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Final report Levee Challenge Team Hans Brinker

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Preface

This project is the first multidisciplinary international design project we have carried out in the field of flood defences. The purpose of the assignment is to learn how to analyse a dike failure mechanism, design a repair solution for the damages and improve the design after overflow tests have been performed.

This report deals with designing the best possible solution for repair of a damaged dike. The effectiveness of the selected repair solution has subsequently been validated by performing full-scale overflow tests. The target group is diverse, anyone who is interested in designing repair solutions for damages on dikes in particular. Prior knowledge on the subject is recommended. The memorandum can be used to provide information about the design of repair solutions for damages and overflow tests on this repair solution.

I would like to thank Dr.ir. Robert Lanzafame, Ir. Stephan Rikkert and the Levee Challenge organization for guiding us during this project and we would like to thank Job Schouten of Gripple for his help during the project.

Delft, March 2021
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Abstract

In this assignment we simulate a two meters wide dike stretch which is subjected to overflow. Three failure mechanisms could occur due to overflow: full erosion of the soil of the dike, macro instability of the levee if too much soil is eroded away, leading to insufficient counterweight on the inside of the levee, and surface slip failure due to reduction of strength of the dike by flow of water in the dike core. Prevention of failure can be achieved by either keeping the water away from the berm surface or holding the soil particles in place while the water flows alongside it. The desired repair is an emergency repair that can placed quickly during a storm, or between two storms to prevent a damaged levee from failing. This is a temporary repair that will later be removed for full reconstruction of the levee. This provides constraints to the installation and repair procedure.

To decide which solution is best, 10 concept solutions are compared based on their score in the Multi Criteria Analysis with 8 weighted criteria. The solution with the highest score is the best solution according to the Multi Criteria Analysis. The selected repair option is to locally cover the damaged area with flexible overlapping sheets of Tyvek®. This is a light and thin material that can easily be transported and cut to size at the location of the repair. These sheets can be easily secured against flow loads using Gripple anchors, while pins are used to keep the Tyvek® in place during windy conditions. An installation plan and cost breakdown was made. Using 3 m wide Tyvek® rolls, the costs would be around 19.19 euros per meter height.

The damaged areas of the levee are covered with Tyvek® which is a waterproof, damp open material. This prevents the penetration of water into the core through the damaged areas. The Tyvek® also prevents the exposed soil from being eroded. Moreover, Tyvek® is a very strong material that won't be torn off. As there is no strength reduction due to water penetration or further loss of surface material the chance for macro instability is minimized.

First, a design was created, with components dimensioned for a dike stretch in the Hedwigepolder. Subsequently, the design was validated with tests. Including two types of damage. The first was removal of a 2 by 2 m grass layer (0.1 m thick) at the top of the dike and the second was a dug-out step-section across the entire width of the dike with a height difference of 0.5 meters at the toe of the dike. Only the second damage went through the clay layer and into the sand core of dike.

During and after the tests some important observations were made. During all test volumes the plastic sheets were kept in place due to the anchors and pins. Some pins however, came loose due to vibration of the sheets (we presumed the cause of vibration is flow of water between two sheets or turbulence of water). The trench of the lower damage was partly washed away by the water. The erosion of soil in the trench did not result in changing the stability of the top sheet. At the lower damage the plastic sheet was torn off after a tear of 1 m was made with a knife.

Our solution is designed to protect any dike from macro-instability by keeping the water flow away from the berm. This is done by layering multiple sheets of plastic foil over the inner berm, fastened with ground anchors and pins. The solution is a durable and reliable design due to proven waterproof, damp open and UV resistant properties, together with Gripple's demonstrated anchoring capabilities. Another major advantage of our solution is that the repair of the damage is selective, i.e. the solution is applied only to the parts of the levee where damage has occurred. In case of only localized and small damage to the levee, the costs and workload are very minimal compared to other solutions that are applied to the entire surface area of the levee.

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Chapter 1: Introduction

Climate change is one of the most extensive and toughest challenges of recent years, in which a broad palette of disciplines is involved in finding a solution to the problems we face now and in the future. Flood defence is one of them, and especially in the region of the Netherlands and Belgium where an increase in sea level can lead to catastrophic consequences. That is why, we decided to practice our theoretical skills on a real-life practical problem and take part in the Polders2C Levee challenge with an interdisciplinary team.

Our team's name is ‘Team Hans Brinker’ and this team consists of two Hydraulic Engineering students (Maarten Buitelaar & Robert Lengkeek), one Structural Engineering student (Rolf Rademaker), and a Construction Management student (Jason Wever) from the master Civil Engineering at the Delft University of Technology. Under supervision of our two main coordinators Dr.ir. Robert Lanzafame and Ir. Stephan Rikkert, we have been working on a solution for overflow damage of a dike.

The aim of this report is to explain the designed repair solution, present the results of the tests and so convince you that this is the best solution for the problem. This is done in the following way. First, our exact design problem is defined. Second, a description of our design approach is given from which our final solution is chosen. Third, this solution will be presented in detail, together with an installation plan for the test site and a cost breakdown. Fourth, the implementation of the repair solution, the execution of the tests and the results will be described. This will be followed by chapter six and seven, a plan for improvement and applications of the solution to problems on dikes. The ninth chapter motivates once more why our solution is the best repair solution. The report ends with a conclusion and discussion.

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Chapter 2: Problem statement

In this section, the problem for which our solution is designed is defined in more detail. The section consists of three parts. First, we describe the initial damage of the dike caused by overflow testing. Secondly, we detail the context of this damage and the constraints this has on the repair conditions. Lastly the test conditions are presented.

The testing dike is approximately seven meters high with a slope of around 1:3 [1]. Our design situation resembles a dike damaged by overflow. This damage is artificially created using spades. In the inner berm two locations are damaged. Near the crest of the levee 2m of the surface grass is removed, and near the toe a cliff with a depth of 50cm is dug. Our testing location itself is a dike-stretch of two meters wide. Initially it was stated that the levee would be damaged by overflow, this leads to unpredictable damage leading to a main requirement in our selection process; the flexibility of the solution.

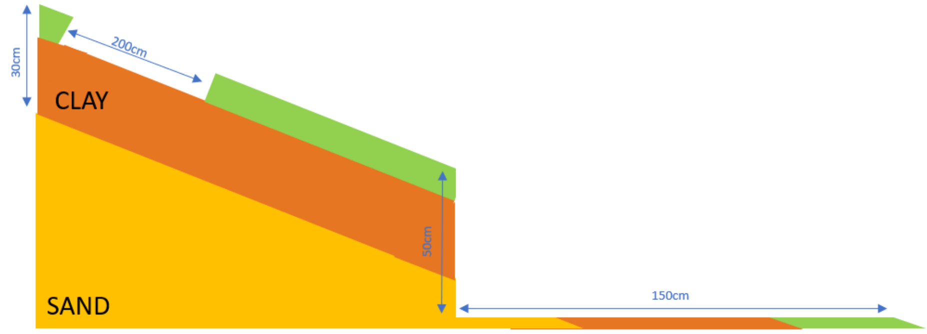

Figure 1 Cross section dike with damages

Overflow will lead to water flowing over the damage, this can lead to further erosion of the soil. The initial erosion will not directly lead to failure of the levee, for this to occur the entire levee must erode. This takes a considerable amount of time.

Initial erosion of soil leads to a changed profile of the levee. It is likely that a large cliff is formed due to the erosion. This will eventually result in macro instability of the levee if too much soil is eroded away, leading to insufficient counterweight on the inside of the levee.

Erosion trough the clay layer near the top of the levee will allow water to enter the core of the levee. This water will flow down through the dike internally. This reduces the strength and was large contributing factor to the collapses in Zeeland in 1953. This can cause a surface slip failure [3].

Our solution needs to prevent all three failure mechanisms. Keeping the soil in place on the levee will prevent all three failure mechanisms. This can be achieved by either keeping the water away from the berm surface or holding the soil particles in place while the water flows alongside it.
The desired repair is an emergency repair that can placed quickly during a storm, or between two storms to prevent a damaged levee from failing. This is a temporary repair that will later be removed for full reconstruction of the levee. This has constraints in the installation and repair procedure. The main constraint is that the levee repair must be executed during low water, which means within 12 hours. For our smaller scale damage this translates to 4 hours. A second constraint is that the dike will be difficult to access for both men and materials during the presumed wet and windy storm conditions. This has

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influence on the installation of materials, every part must be secured against the wind at all times.

After installing the solution, the dike will be tested with overflow conditions from the top of the dike. This will start a 350 l/s and increase to 700 l/s. After this the repair will be damaged and tested again from 350 l/s to 700 l/s.

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Chapter 3: Multi-criteria analysis of possible solutions.

From the problem statement we created 10 different solutions during multiple online calls and brainstorm sessions, that might solve our defined problem. Subsequently, we graded the solutions on 8 weighted criteria to see which had an overall best fit. Some criteria are more important than others, take for example the sustainability of the solution.

Sustainability of course is important, but it will not have a large contribution in the final decision on which solution is best. Therefore, there are different weight values assigned to the criteria. The larger the weight value the more important the criterium is in deciding the solution. From a weight value of 1 (low, not important in the decision) to a weight value of 3 (high, important). The weight values of the different criteria are based on the values which are assessed in the project, described by the Levee Challenge at the time of writing the project proposal. For this specific problem the workability and scalability are of high importance because in cause of overflow the location of the damage is unpredictable and time is of the essence.

The criteria on which each solution is tested is shown in the table below.

Table 1 Criteria used for MCA together with their weights and motivation for ranking.

Criteria	Weight	Motivation
Workload	High (3)	During an emergency it is important that a large space can be equipped with the solution quickly. Because equipment cannot always reach the location and manpower is not always available in abundance, we took special notice to keep the required workload low.
Scalability	High (3)	We found it important that our solution does not only fit for the 2-meter stretch, which is the scope of the challenge, but can also be applied to entire dikes in a real-life situation.
Reliability	High (3)	Our solution should be structurally reliable, so no extra safety precautions are necessary. The solution must be prone to short but intense forces applied to the slope of the Levee. Solution must withstand one storm without any further reparations.
Costs	Medium (2)	Costs should be kept in check if we want this solution to be applied on a larger scale.
Widely applicable	Medium (2)	Our solution should be applicable to any type of dike, independent of the geometry, soil types and already inflicted damage.
Innovative	Medium (2)	Some of the best current emergency flood risk solutions are already in use for a prolonged period of time (e.g. sandbags). For this challenge we believe it is important to challenge the status-quo (‘be innovative in the living lab’) and rely as little as possible on simple old solutions.
Removable	Low (1)	After the flood season the dike will need to be repaired properly and the solution should be removed. We take this criterion into account but with a low weight.

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Sustainability	Low (1)	If possible, we would prefer our solution to be sustainable and have zero climatic effect. However, it is not the priority, and therefore has a low weight.

Each solution is graded with a score of 1, 2 of 3. If the solution has a negative score for the given criterium, a score of 1 will be assigned. For example, if the solution requires many man hours and is hard to apply, a 1 is assigned for the solution for the criterium workload. On the other side, if the solution has positive properties regarding a certain criterium, a score of 3 is assigned. For example, if the solution is prone to large forces and subjected to failure, a score of 1 will be assigned regarding reliability. For each criteria a solution will receive a score which is shown in appendix C.

To decide which solution is best, the solutions are compared based on their score in the Multi Criteria Analysis. The solution with the highest score is the best solution according to the Multi Criteria Analysis. The total score is calculated by multiplying the score for each criterium with the weight value of the given criterium. This is done for each criterium and summed up to give the final score. The total scores are shown in the table below, sorted from best to worst. The different solutions are mentioned in the early process of finding the best solution of the problem and are shown in appendix C.

Table 2 Final scores for each solution.

Solution	Total score
Sandbags with plastic sheets	39
Plastic interconnecting plates	39
Sandbags with geotextile	37
Sandbags	36
Big bags with geotextile	35
Geotextile with armour layer	34
Street tiles	33
Roof tiles	33
Small plastic sheets	32
Sandbags with adhesive	30

Solutions 5 (sandbags with plastic sheet) and 9 (Plastic interconnecting plates) performed best. By integrating these solutions, a repair option was created which is described in the following section.

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Chapter 4: Selection and design of optimal strengthening solution

The selected repair option is to locally cover the damaged area with flexible overlapping sheets of Tyvek®. This is a light and thin material that can easily be transported and cut to size at the location of the repair. These sheets are secured against flow loads using Gripple anchors, pins are used to keep the Tyvek® in place during windy conditions. This section will include a technical description of the design, the plan for the installation of the repair and an overview of the costs.

Figure 2 Installed plastic sheets on upper damage (plastic sheet in figure is Polytex®, not Tyvek®)

Figure 3 Installed sheet with anchors lower damage (plastic sheet in figure is Polytex®, not Tyvek®)

4.1 Technical description

The repair for the levee must protect against the failure mechanisms highlighted in the problem statement. As such the repair must prevent excessive water penetrating the core of the levee (surface-slip-failure), prevent the erosion of the top layer (micro-instability) and therefore prevent a total collapse of the levee (macro-instability).
The damaged areas of the levee are covered with Tyvek® which is a waterproof, damp open material. This prevents the penetration of water into the core through the damaged areas. The Tyvek® also prevents the exposed soil from being eroded. Moreover, Tyvek® is a very strong material that won't be torn off, it could only be cut of using special cut equipment. As there is now no strength reduction due to water penetration or further loss of surface material the chance for macro instability is minimized. The overlap of separate sheets allows water from under the repair to go back to the surface, this prevents a buildup of pressure on the rear side of the repair and will mini

Loads

The permanent loads on the construction are the self-weight of the construction and the pre-tensioning of the Gripple anchors. These loads are always present. For variable loads two load cases have been identified. The first load case is overflow of the levee, in this case the flow of water over the Tyvek® generates a shear stress on the surface in the downhill direction. The second case is when no water flow is present wind could generate an uplift force that flips the Tyvek® sheets over. The magnitude of these loads

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are presented in the table below. A full calculation of these loads can be found in

			Load case
Flow	675 N/m^2	Shear stress downhill	Water
Wind	1287 N/m	Upward	Wind
Dead weight Tyvek®	0.6 N/m^2	Downward	Always present
Pretension steel cable	2.7 kN	Tension in cable	Always present

appendix B.

Table 3 Loads on repair solution

In the figure below is shown how the forces act on one sheet of Tyvek®. The calculation of the loads in shown in Appendix B.

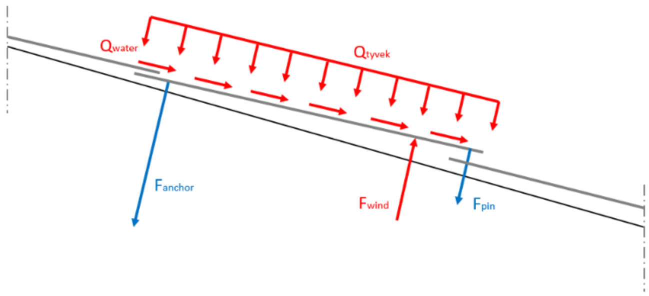

Figure 2 Loads on repair solution

Failure modes of repair
The principle of the repair is to protect the underlying soil by covering it. If the subsoil becomes exposed or erosion can occur, this is considered failure of the repair. The following failure modes of the repair and the consequences of these have been identified:

Table 4 Failure modes and consequences repair solution

	Failure mode	Consequence
1	Failure of soil around anchor	Reduction of reaction force anchor, leading to possible failure of anchor.
2	Failure of steel cable anchor	Failure of anchor leading to possible exposure of subsoil.
3	Uplift of pin	Part of Tyvek® unsecured for wind.
4	Tearing of Tyvek®	Possible exposure of subsoil.
5	Improper overlap of Tyvek® sheets	Possible exposure of subsoil.
6	Water able to flow under top edge of repair	Erosion through the repair.

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7	Hole through Tyvek®	Erosion through the repair.

Strength of elements.
The strength of the different elements has been calculated, the detailed calculation can be found in appendix A. A summary of the strengths is presented in the table below.

Table 5 Strength of elements

Pin in Sand	31.5 N
Pin in Clay	60.1 N
Soil resistance undisturbed Anchor	11.6 kN
Soil resistance undisturbed Anchor	3.87 kN
Steel Cable	7 kN
Tear strength Tyvek®	16 kN/m

Details of Design
Based on the loads, failure mechanisms and the strength of the elements the details of the repair have been designed. For irregularities of the repair such as the edges and the details of these designs are presented below.

<u>Top Detail</u>
At the top of the repair water must go from the preexisting grass cover to flowing over the Tyvek®. To ensure that this can happen the top 50 cm of the Tyvek® will be buried under the surface and existing grass cover. This will minimize the chance of failure mode 6. The placement of the anchors makes a hole in the Tyvek®. To prevent the water flowing through this hole the anchors will also be placed under the grass.

Figure 3 Drilling of TL-DTOOL anchor installation rod with GPD (plastic sheet in figure is Polytex®, not Tyvek®)

Figure 4 Flipping back of grass layer over the sheet at the upper damage (plastic sheet in figure is Polytex®, not Tyvek®)

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Anchor Detail

The anchor supplied by Gripple consists of two elements connected by a steel cable under tension. The top element provides a clamping force at the surface, this is used to secure the Tyvek®. The maximum magnitude of this clamping force depends on the strength of the cable and the maximum resistance of the soil. In the damaged state the resistance of the soil is lower thus governing for the clamping force. This also ensures that failure mode (2) cannot occur. The resulting anchor strength is then 3.89 kN. Otherwise, the strength of the cable is governing leading to a strength of 7.1 kN.

Spacing Anchors

The top plate of an anchor secures 10 cm of the Tyvek®, due to this an anchor can hold 1.6 kN. The anchors will resist the flow loads. The flow load acts on 1.5 m of Tyvek®, this means a load of 0.675 kN per m. This means an anchor spacing of 2. 3 m is necessary. For practical reasons two will be placed in the test strip of 2 m. This prevents rotation of the sheets of Tyvek®.

Spacing Pins

The main function of the pins is to hold the Tyvek® close to the surface until the anchors are placed. This will also prevent water entering under the Tyvek®. Furthermore, they will help carry the wind load.

Cliff detail

At a cliff the surface of the levee is no longer flat due to the formation of a hole. This reduces the strength of the anchors. The anchors that are placed above a cliff should be put into the ground at an angle to minimize this. There is still a reduction strength of the anchors by 50%. Reduced spacing of anchors to 1 m will ensure sufficient strength. Pins also have a reduction in strength as these are now in sand instead of clay. The cliff is also an irregularity of the surface the Tyvek® will not be in contact with the surface at all places. Placing extra pins and folding the Tyvek® will ensure it remains in contact with soil as much as possible.

Figure 5 Drilling of TL-DTOOL anchor installation rod with GPD at upper damage (plastic sheet in figure is Polytex®, not Tyvek®)

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Side Detail wider application

On the sides of the damage the Tyvek® should be extended 1 m onto the areas without damage. This ensures that if water enters under the sides of the repair it will not lead to erosion as there is still grass protecting the surface, see figure 34, the edges of the Tyvek® will be secured with extra pins.

Side Detail Test

During the tests, the sides of the repair cannot extend over the edge of the damage but must connect to boarding at the sides. A solution to this problem is found in chapter 5.

Overlap of Sheets

The placement of an anchor through the Tyvek® creates a hole. To prevent water penetrating this will be cover with another layer. The irregularities of the damage will lead to the Tyvek® not aligning perfectly, extra overlap is needed to take this into account. This is shown in figures 2 and 3.

4.2 Repair Installation Plan

The repair starts below the damaged area and works up the levee till the damaged area is completely covered. The first sheet of Tyvek® will be placed completely on levee that is still intact. Details of the plan and adaptions that were made on the day of the repair can be found in chapter 5.

4.3 Costs of the solution

In this section the made costs for the project are given. First an overview of the realized cost for the repair option is given in table 6 below. Subsequently these costs will be related to a general costs/m^2 and compared with other repair options.
With the purchased materials, two areas of (2x3.5) and (2x4,5) m^2 were covered with 6 and 8 sheets respectively. For each extra meter of height, we need one Tyvek® sheet. Looking in the horizontal direction, the amount of anchors and pins is found with the formulas below.

$$N_{anchor} = 0.70 + W * n_{sheet}$$

$$N_{pin} = 0.70 + W * 2 * n_{sheet}$$

For every additional meter of width, we need 1 anchor, 2 pins and a meter of Tyvek® roll, which is the same for the height. With this, we define the costs per meter width as 2*0.48 + 11.18 + 7 = 19.14. For each additional height meter, we also need another Tyvek® sheet, bringing the cost to 19.14 euros per meter height.

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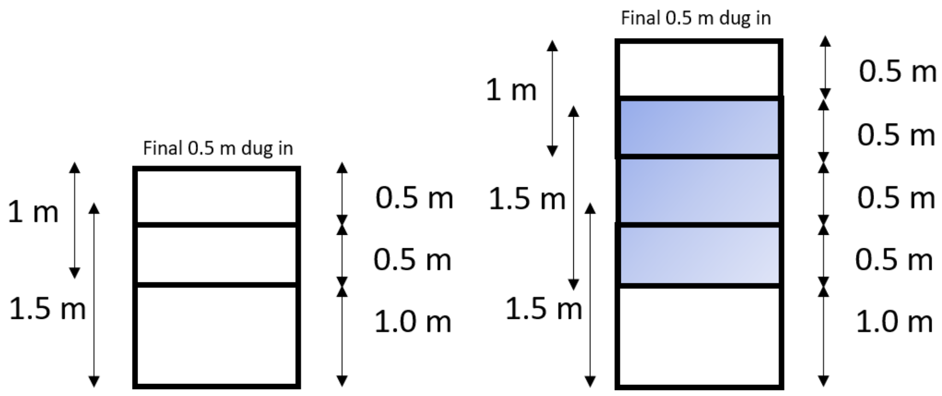

Figure 6 Lay-out and dimensions of 1.5m wide plastic sheets

With this, we can define the average cost at 20 euros, per square meter. This is without the rental costs of the GPD, JackJaw® and anchor rod under the assumption that the installing party has those purchased for a long period of time. Taking amortization costs for the installation material and a buffer for extra materials (e.g. failed anchors) we can likely estimate the installing costs to be below 25 euro/m^2.
If instead of a 1.5 meter wide Tyvek® roll, a 3 meter wide roll is used, the costs drop significantly because each sheet now covers 2.5 meters extra height. The formula for N_{sheet} changing to:

$$N_{sheet} = 2 + \frac{H - 5.0}{2.5}$$

This means less sheets are necessary to create the same height, with the width costs remaining the same. Tyvek® sheets of 3 meters wide are around double the cost, meaning 14 euros/meter, giving 26.14 euros/meter. while also significantly reducing the installation time. The logistical part of installing and transporting 3 meter wide Tyvek® sheets however could pose challenges. For the 3 meter wide sheets, the same amount of ground anchors was used, because over dimensioning was shown in section 4.1.

$$Costs\ (for\ H \leq 5) = 19.14 * 2 * W$$

$$Costs\ (for\ H > 5) = \left(19.14 * 2 + 19.14 * \frac{H - 5}{2.5}\right) * W$$

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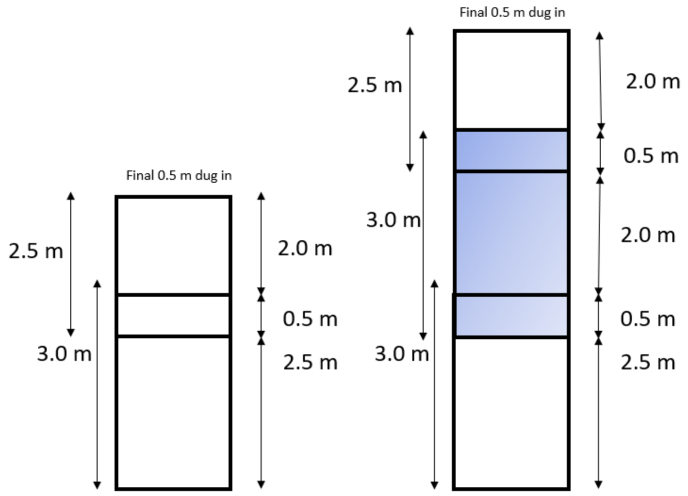

Figure 7 Lay-out and dimensions of 3.0m wide plastic sheets

By using the formula, costs for protecting a large dike section of 25 meters height and 100 meters wide would amount to almost 47.850 euros when using a 1.5 meter wide roll, whereas this would decrease with more than 50% to 19.192 euros by using the 3 meter wide Tyvek® rolls.
The costs made for the test project are shown in table 6. The actual costs are slightly different in reality, due to the negotiation of a sponsorship deal. In reality, the anchors and pins are 15% more expensive, setting their unit prices at 13,15 and 0.56 euro respectively. Furthermore, the anchor installation rod was rented for free, which usually costs a 100 euros. Moreover, the GPD & JackJaw® were rented out for 350 euros. The buying price of these is normally more than 2000 euros. Finally Polytex® sheets instead of Tyvek® sheets were used to reduce the overall costs of the project. In our opinion, the small reduction of the strength with the choice of Polytex® was acceptable due to the large price difference.

Table 6 Project costs for the selected repair options.

What	**Unit price (€)**	**Amount**	**Total costs (€)**	**Supplier**
Terra-Lock anchor (TL-A3-1m-3mm)	11.18	40	447.10	Gripple
TL-P1 (box of 200)	0.48	100	47.60	Gripple
TL-P1 installation tool	17.00	1	17.00	Gripple
TL-DTOOL anchor installation rod	0	1	0.00	Gripple
Gripple Petrol Driver & JackJaw® rent	350.00	1	350.00	Gripple

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Polytex® sheet (roll)	184.50	1	184.50	MG Bouw - Meuwissen Gerritsen B.V.
Total costs Repair (€)			**1096.20**	**Euros**

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Chapter 5: Set-up, execution and elaboration of validation tests

5.1 Log of the testing day

This section will describe the two days on the levee. The first day concerned the application of damage to the dike and the implementation of the repair solution. The second day consisted of performing the overflow tests.

Timeline day of installation

08:30 – 09:00 || Arrival & getting equipment.
09:00 – 09:30 || Explanation of area, program of the day and damage to create.
09:30 – 13:00 || Digging of damage, taking videos, finalizing design fit on damage& attempting to measure the dike profile.
13:30 – 14:00 || Start of dike repair: Cutting sheets, marking placement and gathering Gripple materials.
14:00 – 15:00 || Installing first sheets with GPD.
15:00 – 15:15 || Installing top sheet side.
15:15 – 15:30 || Finished damage at top levee side and start cutting plastic sheet and marking placement bottom damage section.
15:30 – 17:00 || Start sheet installation bottom section.
17:00 – 17:30 || Finished bottom part damage.

<u>Arrival & getting equipment</u>

Upon arrival or the location, we received an explanation of the test area, the Hedwigepolder and safety clothing (safety vests, shoes and gloves) was handed out. After this we drove to the test location. We brought the roll plastic (Polytex®) and small tools such as a drill and shovel ourselves from Delft. The anchors, pins and Gripple equipment were unfortunately not delivered in time in Delft, so would be delivered to the dike on the day itself.

<u>Explanation of area, program of the day and damage to create</u>

On site it was explained where the test strips were, how the water would be pumped up the levee and where we could find tools. The planning for the day was presented. First, each team would apply the damages to the test strip of the other team, then the implementation of the repair solution could begin. The test strip was 2 meters wide and covered the entire dike from crest to toe. The sides of the strip were made of wooden planks with stakes that were hammered into the dike. Halfway up the dike, two measuring installations were set up. Two cameras were suspended above the test strip and could capture images of the dike surface between tests. In addition, the flow velocity just above the dike surface was measured. On top of the dike, the flow velocity was also measured just above the dike surface.

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Figure 8 Measuring equipment on test strip dike

Two different damages had to be applied per test lane, both had to be done with shovels. The first damage consisted of removing the top 10 cm of grass just below the crest of the dike. The damaged area was 2 by 2 meters. This simulates that the core of the dike itself is still intact, only the cover is damaged.

Figure 9 Upper damage dike (removal of 2x2m grass layer)

The second damage was done at the bottom of the dike, at the toe of the dike. A step was dug out across the entire width of the dike with a height difference of 0.5 meters. This damage goes through the clay layer and into the sand core of dike.

<u>Digging of damage, taking videos, finalizing design fit on damage & attempting to measure the dike profile</u>

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During the digging of the damage at the toe of the dike wheel immediately noticed a difference between the two test strips. The strip where we were to test was a lot wetter than the test strip of the KU Leuven team.

Figure 10 Dutch lower damage was much more wet compared to Belgian test strip

Figure 11 Lower damage test strip

At the end of applying the damage, it was checked whether the damage was approximately the same on both test strips before starting to implement the solutions. Despite all the preparations we had made in Delft, the design was discussed again on the dike itself and minor adjustments were made. One adjustment was the folding of the plastic sheet at the sides of the test strip. This would allow the water to flow better over the plastic sheet during the tests, so that less water would flow between the sheet and the wooden planks.

We also tried to measure the dike profile with a GPS device provided by the organisation. Unfortunately, the reception with that device turned out to be insufficient to carry out accurate measurements. Thus, before installing the repair solution and the tests, we were unable to determine the exact dike profile of our test strip.

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Figure 12 GPS device

Start of dike repair: Cutting sheets, marking placement and gathering Gripple materials
After the anchors, pins and Gripple equipment were also (finally) delivered to the dike, we could start implementing our repair solution. The measuring of the installation time was started.
First, it was measured out on the dike where all the plastic sheets had to be placed and where the anchors and pins had to be installed.

Two team members started cutting the plastic sheets from the large roll plastic on top of the dyke. Several sheets were cut in succession to cover the entire damage on the top of the dike. These were then folded up so that they could be easily transported to the damage location. Due to the strong wind on the dike, it was necessary to fold the sheets.

Figure 13 Cutting of plastic sheets at top of dike in windy conditions

The other two team members started digging the trench at the same time. The plastic sheet could later be laid in here to provide a smooth transition between the crest of the dike and the repair solution. Special attention was paid to the grass layer when excavating. This was not dug away but folded away. This reduced the chance of erosion in the trench.

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The plastic sheets were first installed at the top damage, starting at the bottom of this damage. Due to the strong wind, the sheets had to be placed on the dike with four people. Three people held the sheet in place, the fourth person attached six pins, one at each corner and in the middle, at the top and bottom of the sheet. At the edges, the sheet has folded up cleanly. The pins were screwed along the sides in such a way that they went through both layers of the sheet. The drill and the Gripple attachment were used to screw in the pins.

Figure 14 Installation of pins with the drill with Gripple attachment

Installing first sheets with GPD

After the first sheet was attached to the dike surface, the first two anchors could be placed using the GPD. With limited force, the anchor foot could be pushed through the sheet, after which the GPD could be used to drive the rod into the ground. When vibrating the GPD, care must be taken to prevent the anchor plate from sliding along the steel wire. The anchor foot was driven as deep as possible into the ground, after which the rod could be pulled out. At many places on the dike this could be done manually. At a few places, the Gripple JackJaw® had to be used to remove the rod from the ground. After this, the anchor plate could be pressed against the sheet and the dike surface manually. Then the Gripple JackJaw® was used to pull the anchor. This meant that the anchor foot in the dike folded over so that the anchor could take tensile forces. Finally, the steel wire above the anchor head could be cut off so that only the anchor head was above the sheet.

Figure 16 Drilling TL-DTOOL anchor installation rod at start of drilling phase

Figure 15 Drilling TL-DTOOL anchor installation rod at almost end of drilling phase

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Figure 18 Tightening the anchor with JackJaw®

Figure 17 Tighten anchor before cutting of wire

Figure 19 Placed sheets at upper damage

Installing top sheet side

The sheets were laid out according to the designed overlapping system until we reached the last sheet. The last sheet, the upper one, was also fixed to the dike surface with pins. The top of the sheet lay in the trench. This last sheet was secured with three anchors. After this, the trench was filled with soil again and the grass flap was folded back. This finished the repair solution to the upper damage.

Figure 20 Digging trench upper damage (keeping grass layer intact by flipping it)

Figure 21 Putting upper sheet into trench at upper damage

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<u>Finished damage at top levee side à Start cutting plastic sheets and marking placement bottom damage section</u>

Now it was possible to start implementing the repair solution at the toe. Here again, the plastic sheets were first cut and folded by two group members on top of the dike. The other two group members started digging a trench just above the damage. Unfortunately, we were less successful to leave the grass layer intact at this trench. This was probably because digging on the sloping dike surface was more difficult than expected, on the other hand, the dike was a lot wetter at this location.

<u>Start sheet installation bottom section</u>

The plastic sheets laid down one by one, starting at the bottom of this damage. Also here, three people held the sheet in place, the fourth person attached six pins, one at each corner and in the middle, at the top and bottom of the sheet. At the edges, the sheet was folded up cleanly. The pins were screwed along the sides in such a way that they went through both layers of the sheet. The drill and the Gripple attachment were used to screw in the pins.

Some more pins were used to lay down the sheets at this damage because the shape of the damage was quite different. Some pins were screwed in the sides of the step. When laying down, the shape of the step was closely followed. Thus, the sheet always lay directly against the ground.

After the first sheet was attached to the dike surface, the first two anchors could be placed using the GPD. With limited force, the anchor foot could be pushed through the sheet, after which the GPD could be used to drive the rod into the ground. When installing the anchors, great care was taken to ensure that the anchor always made a 90-degree angle to the dike surface, which was more difficult at the lower damage compared to the upper damage. The anchor foot was driven as deep as possible into the ground, after which the rod could be pulled out. At many places on the dike this could be done manually. At a few places, the Gripple JackJaw® had to be used to remove the rod from the ground. After this, the anchor plate could be pressed against the sheet and the dike surface manually. Then the Gripple JackJaw® was used to pull the anchor. This meant that the anchor foot in the dike folded over so that the anchor could take tensile forces. Finally, the steel wire above the anchor head could be cut off so that only the anchor head was above the sheet.

<u>Finished bottom part damage.</u>

With the last sheet, extra attention was also paid during installation. Four anchors were finally placed in the trench to secure the sail. The intention was to use only three anchors, but during the tightening of one of the anchors it turned out that it was not working properly. When installing the anchors, great care was taken to ensure that the anchor always made a 90-degree angle to the dike surface. The anchors on both sides were also partly drilled outwards into the ground. After the last anchor was installed, the trench was filled with soil again and the grass flap was folded back. This finished the repair solution at the lower damage.

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Time line day of testing
08:45 – 09:15 || 30 min overflow test at 350 l/s.
09:15 – 09:20 || 5 min rest to inspect the repair solution and rest of the dike surface.
09:20 – 09:50 || 30 min overflow test at 500 l/s.
09:50 – 09:20 || 5 min rest to inspect the repair solution and rest of the dike surface.
09:55 – 10:25 || 30 min 600 overflow test at l/s.
10:25 – 10:30 || 5 min rest to inspect the repair solution and rest of the dike surface.
10:30 – 11:00 || 30 min overflow test at 700/740 l/s.
11:00 – 11:10 || 10 min rest to inspect the repair solution and rest of the dike surface and make tear of 1 m into lower repair area (at location where water exactly hits the sheet at the bottom).
11:10 – 11:40 || 30 min overflow test at 350 l/s.
11:40 – 11:45 || 5 min rest to inspect the repair solution and rest of the dike surface.
11:45 – 12:45 || 60min overflow test at 700/740 l/s.

5.2 Results of the validation tests

In this part, the results of the overflow tests will be described. Unfortunately, the measured results of the flow velocity and the pictures taken by the equipment of the Levee Challenge organisation could not be obtained before the deadline of this report. Therefore, we could not include these results in our findings in this chapter. The results are therefore purely based on observations by eye and analysis of the photos and videos we took.

<u>Tests without cuts in plastic sheet</u>

- During all test volumes the plastic sheets were kept in place due to the anchors and pins. This is discussed in more detail in the next section.
- Some of the pins (only at the bottom/toe side of some layers) came loose due to vibration of the sheets (we presume the cause of vibration is flow of water between two sheets or turbulence of water). This is discussed in more detail in the next section.

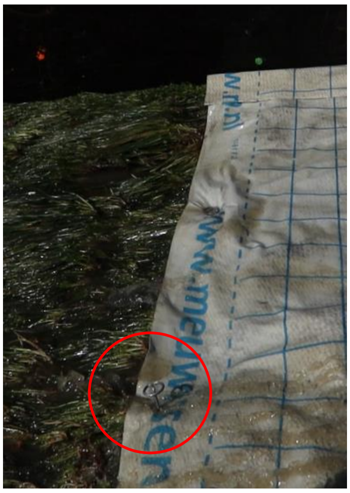

Figure 22 Loose pin at upper damage after overflow tests

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- The grass between the two damages was flattened by the current, a typical image for overflow tests. The grass remained in place, grass clumps with roots were not pulled loose by the current.

Figure 23 Grass between two damages after overflow tests

- The trench of the lower damage was partly washed away by the water. This was to be expected as the grass layer could not be kept intact when the plastic sheet was dug in. The erosion of soil in the trench did not result in changing the stability of the top sheet. The function of the buried sheet therefore remained intact. This is discussed in more detail in the next section.

Figure 24 Trench at lower damage after overflow tests

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<u>Test with cuts in plastic sheet</u>

- The lower repair failed due to high impact of water exactly on the tear. Test was done for 30 min with 350 l/s water. The tear was made through both overlapping sheet layers.

Figure 25 Torn off sheet at lower damage after overflow tests with 1m tear through both sheet layers

- The higher repair sustained all the test also with the tear. Both tears were around 1m in the middle of the test area. The tear was only made in the upper sheet of the overlapping sheets. The soil below the upper damage was not damaged further due to the overflow tests, as could be seen after removing the repair solution.

Figure 26 1m tear through two layers sheet at lower damage

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- The grass between the two damages was flattened by the current, a typical image for overflow tests. The grass remained in place, grass clumps with roots were not pulled loose by the current. So, there was no change visible between the tests with and without the cuts in the plastic sheet.

We would like to discuss here whether a cut through both layers of plastic sheet is a realistic scenario our design has to cope with. Making a cut in the top sheet was already quite difficult, a sharp knife was required to make the cuts. Could such a cut in the sheet occur in real life? If during installation of the repair solution a cut is made by a knife due to an accident, this plastic sheet can be replaced by another one. After installation such a cut could only be made due to vandalism and this can be prevented. Other things, such as branches flowing along during overflow, cannot make a crack in these plastic sheets. Therefore, we think we don’t have to improve the quality of the plastic that will be used for this repair solution.

Figure 27 Upper damage after removing repair solution after all overflow were performed

5.3 Observations of the tests

Day of installation

- Windy conditions, hard to install plastic sheets. The solution was to find a spot in the lee.
- Gripple pins were easy to install using the drill and Gripple attachment.
- The procedure of the installation of the Gripple anchors required some time at the start of the day.
- At the toe of the dike, the soil was very inconsistent. Due to soft spots in the clay layer one Gripple anchor was unable to experience resistance of the soil layer. When tightening the anchor with the Gripple JackJaw®, the anchor was pulled out of the soil.
- During installation of the plastic sheets, we experienced difficulties in the connection between the sides of the plastic sheets and the wooden panels which define our two-meter part of the Levee.
- During installation on the plastic sheets at the toe of the dike, the dugout part of the dike was covered with a pool of water which increased gradually over time.

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<u>Day of tests</u>
The first observation made is regarding the Gripple pins at the cliff damage. Gradually over time the pins came loose from the soil. This is shown in the figure below. However, the pins did not float away and were stuck in the plastic sheet due to the spiral shape at the end of the pins. The pins are not damaged and therefore can be re-used. Some water was flowing below the wooden side boards, this could have influenced the results of the tests.

Figure 29 Water flowing under wooden side boards

Figure 28 Lower damage after overflow tests were performed

In the figure below the part of the dike is shown between the cover damage at the top and the cliff damage at the toe of the dike. It can be seen that no damage has occurred on this part. This is due to the resistance of the cover of the dike. The roots of the grass are strong enough to prevent any erosion of the surface.

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Figure 30 Grass between two damages after overflow test were performed

After a few tests we experienced some leakage between the plastic sheet and the wooden side boards. In figure 34 is shown how this boundary is dealt with. The plastic sheets are cut in stretches of three meter, so at both sides the sheets are folded upwards to prevent water flowing between the wooden side boards and the plastic sheet. However, due to the large forces and turbulent water flow, water was able to find a way between the plastic sheet and the wooden panels, this is shown in figure 31. This however made no significant difference in the damage as the velocity and amount of water was not very large.

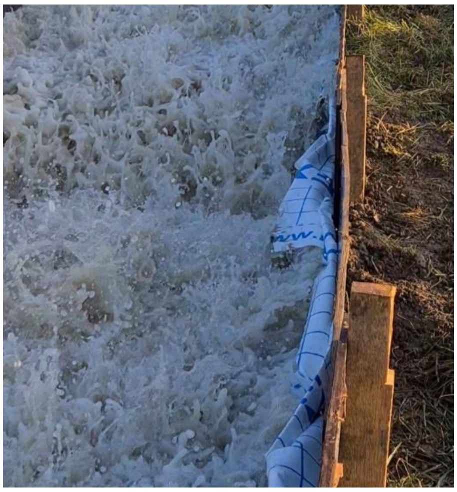

Figure 31 Water-overflow at the boundary with the wooden panels

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One damage occurred relatively quickly, which was at the top of the cliff, where the top plastic sheet is fixated to the levee. Here the same fixation is applied as to the top of the dike, see figure 22 and 23. Here the top part of the sheet is applied under a small strip of soil. The case however at the cliff is that the soil was too loose and the fixation of the loose soil to the rest of the soil was not strong enough. This problem did not occur at the top of the levee, where the same method is applied. Due to the loose soil, the fixation was not enough, and the soil eroded away. This is shown in the picture below, which was taken after the second test.

Figure 32 Double folded sheet at side of the test strip

Figure 33 Trench at lower damage after overflow tests were performed

Removal of the repair solution

The removal of the repair solution is described here. First, the pins could be pulled/twisted out of the ground. After this, the plastic sheets could be pulled away from the surface of the dike. This left only the anchors in the dike. Around the anchors, some soil was removed to free up the entire anchoring plate. Some anchor heads could easily be released from the steel wire by using the release mechanism. At other anchor heads, too much mud had gotten into this system, or the steel wire above the anchor head split too much, making this mechanism inoperable. To remove these anchor heads anyway, the steel wire was simply cut. The anchor feet and the steel wire therefore remained in the dike body.

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Chapter 6: Improvement points to the design

6.1 Technical design improvements

To the design the main improvement that can be made is using plastic sheets with a higher strength as this is the weakest link in the solution, increasing the strength by 50% will allow for a better optimization of the anchor spacing. Using rolls of 3 meter will also have a beneficial effect on the ease of installation and the costs. Now wanted to test applicability of solution to larger scale damages and therefore wanted seams in damaged areas to test if this works.
Further improvements to the design can mostly be made in the execution phase. The speed and quality of construction of the top detail could be improved by the use of an excavator to lift a flap grass and topsoil. As the grass moves more as one mass then the chance that the roots will stay intact is larger.
Some small details lead to preventable initial damage. The cables of the anchors must be accurately trimmed within the top plate of the anchor this will prevent the puncturing of the plastic sheet. Not all pins were completely installed into the ground, a more powerful drill could help in this process. Furthermore, the installation of the pins lead to holes in the plastic sheet, finding a solution to this problem would be helpful.

6.2 Installation plan improvements

During the experiment it was experienced how it was to actually install the designed solution. Two main problems were identified. First, the wind that is most likely even more present on a dike in storm situations, made it difficult to install and move cut plastic sheet pieces around. Second, the team interchanged the different activities (holding plastic sheets, installing anchors etc.) almost randomly. With this knowledge, it is possible to create a clear and structured installation plan that solves both problems and optimizes installation time.

Installation is optimally split up in two groups of two people. The first team will be responsible for placing the plastic sheets, whereas the second team will install the ground anchors.

The first team will start at the bottom of the dike or a few meters below the damage in the dike. The end of the roll will be fastened on top and bottom side to the dike with a drill by one person, while the other holds the roll. The pair will then move horizontally along the dike, fastening the roll with a pin placed every meter on bottom and top side. They should ensure a tight fit against the dike and keep a small amount of plastic unrolled to keep wind catchment to a minimum. If the width is less than 50 meter, the roll will be cut with a knife when sufficient length has been reached.

The second team walks behind the first pair with ground anchors, GPD and JackJaw®. The first person installs an anchor every meter in between the pins, whereas the second person tightens the anchors with the JackJaw® and cuts the extracted cable.
The first team will redo the procedure above the first stretch, covering the anchors placed by the team. When the top row has been reached, only pins at the bottom side will be placed. Before placing the anchors, all four will work on digging the trench. When the trench is finished the first team can place the pins, followed by the second team placing the anchors. When the first team is finished, they can start replacing the soil on top of the anchors.

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When only three people are available, the second team will be reduced by one. The responsibility for cutting off the extracted cable after tightening with the JackJaw® will shift to the first team, before they start placing the stretch above. Installation with only 2 people is also possible but will take up twice as much time.

6.3 Improvements to the removal of the solution

Removing the solution was relatively easy due to the lightweight nature of the plastic sheet. However, two main problems were experienced. First, it was deemed difficult to cut off the heads of the ground anchors during de-installation. Second, a large part of the metal ground anchors remained in the dike, which can be seen as unsustainable.

The first problem can be fixed by using a strong wire cutter during the removal, by simply cutting the head of the cable off. This can possibly be done through some depth of soil. Removing a large portion of the anchor however remains difficult. If this is preferred, a special tool could be designed that is attached around the cable just below the head, subsequently driven into the soil up to above the anchor itself and finally cutting the cable there to allow the extraction. It seems infeasible to remove the Gripple anchor that is blocked 1 meter into the soil.

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Chapter 7: Application to different situations

In the Levee Challenge the assignment was to apply our solution to a two-meter wide part of the dike. The experimental part of the levee was bounded by wooden sheets approximately one meter long. The wooden sheets are stiffened by wooden piles attached to the ground. The assignment described to find the perfect solution to the problem where these boundary conditions must be kept in mind. We found the appropriate sheets, the Polytex® sheets, which would fit in this two-meter wide section. The required length of the plastic sheet needed to repair the local damage was not a limiting factor as the plastic sheets could easily be cut to the required length.

One advantage of our solution is that the repair of the damage is selective, i.e. the solution is only applied to the parts of the levee where damage has occurred. In case of very localized and small damage to the levee, the costs and workload are very minimal compared to solutions where the solution is applied to the entire surface area of the levee. One problem however, is that the length of the plastic sheets is fixed, and in case of damages larger than the length of the plastic sheets, new problems arise. If no longer sheets are available, the sheets must overlap not only in the direction of the water flow but also perpendicular to the flow of water, which is a problem harder to solve. Rolls with a length of 100 m are available, if such a damage occurs, the dike has likely already failed.

In our solution we choose not to use sandbags to fill the damage caused by overflow. We choose not to use sandbags to save time and costs of the solution. However, during the last test where a cut was made in plastic sheet at the bottom of the dike, the forces of the overflow from the cliff were too large which caused the ground under the plastic sheet to erode. This is what happened when a cut was made in the plastic sheet, shown in the figure below. The amount of damage in this case is dependent on the soil type and the saturation of the soil. But this damage only occurred when a cut was made in the plastic sheet, which happens rarely and can only be caused by vandalism. From the cliff damage we can conclude that the Tyvek® sheets are a good solution to the non-uniform shape of the damaged slope, in the axial and in the lateral direction.

Figure 34 Torn off sheet at lower damage after tear was made

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Chapter 8: Motivation for the selected solution

Our solution is designed to protect any dike from macro-instability by keeping the water flow away from the berm. This is done by layering multiple sheets of plastic foil over the inner berm, fastened with ground anchors and pins. The solution is a durable and reliable design due to proven waterproof, damp open and UV resistant properties, together with Gripple's demonstrated anchoring capabilities.

The solution has three main strengths:
1. Easy Installation
2. Cheap
3. Reliability

First, its easy instalment will prove invaluable during an emergency, during which time is of the essence. With only two to four people requiring no special technical training, a large dike stretch can be protected in a matter of hours. The small amount and light-weight nature of the materials ensure that logistics will not pose a problem, also during stormy conditions that make dikes difficult to enter.

Second, the materials are relatively cheap for larger sections. Also because no machines or large area is necessary for storage, the maintenance costs to have this solution in stock is low.

Storage brings us to the third point of reliability. Because the materials are made of durable plastics and steel, storing the materials for longer periods of time until a calamity occurs is unproblematic. The plastic sheet would be the most problematic, but can be stored for many years as long as kept outside of direct sunlight. The UV resistant properties of the plastic sheet protect it from sunlight during its installation outside. These factors ensure the reliability of the solution, also after prolonged periods of storage. If any damage occurs to the solution as in the tests, this could be easily seen through movement of the plastic sheets and repaired with extra pins. Finally, the flexibility of the solution ensures reliable applicability with different dike-geometries, and together with the absence of sandbags, easy scalability to large dike-damages.

The solution performed as expected in the tests, with the further improvements described in this report mitigating the largest shown risks. With this updated design, our solution is optimally prepared to protect dikes from overflow and following macro-instability.

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Chapter 9: Discussion

After presenting the results and improvement points, a few points of discussion remain. First, an unexpected problem was the vibrating of the plastic sheets that resulted in the extraction of the pins. It's uncertain what the long-term effect of this phenomena is, but the process may likely give positive feedback and result in a large amount of deflection. If the sheet is not tight on the dike anymore, water will flow under it resulting in erosion. Further research into mitigating this effect will be necessary. This could simply include installing more pins or trying out different straight pins to reduce the free margin around the installation point.

A second point of concern is the proposed use of a 3 meter wide plastic sheet. Although this will reduce installation costs and time significantly, applying this sheet size under storm conditions is likely problematic. This can be best tested out by waterboard personnel in a storm situation to see the actual effects.

Third, the effects of installation errors at the head of a plastic sheet section are not yet known enough. Some initial damage was seen at the head of the bottom section, but did not propagate. Although it is unlikely that water will flow under the sheet immediately because of its curved vertical installation, it remains a critical point. What happens during installation if the soil layer is very weak after digging? Installing another sheet over the head might be a solution, but this will need to be tested further to give a reliable advice.

Fourth, a large part of the anchors remains in the dike, irrespective of the proposed solution in section 6c. Although we believe this problem to be inferior with respect to the reliability and installation time during a calamity at which human lives are at stake, it remains a drawback of the solution.

A final consideration is the difference in material between our used Polytex®, a Tyvek® substitute. Although Polytex® has much lower costs, the UV resistance and quality of Tyvek® might be beneficial when storing and installing the solution for prolonged periods. More research on the material qualities can contribute to the actual reliability.

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Chapter 10: Conclusion and recommendation

Concluding, the presented Tyvek design is an interesting solution that may well be a good contribution to the future flood protection arsenal of waterboards and other governments. The benefits related to low production costs, easy installation, and reliable storage and scaling make this innovative solution a possible advancement from classical flood protection measures, like sandbags. Further research is advised to analyse and mitigate the presented weaker spots and drawbacks.

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Appendix A: Structural Analysis, Anchors and Pins

In this Appendix, the structural analysis of the pins and anchors will be described in detail [3][4].

Strength Pin:
The pins have an installation depth of 0.2 m. The clay layer on the surface of the levee is 0.5 m thick therefore in the parts of the levee without damage the pin is placed in the clay layer. If the pin is placed in a damaged part of the levee the thickness of the clay layer will be reduced leading to part or the full pin being installed into sand. For the calculation of the strength of the pin in the sand the clump criterion calculation will be used. This calculation is done in Newtons and meters. Pin has influence radius of 0.05 m and an installation depth of 0.2 m. For the weight of the sand a reasonable value of 17000 N/m^2 is used. The resulting strength is:

$$F_{pin,sand} = \pi * 0.05^2 * 0.2 * 17000 = 31.4\ N$$

In clay there will be an additional strength due to the cohesion of the clay, this will be taken into account by increasing the radius of influence to 0.075 m.

$$F_{pin,clay} = \pi * 0.075^2 * 0.2 * 17000 = 60.1\ N$$

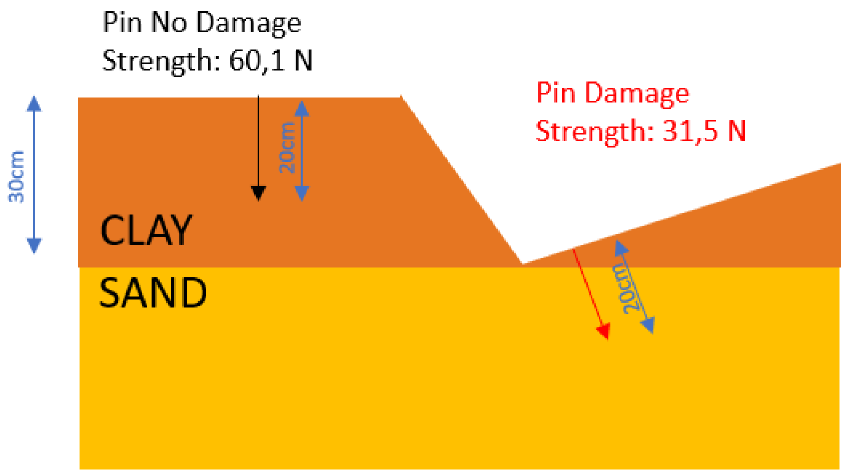

Figure 35 Pin strength

Strength Anchor:
The Gripple anchor has a cable length of 1m as this cable is pulled out of the ground for tensioning the final installation depth is between 0.9 m and 0.8 m. 0.8 m will be used as the installation depth to be conservative. For all cases this will result in installation into the sand core of the levee. As there are many uncertainties with the calculation of the strength a factor of safety (FOS) of 2 will be applied. The Hergarden (1983) anchor formula will be used to calculate the strength. For sand this is:

$$F_r = 0.4 * A_a * q_c \ / \ FOS$$

The anchor 2 from Gripple has a surface area of 0.00387 m^2 (A_a). For the anchors with no damage a soil resistance (q_c) of 15000 kPa will be used. This equates to 15 000 000 N/m^2. This is relatively high for sand near the surface however the tensioning of the cable causes an increase in strength. This results in an anchor strength of:

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$$F_{r,inital} = 0.4 * 0.00387 * 15000000 / 2 = 11600\,N = 11.6\,kN$$

For the anchors that are entered near a significant damage the insertion length is decreased and the soil is more disturbed to compensate a q_c of 5000 kPa will be used. This is 5000000 N/m^2. This results in an anchor strength of:

$$F_{r,damage} = 0.4 * 0.00387 * 5000000 / 2 = 3870\,N = 3.87\,kN$$

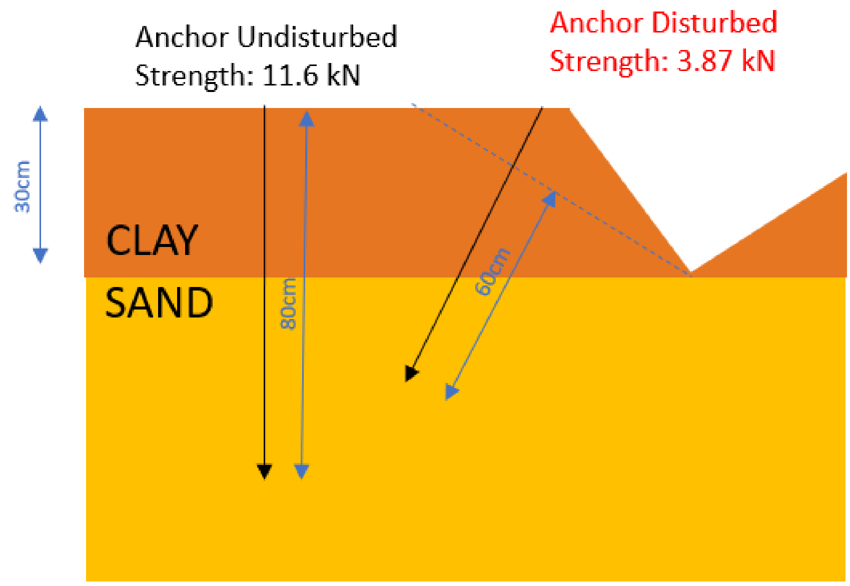

Figure 36 Anchor strength

<u>Cable Strength:</u>
The cable has a diameter of 3 mm, and the high tensile strength steel used has an ultimate tensile strength of 1000 MPa, which is also 1000 N/mm^2. This leads to a strength of:

$$F_{wire} = \pi * r^2 * UTS = \pi * 1.5^2 * 1000 = 7069\,N = 7.069\,kN$$

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Appendix B: Structural Analysis, Loads

Consequence class

The consequence class states, as the name suggests, the severity of the consequences in case of failure. The classes are defined based on the loss of life and the economic, social and environmental consequences. There are three consequence classes, from CC1 where there is small of negligible consequences on the aspects mentioned above, to CC3 where the consequences will be large. The considered consequence class determines the value K_{KI} which has to be multiplied with the load factors.
For the Levee Challenge the considered consequence class is CC2. The reason why CC3 is not considered, is because the levee is already subjected to overflow and thus the dike has already failed. However the goal of our solution is to prevent further damage to the levee, and if the solution is not applied the levee will be subjected to more forces and eventually fail further which may lead to unrepairable damage.
The K_{KI} value of consequence class 2 is 1,0.

Load combinations

Every structure has to comply with two possible limit states which are directly related to the reliability (strength) and usability of the structure. The Ultimate Limit State (ULS) is used to check structural safety and the Serviceability Limit State (SLS) is used to check usability. The usability of our solution to the problem, protection of the levee, is not relevant and thus the SLS will not be considered.
Load combinations consist of an combination of design values of the permanent loads and variable loads. In our solution the only permanent load is the self-weight of the sheet. The two variable loads are the loads present due to overflow of water and the wind load. These two variable loads may act simultaneously. Other loads are not considered in this analysis.
The formula for the ULS is:

$$\gamma_G \cdot G_k + \gamma_{Q;1} \cdot Q_{1;k} + \sum(\gamma_{Q;i} \cdot \Psi_{0;i} \cdot Q_{i;k})$$

Permanent loads

The only permanent load G_k is the self-weight of the Tyvek® sheet. The weight of the Tyvek® sheet is 60 g/m^2, which is 0,6 N/m^2.

Variable loads

Two variable loads are considered, the load of the overflow and the load of the wind. First the load from the overflow of water.

The flow load will be calculated by determining the shear stress using a terminal flow velocity approach [5].

q = 0.35 [m^3/s]
g = 9.81 [m/s^2]
alpha = arctan(1/3) [rad] (maximum slope)
f = 0.17 [-] (estimation for Tyvek®)

$$U_{terminal} = \frac{8 * g * q * sin(\alpha)^3}{f} = 5.2\ [m/s]$$

Using this the bottom shear stress formula with u is the terminal velocity and the density of water as 1000 kg/m^3.

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$$\tau = \frac{f * \rho_w * u^2}{8} = 675\ [N/m^2]$$

The other variable load considered is the wind load. The Tyvek® sheets may be subjected to forces due to wind forces acting perpendicular to the dike, show in the figure below.

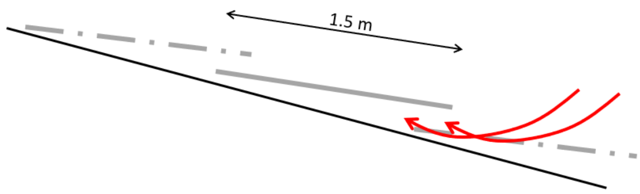

Figure 37 Wind force acting on the Tyvek® sheets.

The wind force acting on one sheet of Tyvek® is given by the simplified formula for wind loading:

$$F_i = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

In this formula $c_s c_d = 1$, c_f is the force component, $q_p(z_e)$ is the peak velocity pressure at the reference height and A_{ref} is the area of the sheet.
The location of the resulting force on the wind is shown in the figure below.

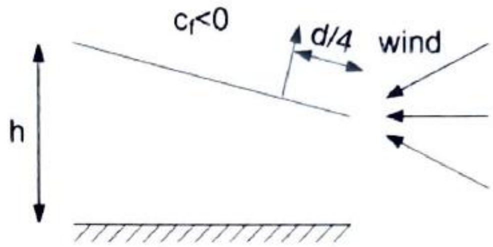

Figure 38 Wind zones for canopies [2]

The value of c_f is determined according to NEN-EN 1991-1-4 [2], which in our case with an angle of the levee of approximately 15° (≈1:4) is equal to -1,1.
The value of $q_p(z_e)$ is dependent on the location and height of the structure. According to the NEN, the considered windregion in The Netherlands is Area 2 Coastal. With an assumed average height of 1 meters (the Tyvek® sheets are in contact with the levee), the value for $q_p(z_e)$ is equal to 0,78 kN/m^2 [2].
The forces on the sheets is considered per unit length over the width of the dike. The value of A_{ref}, the area of the sheet, is therefore assumed as 1,5 meters, the width on one Tyvek® sheet.

The wind force acting on the Tyvek® sheets thus is equal to:

$$F_i = 1 \cdot 1{,}1 \cdot 0{,}78 \cdot 1{,}5 = 1{,}28\ kN/m$$

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This force acts on the sheets as shown in figure 4.

Because the downward force and self-weight of the water is much greater than the upward force of the wind, the situation where both variable forces act at the same time is not relevant. The situation where there is only the variable wind force is significant, as in this case the Tyvek® sheet could separate from the levee.

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Appendix C: Other solutions and concept sketches

Prior to choosing our solution, different options were considered, which were evaluated based on the criteria in table 1. The different options were existing options and new solutions. The solutions, some with concept sketches, we considered in the early stage of the project are shown below.

Sandbags - With this repair option a couple of sandbags will be placed in the holes of the dike and /or on dike surface.

Plastic sheet covering the inner berm – A plastic sheet will be placed on the surface of the inner berm. This sheet will reduce the erosion of the inner dike surface but makes is difficult for the water in the dike body to flow out of the dike. A semi-permeable plastic sheet could resolve this problem but could also increase the costs a lot compared to a normal plastic sheet. This will be more explained at the repair option 'geotextile'. To stabilize the plastic sheet on the dike surface, a couple of sandbags or stakes could be used.

Figure 39 Concept sketch plastic sheets

Small plastic sheets on stick - Small plastic sheet (for example 0.3x0.3m) on sticks could be placed on the surface of the inner part of the dike. The sticks are manually pushed into the dike body and the sheet covers the surface. Overflowing water will flow over the sheets and at the same time, water could flow out of the dike body because the separated smaller plastic sheets. Special attention must be paid to prevent the overflowing water to flow under the plastic sheets. The stick must have enough pulling resistance to prevent pulling out of the ground. When one of the plastic sheets on a stick will be demolished/pulled out of the ground, the other ones won't immediately fail, although a chain reaction of failing of plastic sheets could be triggered.

Figure 40 Concept sketch plastic sheets on stick

Plastic plates with interconnecting edges - Plastic plates will be placed on the inner dike surface. The edges of the plates are interconnecting, to prevent local failure.

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Figure 41 Concept sketch interconnecting plastic plates

Geotextile - A geotextile could be seen as an advanced plastic sheet covering the inner surface of the dike. The geotextile will function like a drainage system but prevent erosion of the dike surface.

Street tiles - With this repair option, an armour layer of street tiles will be placed on the inner dike surface. The word ‘placed’ means that the street tiles are not randomly positioned on the dike surface.

Figure 42 Concept sketch street tiles

Sand mixed with adhesive - A layer of sand mixed with adhesives will be placed on the inner part of the dike. The adhesive increases the cohesion of the mixed material and so increases the erosion strength of the dike.

Figure 43 Concept sketch mixed sand

Big bags - This option could be seen as very large sandbags placed on the inner surface of the dike.

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Figure 44 Concept sketch big bags

<u>Geotextile with armour layer on top</u> - This repair option is a combination of the geotextile repair option and placing an armour layer on top of the dike surface.

Figure 45 Concept sketch geotextile with armour layer

<u>Something that guides the water (e.g. open pipe or open plate)</u> - Overflowing water will be guided into a pipe/open plate on top of the dike. In this way erosion of the dike by the overflowing water is prevented.

<u>Roof tiles coverage</u> - This repair option consists of plastic sheet (with for example a size of 0.3x0.3m) that will be placed on the inner dike surface. The difference with the 'small plastic sheets

As mentioned before, these options are evaluated based on the criteria shown in table 1. The score of each solution is shown below. The total scores of the solutions in shown in table 2. Based on these scores, the solution is chosen.

Table 7 Multi-criteria analysis repair solution concepts

Criterium	Value	Sandbags	Sandbags with geotextile	Sand mixed with adhesive	Big bags with geotextile	Sandbags with plastic sheet	Geotextile with armour layer	Small plastic sheets	Street tiles	Plastic interconnecting plates	Roof tiles
Work load	3	3	2	1	2	2	1	1	1	2	1
Scalable	3	2	2	2	2	3	3	2	2	2	2
Reliability	3	1	3	3	3	2	3	2	1	3	1
Costs	2	3	2	1	2	3	1	2	3	2	3
Widely applicable	2	3	2	2	1	2	2	2	2	3	2
Innovative	2	1	2	2	2	2	2	3	3	2	3
Removability	1	2	2	1	2	2	1	2	2	2	2
Sustainability	1	2	2	1	2	2	2	1	3	2	3
Total		36	37	30	35	39	34	32	33	39	33

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