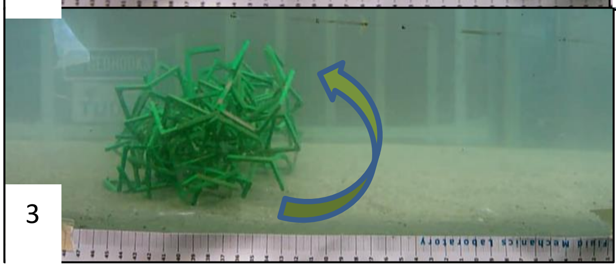
6.4 Results

The results of experiment 3 can be described in two different subjects.

Moment of instability and failure mechanism

The moment of instability is the moment in time when the whole mattress is moving. From this moment on the mattress will not find a new point of stability. All the batches are constructed with a current of 0.21 m/s in the flume. The moment of instability is measured from the moment the current starts increasing. The failure mechanism is qualitative description of what happens when the instance of instability is reached. The two different situations with one batch and with three batches are described below.





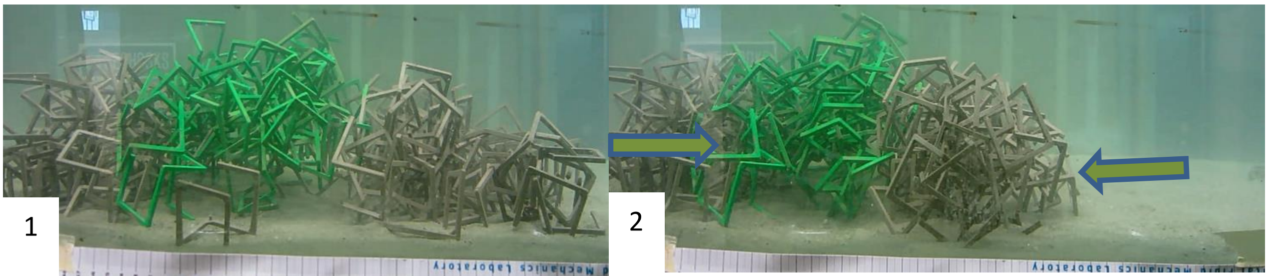
Situation: 1 batch, test 3

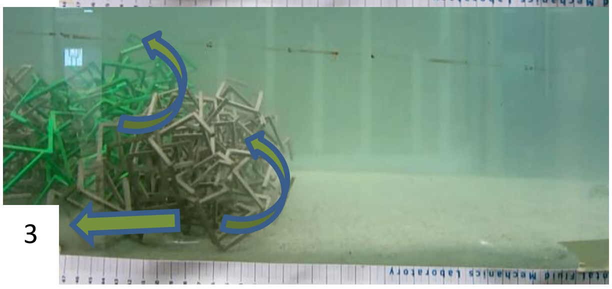
1. Batch direct after construction.
2. Single GC’s at upstream and downstream side starts moving.
3. Area decreases and batch toe starts rolling over at velocity of ± 0.36 m/s

Figure 10 Observed failure mechanism of 1 batch

One batch
In Figure 10 the failure mechanism of one batch is shown. By one batch is it clear that the stability can only be found from within the batch. Therefore the instance of instability by one batch is found quite soon after starting to increase the current velocity in the flume. The batch will compress first a bit but soon after it will become a sort ball and just rolls over. This will happens by a velocity of 0.36 m/s in the flume.

Three batches
In Figure 11, the failure mechanism of three batches is shown.





Situation: 3 batches, test 2

1. Batch direct after construction.
2. The mattress starts compressing
3. The whole mattress moves with the current direction and the batches will roll over

Figure 11 Failure mechanism of 3 batches

There is in fact a great difference between a single batch and three batches. For the single batch it took only 0.36 m/s to make it drift away and with a mattress it takes 0.49 m/s to make it drift away. From these results it can be concluded that the batches find stability by the batches surrounding them because of the interlocking behaviour.
Before the batches are instable they compress. This is only good for the firmness of the batch and the density. Because there were only a few tests in this experiment it cannot be said this result is significant, but it is clear that a mattress can hold out against a quite high velocity.

6.5 Conclusion

Below the hypotheses are discussed.

1. When a mattress is constructed out of several batches, it will indeed happen that it washes away at a higher current velocity. The more batches in the mattress the more stable the mattress will be. This is because the batches will find stability in the surrounding batches.
2. The point of instability at the toe of the mattress is also proven in the figures in the appendix G. First the batches will compress at the same time. They will move as one in the horizontal direction. At a certain point the front of the batch burrows into the sand, resulting into a difference in velocity over the mattress. The toe (with a higher velocity) will be lifted and will be rolled over the batch because of the interlocking. This causes the entire mattress to roll over, dragging the rest along.
3. The influence of the peaks cannot be concluded from this experiment because there is no significant relation found between the velocities at the instance of instability and the layer height. Therefore this hypothesis cannot be stated true or false. It is advised to do some more research on the effect of the peaks on the failure mechanism and the current velocity that leads to instability.

The overall conclusion for these tests is that one batch isn't capable of holding out in high velocities and starts moving at current velocities of 0.36 m/s. But when a mattress is made with a large amount of batches, they will work together and hold out in very high velocities.
It is also important to state that the batches can't be placed at velocities more than 0.36 m/s (1 m/s at the Waddensea) because than a batch of 60 GC's will drift away and no construction can be performed.

7. Results placing around a pipeline, experiment 4

The results of experiment 4 "Placing around a pipeline" are described below. For all the information, calculations and analyses, see Appendix H and I.

7.1 Experiment setup

Experiment 3 was based on the setup of experiment 1. The flume was used as described in chapter 2.2. For this experiment a pipeline was needed which was also scaled with a factor 1:8, so the pipeline had a diameter of 0.125 m. The pipeline is shown in Figure 71, Appendix H. For the first part of experiment 4 the pipeline was used as one without a free span. Therefore it was placed on the sand bed. The mattress was then built in the situations around the pipeline as described in the geometry of the experiment. After those experiments were done the pipeline was raised to have a free span of 0.125 m. For more information about the experiment setup see Appendix H.

7.2 Objective

The objective of this experiment is to combine everything learnt and measured in the previous experiments to evaluate what the ideal method is for placing a mattress around a pipeline. With the insights found before, this next experiment can be set up.

7.3 Hypotheses

Before beginning these experiments some hypotheses were made about the results of the experiment:

1. Before reaching the point of instability, the loose elements will start to move, but this will only result in a higher density of the mattress. This is because the loose elements will interlock eventually still with the mattress.
2. When starting to build the mattress it is always necessary to start building on the upstream side. Therefore the increased flow over the flume and under won't have any influence on the mattress. The rest of the mattress can be build supporting on this first stable part.
3. The batches need to be placed in two layers to reach the desired height.

7.4 Results

The results of the experiment can be divided in failure mechanisms and instance of instability.

Constructing without a free span

The different situations invented for these experiments have their own particular failure mechanism and therefore some situations are better to use at the Waddensea than others. In the situation without a free span several tests were performed where the mattress would also be placed on top of the pipeline. It was clear that the smoothness of the pipe and the high velocities of the current around the pipeline negatively influenced the mattress, which made it drift away way at a lower current velocity. The batches on top of the pipeline were the ones to initiate the movement, making them weak spots within the mattress. Other situations were tested where a mattress was built on both sides of the pipeline or only one side, and not covering the pipeline. The best situation is shown in Figure 12. This situation would hold on until a current velocity of 0.58 m/s. Is it advised to construct this best situation against the current direction and always at the upstream side of the pipeline. Constructing downstream a pipeline is hard because of the increased current and on the upstream side, the pipeline will be used as a fixed point to support the mattress.

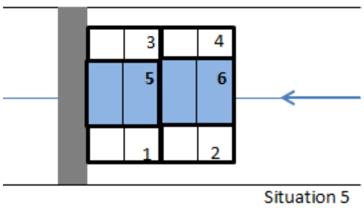


Figure 12 Best construction situation

Constructing with a free span

Concerning the free span, two situations were tested. In the first situation, on both sides of the pipeline a mattress of three batches was constructed. In the second situation the bahaviour of a mattress constructed only at the upstream side of the flume was tested. When comparing the results, it was obvious that both satisfied the condition for layer height and stability up to the maximum velocity as scaled from the Waddensea. This maximum velocity in the Waddensea is approximately 1.1 m/s at a spring tide condition, (see also appendix J) which equals a velocity in the flume of about 0.39 m/s. Both situations would not drift away by this current. They both drifted away by a current with a velocity of 0.46 respectively 0.47 m/s. Because the eventual mattress must be placed on both sides of the pipeline and must fulfill a requirement in length, the best solution to construct the mattress is to combine both situations into the situation shown in Figure 13. From observations it can be stated that it is important to get a sufficient height so that the mattress reaches the top of the pipeline. If that is the case, the mattress will not move below the pipeline but stay in place.

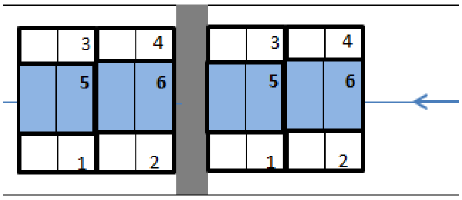


Figure 13 Combined situation by a free span

Failure mechansim

The failure mechanisms of the mattresses are shown in Figure 14. For the situation without a free span it is clear that the batch of GC's will be pressed into the corner between the pipeline and the sand bed. With this mechanism the mattress will be very stable until the moment of instability is reached and the batch will move over the pipeline and drift away. For the situation with a free span, the batches will be stable because they will be pressed against the pipeline on the top of the batch. When the batch compresses it will be smaller and eventually the batch will drift through the free span and is gone. Therefore it is important to get a sufficient layer height to reach the top of the pipeline, which can only be the case if several batches are dropped above each other. Again, both failure mechanism will not occur at the conditions near the free spans in the Waddensea.

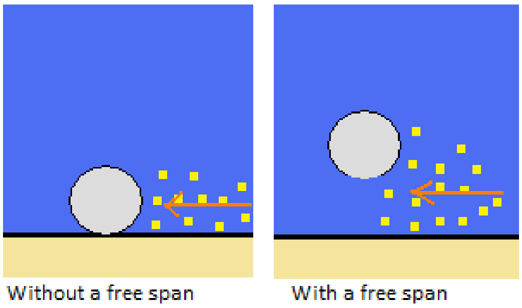


Figure 14 failure mechanisms

7.5 Conclusion

Below the hypotheses are discussed.

1. From the results from this experiment this hypothesis can be stated true. For this bahaviour a term is developed in the results, the instance of compression. Because in every footage it was shown that loose or small strings will compress into the larger batches, this term was used to describe this bahaviour. And with that the hypothesis can be immediately stated as true.
2. From the results of the analyses with and without the free span it can be concluded that this is also true. Every situation should be built from the upstream side of the pipeline. Because the mattress will find stability on the pipeline. From then on other batches can be laid against those, upstream from the first batch.
3. The desired height for the mattress is in real life 1m, so scaled to the experiments this will be 0.125m. This could be reached with only one batch. However a second batch must be placed on top of the first batches not to guarantee the desired height, but to guarantee the interlocking between those batches and therefore the stability of the mattress.

So as stated above is the most important conclusion that the mattress should not be constructed on top of the pipeline. Also it is important to always start constructing on the upstream side of the pipeline and that the mattress height must be equal to the top of the pipeline in case of a free span.

8. Conclusion

In this chapter, the answer will be given on the main question as stated in the introduction of this report. A final conclusion will be stated, but first an overview of the experiment will be presented.
Based on the results of the first experiment, the best handling method of the clamshell can be advised. Due to an extra rolling over effect and therefore an increased interlocking, it is advised to open the clamshell slowly. This effect is different from the experiments in the dry because of the influence of the inertia caused by the underwater situation.
The amount of GC's in the clamshell is important for the eventual batch properties. It is can be concluded that the amount of GC's in the clamshell, the volume and interlocking parameters are positively correlated. It is important to check the loading capacity because at a certain point the GC's will stick on the ribs of the clamshell. The optimum amount of GC's per clamshell was found on 60. To avoid the GC's sticking behind ribs, it is advised to use a clamshell with smooth containers.
The current velocity has a great impact on the eventual falling position of the batch center. Because of the complex unloading situation, the batches fall closer than the theoretical falling position of one object with the same properties would predict. An increased current velocity has a positive influence on the interlocking behaviour. This holds up to a current velocity of 1 m/s. This is the velocity were one batch becomes instable and construction isn't possible anymore.

Based on the second experiment, it is advised to construct the mattress in a stretching bond order. Thereby it is advised to first drop the batches on the bottom and then place one batch on top, so this top batch falls into the gaps between the batches. This increases the mutual interlocking.
When constructing in line with the current direction, it is advised to construct in the upstream direction, so against the current. Because of this construction order, the batches fall into each other, and the first batch will form a fixed point. Again, similar to construction perpendicular to the current, it is advised to construct in stretching bond order and to first construct a bottom layer.
Based on these results one can conclude that several batches in fact interlock with each other when they are placed in the right order.

Experiment 3 shows that the main failure mechanism starts at the toe of the batch. Once the toe starts moving it rolls over the entire batch. One batch will drift away at a current velocity of 1 m/s (at sea conditions), so it is advised to always construct the mattress in conditions with a lower velocity. When the mattress consists out of more batches in line with the current direction, the stability increases. When the interlocking quality between the batches is good, the mattress will float away horizontally and then rolls over at its toe. If not, the individual batches will roll over for themselves while the complete mattress moves away.

Based on experiment 4, some important advises can be given concerning the construction near a pipeline. First, it is advised to always construct at the upstream side of the pipeline. When constructing on the downstream side, the positioning accuracy and the deviation of the parameters decreases. When building upstream, the pipeline can be used as a fixed point to construct the mattress against.
When constructing the mattress on top of the pipeline, the resistance against instability decreases because of the increased velocities around the top. This will lead into a current of instability that is below the spring tide condition at the Waddensea (1.1 m/s).
Peaks in the mattress (especially near the pipeline) are harmful for the stability of the mattress. Because of increased current velocities, the peaks will catch more velocity and a failure mechanism can start locally, causing a part of the mattress to move away. Loose elements will be caught inside the mattress when they get loose at the upstream side of the mattress.

In the case of a free span under the pipeline, it is important that the mattress is as high as the top of the pipeline. Otherwise the complete mattress will move under the pipeline. When the mattress reaches the top, it will decompress.

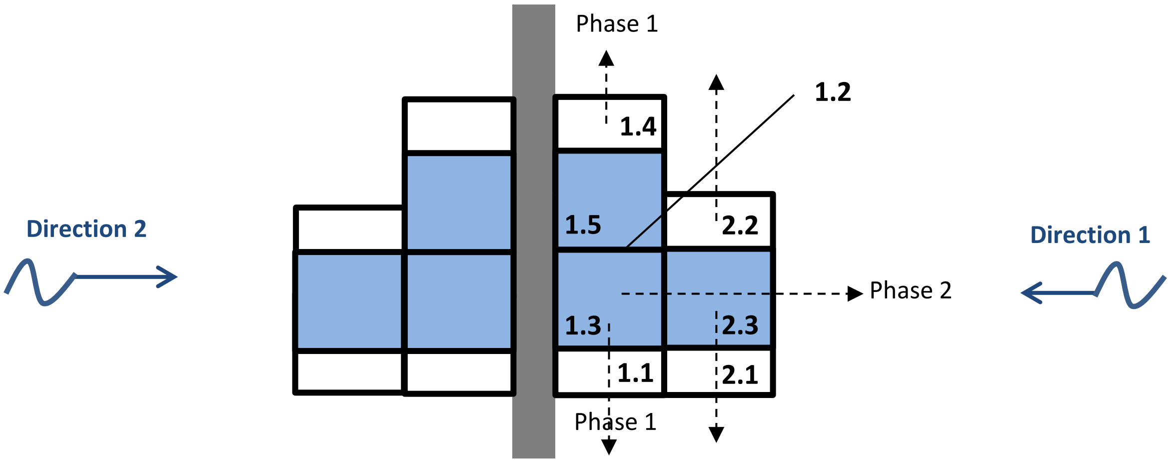
These results will be used the answer the main question of this report:

What is the best construction method in relation to dropping several batches in the water in such a way that they form a stable mattress on the seabed?

To answer this question, an execution plan based on the previous results will be given. This includes both the construction order of the mattress and the handling method of the clamshell.

- A modified clamshell is advised, with smooth containers so the GC's can fall out easily without getting stuck behind ribs.
- The clamshell must be filled with as many GC's as possible, based on its maximum capacity before an unacceptable amount of strings gets stuck on the ribs and the edges.
- Then the clamshell will be placed on the upstream position of the clamshell, with a falling height of 1 m.
- The clamshell must be opened slowly and with a low current velocity.
- Then the clamshell is lifted up to the pontoon and gets filled in the same manner, so the GC's must be placed one by one in the clamshell.
- Again the clamshell is lowered to the pipeline with a falling height of 1 m, placing the next batch alongside the pipeline.
- This third batch must fall one layer height higher than the previous two batches to be sure the top batch falls in the correct place.
- This must be repeated to construct one line of the mattress along the pipeline until the currents increases too much.
- Once the current increases, it is advised to start construction in the current making sure the strings fall into each other. When the current direction changes, construction on the other side is advised.

With this execution method it is important the first string of batches reaches the top of the pipeline before the current velocity increases too much. When the current increases, the mattress will then find support from the pipeline and the new constructed parts will stay in place.



- First drop the batches in a row along the pipeline (phase 1), according to its number (1.1, 1.2, 1.3 ..)
- When the current increases, start construction in the other direction (phase 2)
- At the turning of the tide, start constructing in the opposite direction, (direction 2)

The blue layer expresses the second layer on top of the white layer.

Figure 15 Proposed execution method for the mattress, top view

9. Recommendations

In the previous chapter, the final conclusion of this report was stated. The best way of constructing the mattress near a pipeline is displayed there. This constructing method is based on the results from the scaled tests in the flume. The test conditions resulted in limitations on the possible methods and the tested behaviour. Because of these limitations, and based on other observations made during the experiment execution, some future experiments are recommend here to expand the results of this report:

- For the positioning of the batches on the bed and within the mattress, the exact falling position depends on the current. In this experiment, a linear relation was found, but this was based on small current differences and therefore only suitable for usage in the experiment. When constructing at sea, the exact falling position in relation to the real time current must be calculated, so its advised to do further research to find a method to calculate the falling position based on real time data. With this information, the mattress can be constructed more accurately and the construction can be done at higher current velocities (up to 1 m/s, as seen from the experiments in this report).
- The filling method of the clamshell is important for the eventual batch properties. In the reference experiment, it was already been tested that the placement of GC's in so called transportation orientation (so right from the transportation pallet), results into less interlocking. It is recommended to find a clear instruction method for personnel at sea to fill the clamshell in the right way. Also some experiments can be done to find the optimum filling method.
- When using a different clamshell (not based on the scaled clamshell used in this experiment) it is recommended to first test the maximum amount of GC's that fits the clamshell. At a higher amount, GC's will get stuck on the edges, so a quick test in the dry with the clamshell beforehand will prevent the GC's from getting stuck during the operational phase.
- As seen in experiment 3 and 4, the height of the peaks is important for the moment of instability. Because the used flume wasn't that accurate, it is advised to do some research on the relation between the unevenness of the layer height and the current velocity that leads to the moment of instability.
- In the used flume it was only possible to test the construction of the mattress with a current direction perpendicular to the mattress. At sea, the current direction rotates constantly, so further research must be done to evaluate to influences of that and to see if the construction order can be adjusted and optimized for this. The proposed construction method is only optimized for currents perpendicular to the mattress.

In the near future, further research will be done by Deltares and at the TU Delft. Deltares will test the construction method in more realistic conditions. Especially recommendation 5 will be tested there.

At the TU Delft, a master thesis will probably start in February 2014. This research will be done by Danker Kolijn and will focus on the velocity's inside the mattress.

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