TEMPORARY FLOOD BARRIERS

BSc Thesis TU Delft

Famke Michielsen

Delft, June 2023

Colophon

Title
Temporary Flood Barriers

Author
Name: Famke Michielsen
5168724
E: f.michielsen@student.tudelft.nl

Fist supervisor
Name: Davide Wüthrich
E: d.wüthrich@tudelft.nl

Second supervisor
Name: Roelof Moll
E: j.r.moll@tudelft.nl

Preface

This BSc thesis is part of the Bachelor Civil Engineering at Delft University of Technology. The objective of this report is to investigate how video analysis can be used as a new monitoring tool for the behaviour of temporary flood barriers.

I would like to thank my supervisors Davide Wüthrich and Roelof Moll for their guidance, support and feedback during my BSc thesis. I also would like to thank Kou Wai Chan for helping me throughout the entire process and answering all my questions. Furthermore, I would like to thank Jean-Paul de Garde for helping out during the tests in Roermond. Lastly, I would like to thank all the parties that helped making the tests in Roermond possible.

Famke Michielsen

Delft, 23 June 2023

Summary

In this report temporary flood barriers are investigated. Temporary flood barriers are barriers that are installed during a flood event and are removed after the flood event. With the increasing climate change effects, flood events are becoming more frequent. During floods, sandbags are often used as temporary flood barriers. Filling and placing sandbags is time-consuming and requires a lot of manpower. That is why in this report other forms of temporary flood barriers are investigated, namely the Mobile Dike, Boxwall and Geodesign Barrier. The research question that is answered in this report is:

How can video analysis be used as a new monitoring tool for the behaviour of temporary flood barriers?

This question is answered by investigating the failure mechanisms of the temporary flood barriers and by testing the temporary flood barriers on a test site in Roermond, The Netherlands. Five cameras were installed to observe the water levels. Furthermore, the water levels were measured by divers that measure the hydrostatic pressure, from which the water level can be derived.

All the temporary flood barriers remained stable during the tests. This was not predicted in the failure mechanism calculations, which indicated that the Boxwall and the Geodesign Barrier were not stable when no water was present. In the calculations the wind force for the design of structures was used. During the tests there was a much smaller wind force, which explains why the flood barriers remained stable.

The water level was detected in two ways: with cameras aimed at water level scales and with divers. Graphs were made of the water level plotted against the time. The graphs from the water level scale data resemble the graphs from the diver data, but the graphs from the diver data are much more precise.

Video analysis can be effectively used as a new monitoring tool for the behaviour of temporary flood barriers. In this report is focused on water level monitoring, but for further research, video analysis can also be used to detect deformation, displacement or damage of the temporary flood barriers. Another possibility for further research is the use of video processing techniques in Python to improve the accuracy of the water level detection in the video analysis. Video analysis can also be used to detect the water level before the temporary flood barriers are installed. If the water level exceeds a certain value, a signal can be given indicating a flood and the need to install the temporary flood barriers.

Table of contents

1. Introduction

With the increasing climate change effects, the chances of floods increases as well. An example of these floods is the flood in Limburg, The Netherlands in July 2021 (Rijkswaterstaat, 2022). This flood was caused by heavy rains and the rivers could not handle all this water. Traditionally, flood protection is organised with permanent flood barriers (Ogunyoye & van Heereveld, 2002). Temporary flood barriers can also be used, for example in the form of sandbags. Sandbags have many disadvantages, as it takes a long time to fill the bags with sand and to place the sandbags. Also, it requires a lot of manpower (Damen, 2022). However, there can be many other forms of temporary flood barriers. These temporary flood barriers are more flexible than permanent flood barriers. They can be really helpful where permanent flood barriers offer insufficient protection. That is the reason why in this report temporary flood barriers are investigated.

1.1 Problem analysis

Temporary flood barriers are barriers that are installed during a flood event and are removed after the flood event. The results of failure and unsuitability of flood barriers can be disastrous, therefore there has to be done more research about these temporary flood barriers before they can be used more widely. The difference between temporary and permanent flood barriers is that temporary flood barriers only fulfil their function when the barrier is closed in time, which means before the lowest allowable water level has been reached. When using temporary flood barriers, not only the design of the flood barriers itself is important, but also the mobilisation, installation and closure of the flood barriers (Ogunyoye & van Heereveld, 2002). In this report, the traditional method of temporary flood barriers, sandbags, is considered first. After that three types of other temporary flood barriers are investigated: Mobile Dike, Boxwall and Geodesign Barrier. These three types are tested on a test site in Roermond on the 10th and 11th of May 2023. These three types are selected based on an administrative and technical selection. The companies from the barriers must have submitted a complete and correct application. The barriers also need to have a minimum score of ‘good’. This score is based on 14 evaluation criteria, such as the time needed for setting up the barrier and the displacement of the barrier. All the evaluation criteria can be found in Appendix B.

1.2 Objective

The objective of this report is to evaluate the performance of the Mobile Dike, Boxwall and Geodesign Barrier. This is done by tests on the 10th and 11th of May 2023. The tests will be explained in more detail in Chapter 2. The water levels in the tests are measured in two ways. This report will compare these two results and draw a conclusion from these results. This report will answer the following research question:

How can video analysis be used as a new monitoring tool for the behaviour of temporary flood barriers?

To answer the research question, the following sub-questions are formed:

- *What are the failure mechanisms of the temporary flood barriers?*
- *How can 5G monitoring system be used to assess the stability of temporary flood barriers?*

1.3 Methodology

The tests take place in Roermond, The Netherlands. The objective of these tests is to assess the three types of temporary flood barriers. There are five cameras installed to monitor the displacements of the flood barriers and observe the water levels and amount of leakage. The cameras are aimed at four different water level scales so that the water levels can be observed during the tests.

Furthermore, the water levels are measured at two places by divers that measure the hydrostatic pressure, from which the water level can be derived. In this report the two different ways of measuring the water levels will be compared.

1.4 Outline final report

The outline of this report is as follows. In the second chapter, there is a detailed description of the tests in Roermond. In the third chapter, a literature study is done about the three types of temporary flood barriers that are investigated. In the fourth chapter, the failure mechanisms of the temporary flood barriers are calculated. In the fifth chapter, de data from the cameras and from the divers are analysed and a comparison is made between the two different ways of measuring the water level. The report ends with a conclusion and gives recommendations regarding further research.

2. Description of the tests in Roermond

In this chapter the tests in Roermond are explained in detail. The purpose of the tests is explained and information is given about the organisations that made the tests possible.

The first day of the tests the Geodesign Barrier will be tested, the second day Mobile Dike and Boxwall. The Geodesign Barrier will be tested on two lanes: on asphalt and on grass. The Mobile Dike will only be tested on grass and the Boxwall only on asphalt. A water pump is installed at the top of the asphalt lane. A map of the test site with the two lanes and the location of the five cameras can be seen in Appendix C.

The first part of the asphalt lane is on a slope, the purpose of this part of the test is to see if the barrier is able to transfer the water. The second part of the asphalt lane is on a horizontal surface. The purpose of this part of the test is to see if the barrier can withstand rising water and prevent it from passing through.

The tests are organised by Waterboard Limburg ('Waterschap Limburg'). The test is only conducted with the temporary flood barrier companies that have submitted a complete and accurate application. The Geodesign Barrier, Mobile Dike and Boxwall are selected based on the previous requirement and on the 14 evaluation criteria that can be found in Appendix B. During the tests, Waterboard Limburg evaluates the three temporary flood barriers and selects the flood barrier they will purchase and use in future floods. The temporary flood barrier companies have already tested their own barriers multiple times, but Waterboard Limburg will purchase one of these temporary flood barriers and therefore wants to see for themselves which flood barrier works best. What is unique about these tests is that the temporary flood barriers are tested on two different surfaces, namely grass and asphalt.

The test is completely monitored by five cameras that are installed at the test site. The cameras are connected to laptops and this way the test is recorded. Also, a diver is placed on the grass lane and on the asphalt lane. These divers measure the hydrostatic pressure, from which the water level can be derived. This is done by the company AccessHub B.V., a Dutch scaleup that is specialised in monitoring and processing data.

3. Literature study

In this chapter sandbags and the three types of temporary flood barriers that are used at the test field location are investigated.

3.1 Sandbags

For a long time, sandbags have been used as temporary flood barriers. Advantages of using sandbags are that it is cheap and familiar to many people. Disadvantages are that filling the bags with sand and placing the sandbags takes a long a time and requires a lot of manpower (Damen, 2022).

Sandbags are made of jute or plastic. The bags are not completely filled with sand, but only for two-thirds full. This is because a sandbag that is completely filled cannot provide a good seal with other sandbags. When the bags are filled with sand, the bags are tied tightly or sewn shut. Water enters the sandbags and causes saturation of the sand, which is the optimal point for the temporary flood barrier. Filled sandbags have dimensions of 30 x 60 x 6 cm. The weight of a sandbag should not be larger than 15 kg, because otherwise people who are building the barrier will become tired too quickly (WIKI-noodmaatregelen, n.d.).

Placing the sandbags must be done very thoroughly. The sandbags need to be placed parallel to the waterflow. The minimum height of the barrier should be 15 cm (WIKI-noodmaatregelen, n.d.). To build a barrier of 19 m length and 60 cm height, approximately 600 sandbags are needed. It is estimated that building this barrier with 3 people takes approximately 3 hours (Damen, 2022).

3.2 Mobile Dike

3.2.1 General information

The Mobile Dike is a temporary flood barrier that consists of PVC tubes that are filled with water (Haase, 2021). The Mobile Dike is self-supporting and can stand on any solid ground. Moreover, the dike can easily be set up by untrained man (ProQuest, 2014).

The Mobile Dike consists of three components, as can be seen in Figure 1.

- Component 1 is the dike body. Two or three dike bodies are part of the Mobile Dike. The dike bodies are filled with water and are responsible for the self-weight of the dike.
- Component 2 is the net cover. The net cover ensures the stability of the dike by holding the dike bodies together. All the forces that the dike experiences are absorbed by the net cover (Mobiele Dijken Nederland BV, 2016).
- Component 3 is the sealing membrane. The sealing membrane prevents the water from going underneath the dike. Without a sealing membrane the dike fails at 60-80% water level (Mobiele Dijken Nederland BV, n.d.).

With these three components, the mobile dike can turn 100% of its own height (Mobiele Dijken Nederland BV, 2016).

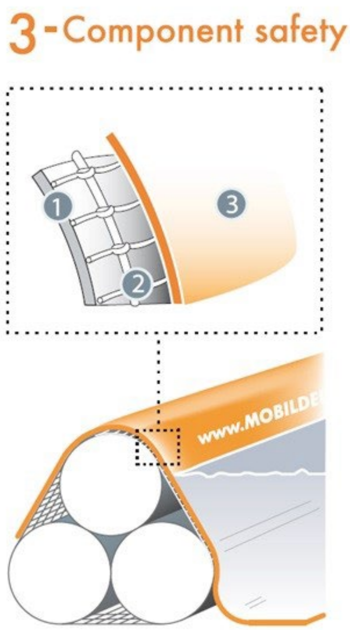


Figure 1: Components of a mobile dike (Mobiele Dijken Nederland BV, 2016)

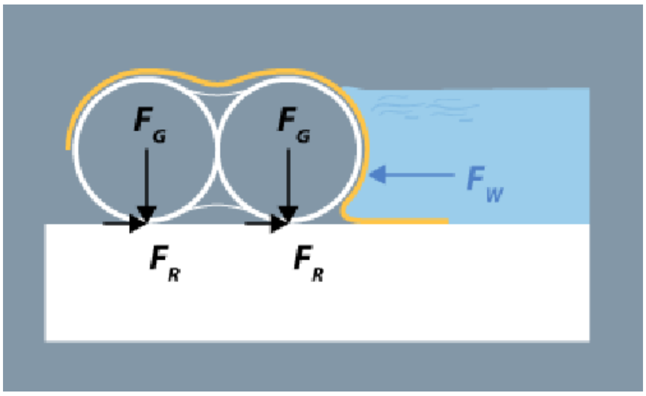


Figure 2: Forces on the Mobile Dike (Mobiele Dijken Nederland BV, n.d.)

In Figure 2 the forces on the Mobile Dike can be seen. The weight of the two dike bodies filled with water creates two gravitational forces (F_G) that act at the centre of mass. The water causes a force that acts perpendicular on the Mobile Dike (F_W). The water force is opposed by the resistance force (F_R).

3.2.2 Limitations and strengths

The limitations and strengths of the Mobile Dike can be seen in Table 1.

Table 1: Limitations and strengths of the Mobile Dike

Limitations	Strengths
A water pump is needed to fill the barrier	People can walk over de barrier
Membrane needs to be cleaned after using	Quick and easy to set up

3.2.3 Dimensions of the Mobile Dike used during the tests

The Mobile Dike model that is used during the tests is the MD60-2. This barrier has a height of 60 cm and consists of two dike bodies (D. Bon, personal communication, May 26, 2023). Two barriers are coupled to each other, the first barrier has a length of 36 m and the second barrier a length of 22 m. Both barriers have a width of 4.4 m.

3.3 Boxwall

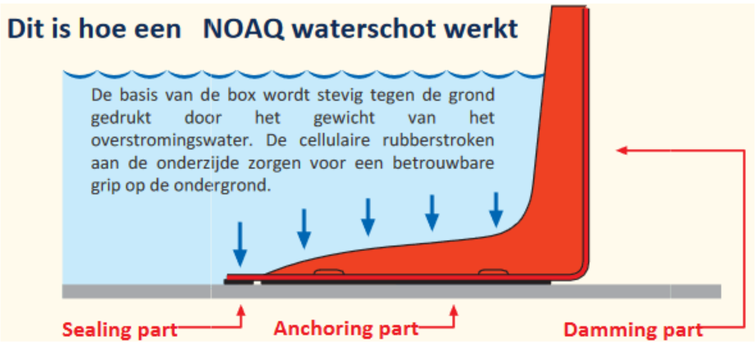
3.3.1 General information

The NOAQ Boxwall is a thin barrier that is able to stand on its own (Gutierrez et al., n.d.). The Boxwall creates a barrier to hold back water of a height of 50 cm or 100 cm (Waterschot, n.d.-a). The Boxwall is very light and can be quickly set up. In less than 24 minutes a Boxwall of 100 metres can be built up by only two men (NOAQ Flood Protection AB, n.d.). Despite the low weight of the Boxwall, the Boxwall remains stable because of the weight of the flood water that flows above it (NOAQ Flood Protection AB, n.d.). The Boxwall consists of many boxes that can be coupled to each other with a coupling mechanism and a locking mechanism, see Figure 3.

Figure 3: Coupling of the boxes (Waterschot, n.d.-a)

The Boxwall can protect roads, cities, industrial estates, etc. The Boxwall is able to avoid various obstacles, because there exist not only rectangular shapes of the Boxwall, but also round shapes (Waterschot, n.d.-a). This can be seen in Figure 4.

Figure 4: Round shape of the Boxwall (Waterschot, n.d.-a)



De basis van de box wordt stevig tegen de grond gedrukt door het gewicht van het overstromingswater. De cellulaire rubberstroken aan de onderzijde zorgen voor een betrouwbare grip op de ondergrond.

Figure 5: The three parts of a Boxwall (Waterschot, n.d.-a)

The Boxwall consists of three parts: the sealing part, the anchoring part and the damming part, see Figure 5.

- Under the front of the Boxwall is a cellular rubber sealing strip. The sealing part prevents leakage of the water.
- The Boxwall is anchored by the weight of the flood water. At the bottom of the barrier rubber is placed that has a high friction coefficient that provides sufficient grip.
- The main function of the damming part is forming the barrier against the water. The water pressure against the damming part is absorbed by the bumps that can be seen in Figure 3 (Waterschot, n.d.-a).

The Boxwall can be used on streets, concrete floors or grass (Waterschot, n.d.-a). However, Massolle et al (2018) showed that when using the Boxwall on grass, there will be a lot of seepage through the boxes. A Boxwall placed on grass has approximately the same seepage rates as when using sandbags as a flood barrier.

3.3.2 Limitations and strengths

The limitations and strengths of the Boxwall can be seen in Table 2.

Table 2: Limitations and strengths of the Boxwall

Limitations	Strengths
Coupling of the boxes to each other can only be done from one side	Quick and easy to set up
Not stable when there is a lot of wind and no water yet	No tools needed to set up

3.3.3 Dimensions of the Boxwall used during the tests

During the tests, the Boxwall with a height of 50 cm is used. The length of the Boxwall is 98 cm and the width is 68 cm (Waterschot, n.d.-b).

3.4 Geodesign barrier

3.4.1 General information

Geodesign Barriers are flood barriers made of steel, see Figure 6. The weight of the water that flows above the barriers causes the anchorage of the barriers to the ground. As the water level rises, the barriers become more stable (Geodesign Barriers Ltd, n.d.). The barriers are placed at a 45-degree angle. Aluminium panels are placed on the steel structure and covered with a plastic membrane that is waterproof. Chains are placed on the membrane to ensure the anchorage of the barriers to the ground until the water arrives (Hydro Response, n.d.).

There are three types of Geodesign Barriers, namely 'Economy', 'Premium' and 'Classic'. The Economy Geodesign Barrier can be seen in Figure 7. This barrier is very simple and non-extendable.

Figure 6: Example of a Geodesign Barrier
(Geodesign Barriers Ltd, n.d.)

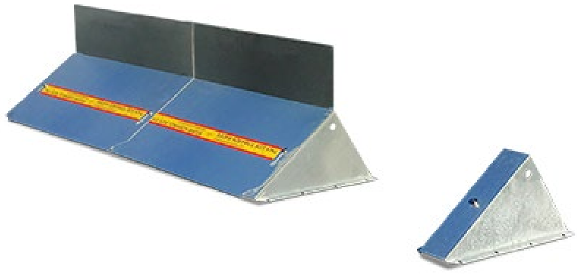


Figure 7: Economy Geodesign Barrier
(Geodesign Barriers Ltd, n.d.)

The Premium Geodesign Barrier can be seen in Figure 8. This barrier can be more easily set up than the Economy Geodesign Barrier and the forces to the ground have increased. Like the Economy Geodesign Barrier, the Premium Geodesign Barrier is non-extendable.

The Classic Geodesign Barrier can be seen in Figure 9. This barrier is used most frequently and is extendable. This way the height of the barrier can be increased when the water level rises more than expected (Hydro Response, n.d.).

Figure 8: Premium Geodesign Barrier (Geodesign Barriers Ltd, n.d.)

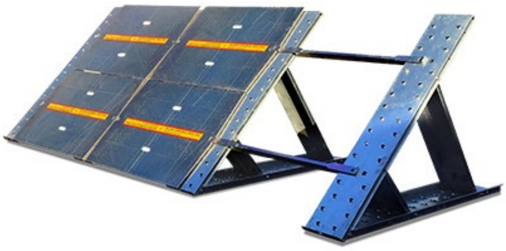


Figure 9: Classic Geodesign Barrier (Geodesign Barriers Ltd, n.d.)

3.4.2 Limitations and strengths

The limitations and strengths of the Geodesign Barrier can be seen in Table 3.

Table 3: Limitations and strengths of the Geodesign Barrier

Limitations	Strengths
Takes a bit more time to set up than the Boxwall	No tools needed to set up
Membrane needs to be cleaned after using	Quick and easy to set up

3.4.3 Dimensions of the Geodesign Barrier used during the tests

The Geodesign Barrier model that is used during the tests is the E20|51 Elemental barrier. This barrier has a height of 50 cm, a width of 85 cm and a length of 100 cm (D. Bon, personal communication, May 26, 2023).

4. Failure mechanisms of the temporary flood barriers

This chapter gives the possible failure mechanisms than can occur for the three different types of temporary flood barriers.

4.1 Mobile Dike

The failure mechanism that needs to be taken into account for the Mobile Dike is horizontal stability. The situation where the water is present and the situation where the water is not present will be discussed. For a detailed calculation, see Appendix D.

The horizontal stability can be calculated with the following equation (Voorendt, 2023):

$$\sum H < f * \sum V$$

where:

$\sum H$ [kN] = the total horizontal forces
f [-] = the dimensionless friction coefficient
$\sum V$ [kN] = the total vertical forces

In Figure 10 a sketch of the two situations can be seen.

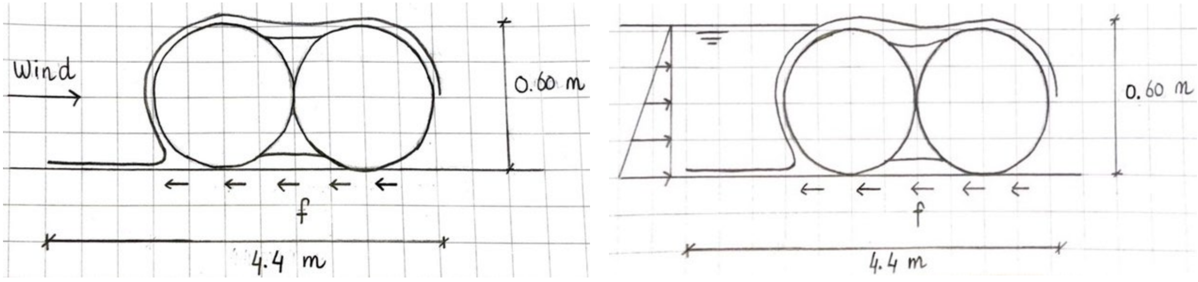


Figure 10: Sketch of the Mobile Dike with no water present (left) and with water present (right)

Water is not present:
Water is not present, so the only horizontal force is the wind force. The wind load equation that is used is (Voorendt, 2023):

$$p_{rep} = C_{dim} * C_{index} * p_w \text{ [kN/m}^2\text{]}$$

where:

p_{rep} [kN/m^2] = wind load as a result of wind pressure, suction, friction and over- or underpressure
C_{dim} [-] = factor for the dimensions of the structure
C_{index} [-] = wind type factor
p_w [kN/m^2] = peak velocity pressure, depending on the height and location of the structure

The result is p_{rep} = 307 N/m.
The only vertical force that needs to be taken into account is the self-weight of the Mobile Dike. The self-weight is equal to 5723 N/m (D. Bon, personal communication, May 26, 2023).
The friction coefficient that is used is f = 0.64 (Smeijers, 2023).
$307\ N/m < 0.64 * 5723\ = 3663\ N/m$ therefore there is horizontal stability.

Water is present:
Instead of the wind force, there is a hydrostatic force. The hydrostatic force can be calculated with the following equation:

$$F = \frac{1}{2} * \rho_w * g * h^2$$

where:

F [N/m] = hydrostatic force

ρ_w [kg/m^3] = density of water ($\rho_w = 1000$)
g [m/s^2] = acceleration due to gravity = 9.81 m/s^2
h [m] = water level

The result is F = 1766 N/m.
The vertical force stays the same and is equal to 5723 N/m.
The friction coefficient that is used is f = 0.64 (Smeijers, 2023).
$1766\ N/m < 0.64 * 5723\ = 3663\ N/m$ therefore there is horizontal stability.

4.2 Boxwall

There are two possible failure mechanisms that need to be taken into account for the Boxwall: horizontal stability and rotational stability. For a detailed calculation, see Appendix E.

Horizontal stability:
For the horizontal stability, the situation where water is present and the situation where water is not present will be discussed.

The horizontal stability can be calculated with the following equation:

$$\sum H < f * \sum V$$

In Figure 11 a sketch of the two situations can be seen.

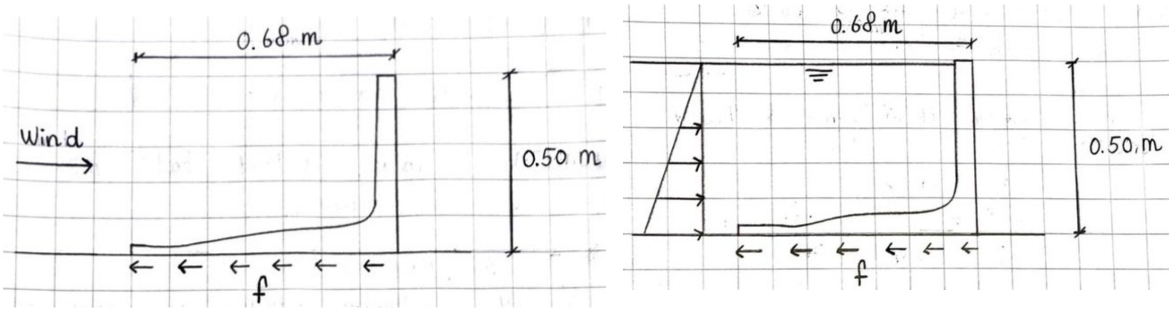


Figure 11: Sketch of the Boxwall with no water present (left) and with water present (right)

Water is not present:
Water is not present, so the only horizontal force is the wind force. The wind load equation that is used is:

$$p_{rep} = C_{dim} * C_{index}\ * p_w \text{ [kN/m}^2\text{]}$$

The result is p_{rep} = 256 N/m.
The only vertical force that needs to be taken into account is the self-weight of the Boxwall. The self-weight is equal to 62.1 N/m.
The friction coefficient that is used is f = 0.76 (Smeijers, 2023).
$256\ N/m > 0.76 * 62.1 = 47.2\ N/m$ therefore there is no horizontal stability when there is a wind force of p_{rep} = 256 N/m. This wind force is used for the design of structures, therefore this is a very large wind force that does not happen very often. On the day the Boxwall was tested, a wind speed of 4.0 m/s has been measured at weather station Ell, which is located 15 km away from Roermond (KNMI, n.d.). This corresponds to a wind force of 9.8 N/m, which is a much smaller force than p_{rep} = 256 N/m. This explains why the flood barrier was horizontally stable during the tests, unlike what is predicted by the horizontal stability calculation. To ensure horizontal stability when there is a wind force of 256 N/m, the weight of the Boxwall will need to be significantly increased. However, a great advantage of the Boxwall is that it is very easy and quick to set up, and this is due to its lightweight construction. Another option to ensure horizontal stability when there are higher wind forces, is to increase the friction coefficient. This can be done by placing more rubber at the bottom of the Boxwall.

Water is present:
Instead of the wind force, there is a hydrostatic force. The hydrostatic force can be calculated with the following equation:

$$F = \frac{1}{2} * \rho_w * g * h^2$$

The result is F = 1226 N/m.
In addition to the self-weight of the Boxwall, there is also the weight of the water. The total vertical forces can be calculated by adding the weight of the water to the self-weight of the Boxwall. The result is 2843 N/m.
The friction coefficient that is used is f = 0.76 (Smeijers, 2023).
$1226\ N/m < 0.76 * 2843 = 2161\ N/m$ therefore there is horizontal stability.

Rotational stability:
For the rotational stability two criteria must be met. First, the sum of the stabilising moments should be higher than the sum of the de-stabilising moments. Second, there have to be zero tensional stresses at the bottom of the Boxwall.

The first criterium can be checked with the following equation:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

where:

$|M_{stabilising}|$ [Nm] = the absolute value of the sum of the stabilising moments about the rotational point P
$|M_{de-stabilising}|$ [Nm] = the absolute value of the sum of the de-stabilising moments about the rotational point P

The situation where water is present and the situation where water is not present will be discussed.

In Figure 12 a sketch of the two situations can be seen.

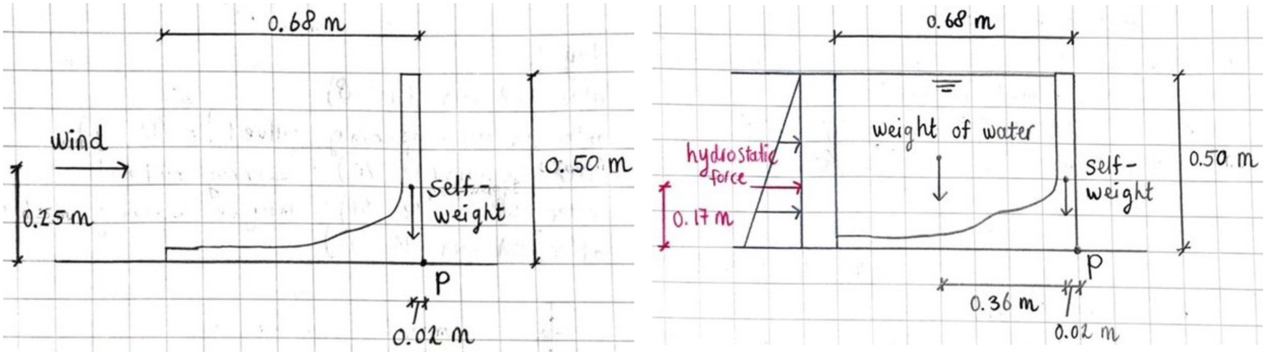


Figure 12: Sketch of the Boxwall for checking the stabilising and de-stabilising moments with no water present (left) and with water present (right)

Water is not present:
The only stabilising force is the self-weight of the Boxwall. The self-weight is equal to 62.1 N/m and the moment due to the stabilising forces is equal to $/M_{stabilising}/$ = 1.2 Nm/m.
The only de-stabilising force is the wind force. The wind force is equal to p_{rep} = 256 N/m and the moment due to the de-stabilising forces is equal to $/M_{de\text{-}stabilising}/$ = 64.0 Nm/m.
1.2 Nm/m < 64.0 Nm/m, therefore the de-stabilising moments are larger than the stabilising moments and the first criterium for rotational stability is not met. As a result, the Boxwall will tip over when there is a wind force of p_{rep} = 256 N/m.

Water is present:

In addition to the self-weight of the Boxwall, there is also the weight of the water. The moment due to the stabilising forces is equal to $|M_{stabilising}|$ = 1058 Nm/m.
The only de-stabilising force is the hydrostatic force. The hydrostatic force is equal to F = 1226 N/m and the moment due to the de-stabilising forces is equal to $|M_{de\text{-}stabilising}|$ = 208 Nm/m.
1058 Nm/m > 208 Nm/m, therefore the stabilising moments are larger than the de-stabilising moments and the first criterium for rotational stability is met.

The second criterium can be calculated with the following equation (Voorendt, 2023):

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6} b$$

where:

e_R [m] = distance from the middle of the structure (K) to the application point of the resulting force and the bottom line of the structure

$\sum V$ [N] = total vertical forces

$\sum M$ [Nm] = total of the acting moments around point K, halfway the width

b [m] = width of the structure

The situation where water is present and the situation where water is not present will be discussed.

In Figure 13 a sketch of the two situations can be seen.

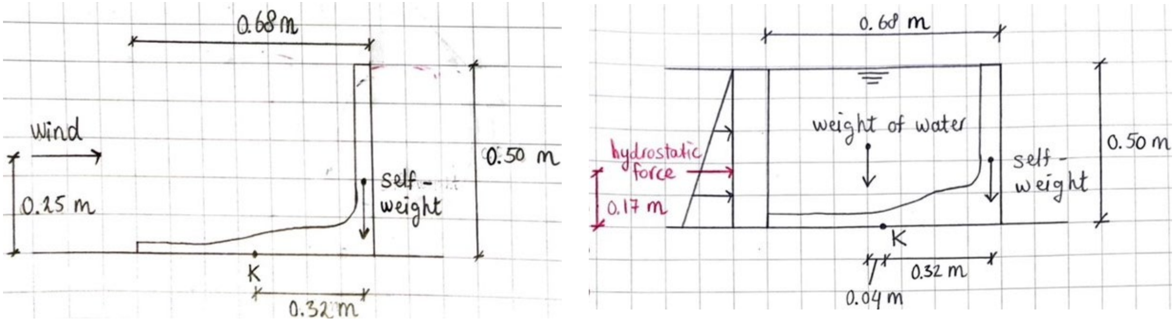


Figure 13: Sketch of the Boxwall for checking the tensional stresses at the bottom with no water present (left) and with water present (right)

Water is not present:
Water is not present, so the only horizontal force is the wind force. The wind force is equal to p_{rep} = 256 N/m and the moment due to the horizontal forces is equal to M_{wind} = 64.0 Nm/m (clockwise is considered positive).
The only vertical force that needs to be taken into account is the self-weight of the Boxwall. The self-weight is equal to 62.1 N/m and the moment due to the vertical forces is equal to $M_{self\text{-}weight}$ = 19.9 Nm/m.
The total of the acting moments around point K is equal to $\sum M$ = 83.9 Nm/m and the total vertical forces are equal to $\sum V$ = 62.1 N/m. $\frac{\sum M}{\sum V} = 1.4$ and $\frac{1}{6} b = 0.11$, therefore there are tensional stresses at the bottom of the Boxwall and the second criterium for rotational stability is not met. Tensional stresses are a problem when concrete is used in the structure, because concrete has a very weak tensile strength. The Boxwall is made from polypropylene (Waterschot, n.d.-b), and polypropylene has a high tensile strength (Omnexus, n.d.), therefore the tensional stresses at the bottom of the Boxwall do not have a significant effect on the rotational stability.

Water is present:
Instead of the wind force, there is a hydrostatic force. The hydrostatic force is equal to F = 1226 N/m and the moment due to the horizontal forces is equal to $M_{hydrostatic}$ = 208 Nm/m (clockwise is considered positive).
In addition to the self-weight of the Boxwall, there is also the weight of the water. The weight of the water is equal to 2781 N/m and the self-weight stays the same. The moment due to the vertical forces is equal to -91.3 Nm/m (clockwise is considered positive).
The total of the acting moments around point K is equal to $\sum M$ = 117 Nm/m and the total vertical forces are equal to $\sum V$ = 2843 N/m. $\frac{\sum M}{\sum V} = 0.04$ and $\frac{1}{6}b = 0.11$, therefore there are no tensional stresses at the bottom of the Boxwall and the second criterium for rotational stability is met.

In conclusion, the first and second criterium are not met for the situation where water is not present, therefore there is no rotational stability in this situation. The first and second criterium are met for the situation where water is present, therefore there is rotational stability in this situation. In the calculations where the water is not present, a wind force of 256 N/m is used, while during the tests there was a wind force of 9.8 N/m. This explains why the flood barrier was rotationally stable during the tests, unlike what is predicted by the first and second criterium for rotational stability.

4.3 Geodesign Barrier

There are two possible failure mechanisms that need to be taken into account for the Geodesign Barrier: horizontal stability and rotational stability. The horizontal and rotational stability are calculated the same way as for the Boxwall, therefore only the results from these calculations are given in this section. For a detailed calculation, see Appendix F.

Horizontal stability:
In Figure 14 a sketch of the two situations for the horizontal stability can be seen.

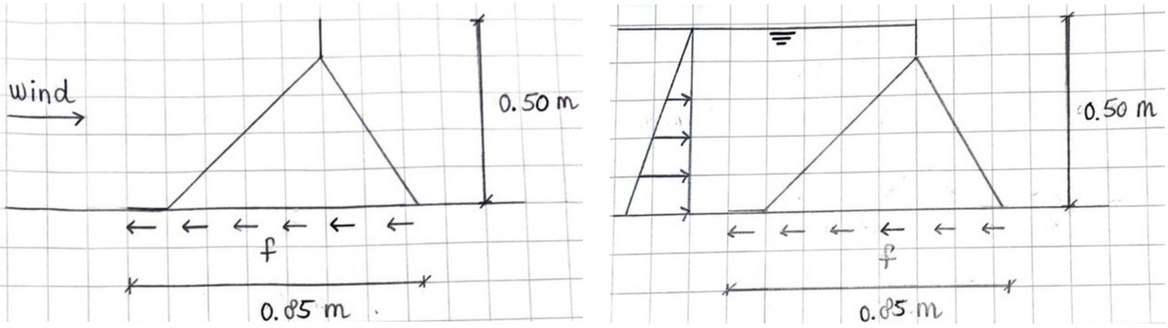


Figure 14: Sketch of the Geodesign Barrier with no water present (left) and with water present (right)

Water is not present:
The result of the horizontal stability equation is $256\ N/m > 0.64 * 147 = 94.2\ N/m$. Therefore there is no horizontal stability when there is a wind force of p_{rep} = 256 N/m. This wind force is used for the design of structures, therefore this is a very large wind force that does not happen very often. On the day the Geodesign Barrier was tested, a wind speed of 6.0 m/s has been measured at weather station Ell, which is located 15 km away from Roermond (KNMI, n.d.). This corresponds to a wind force of 22 N/m, which is a much smaller force than p_{rep} = 256 N/m. This explains why the flood barrier was horizontally stable during the tests, unlike what is predicted by this calculation. To ensure horizontal stability when there is a wind force of 256 N/m, the weight of the Geodesign Barrier will need to be significantly increased. A disadvantage of this is that it becomes more difficult to set up the flood barrier. Another option to ensure horizontal stability when there are higher wind forces, is to increase the friction coefficient. This can be done by placing more rubber at the bottom of the Geodesign Barrier.

Water is present:
The result of the horizontal stability equation is $1226\ N/m < 0.64 * 2060 = 1318\ N/m$, therefore there is horizontal stability.

Rotational stability:
In Figure 15 a sketch of the two situations for checking the stabilising and de-stabilising moments can be seen.

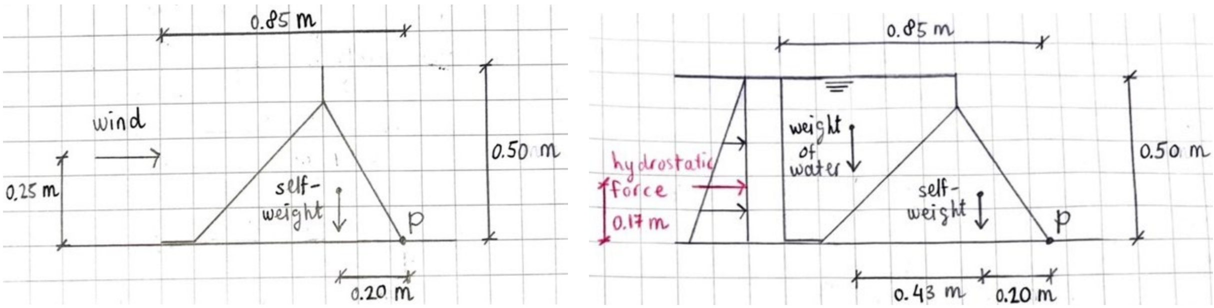


Figure 15: Sketch of the Geodesign Barrier for checking the stabilising and de-stabilising moments with no water present (left) and with water present (right)

Water is not present:
The result of the stabilising and the de-stabilising equation is 29.4 Nm/m < 64.0 Nm/m. Therefore the de-stabilising moments are larger than the stabilising moments and the first criterium for rotational stability is not met. As a result, the Geodesign Barrier will tip over when there is a wind force of p_{rep} = 256 N/m.

Water is present:
The result of the stabilising and the de-stabilising equation is 1234 Nm/m > 208 Nm/m. Therefore the stabilising moments are larger than the de-stabilising moments and the first criterium for rotational stability is met.

In Figure 16 a sketch of the two situations for checking the tensional stresses at the bottom can be seen.

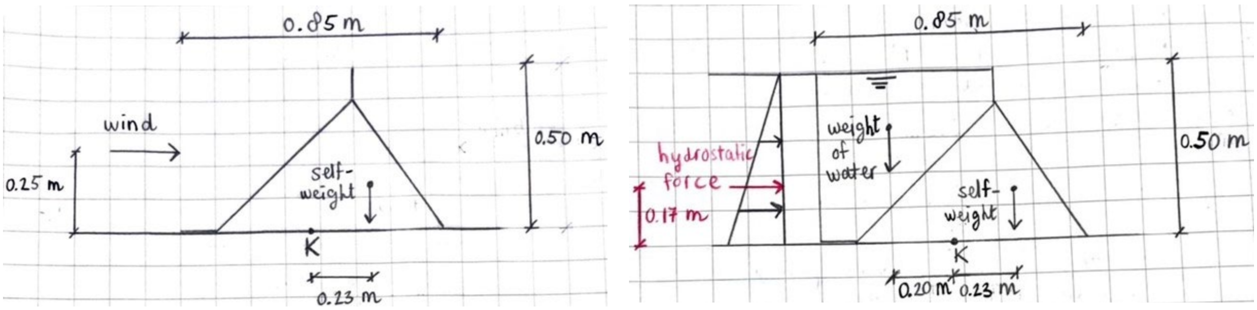


Figure 16: Sketch of the Geodesign Barrier for checking the tensional stresses at the bottom with no water present (left) and with water present (right)

Water is not present:
The result of the tensional stresses equation is 0.67 m > 0.14 m. Therefore there are tensional stresses at the bottom of the Geodesign Barrier and the second criterium for rotational stability is not met. Tensional stresses are a problem when concrete is used in the structure, because concrete has a very weak tensile strength. The Geodesign Barrier is made from steel (Hydro Response, n.d.), and steel has a high tensile strength (The Engineering ToolBox, n.d.), therefore the tensional stresses at the bottom of the Geodesign Barrier do not have a significant effect on the rotational stability.

Water is present:
The result of the tensional stresses equation is -0.07 m < 0.14 m. Therefore there are no tensional stresses at the bottom of the Geodesign Barrier and the second criterium for rotational stability is met.

In conclusion, the first and second criterium are not met for the situation where water is not present, therefore there is no rotational stability in this situation. The first and second criterium are met for the situation where water is present, therefore there is rotational stability in this situation. In the calculations where the water is not present, a wind force of 256 N/m is used, while during the tests there was a wind force of 22 N/m. This explains why the Geodesign Barrier was rotationally stable during the tests, unlike what is predicted by the first and second criterium for rotational stability.

5. Water level data analysis

In this chapter the water level data measured by the cameras is compared to the water level data measured by the divers. The data from camera 2 and camera 4 is compared to the data from the diver on the grass lane (see Appendix C for the position of the five cameras).

5.1 Water level data analysis from the divers

In Figure 17 two graphs of the water level variation during the tests on the 10th and 11th of May can be seen.

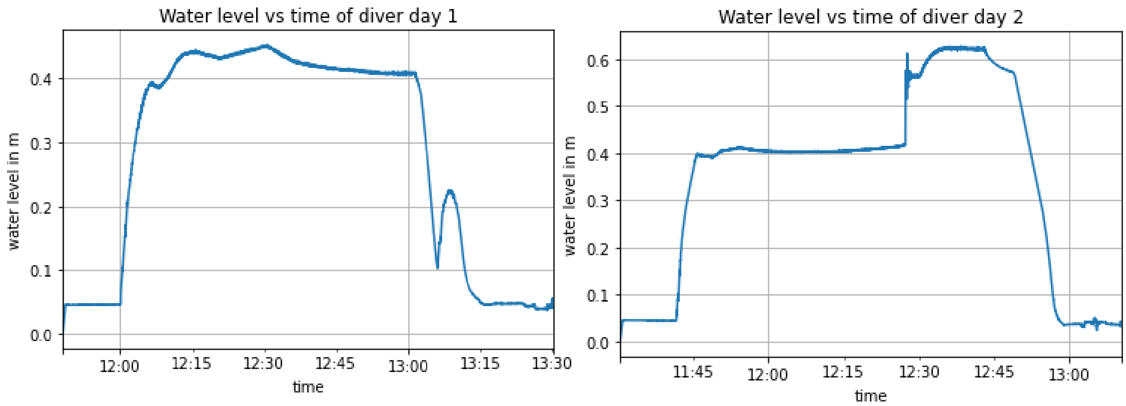


Figure 17: Water level vs time monitored by the diver on the grass lane during the tests on the 10th and 11th of May 2023

Day 1 of the tests:
In the first graph of Figure 17 it can be observed that the water level rises to approximately 0.45 meters and after a while decreases. There are severable notable observations in the graph that can be explained by looking at the video footage from camera 2 and camera 4.

- At 11:48 the pump is turned on, you can see an immediate rise of the water level to approximately 0.05 m. This is the result of leakage from the Geodesign Barrier to the grass lane. At 11:57 the asphalt lane is completely filled with water and overtopping starts. From that moment on, the grass lane starts to fill with water. You can see that after the start of the overtopping, the water level starts to rise very quickly.
- Around 12:06 you can see a small decrease in the water level. In the video it can be seen that at 12:04 a culvert is opened. There are two culverts on the test site, culvert 1 regulates the water flow from the asphalt lane to the grass lane and the culvert 2 regulates the water flow from the grass lane to outside the test area. At 12:04 culvert 2 is opened, which explains the small decrease of the water level.
- At 12:13 culvert 2 is opened again. This explains the small decrease in de water level around 12:15.
- At 12:30 culvert 2 is opened again. This explains the decrease from approximately 12:30 until 13:01.
- At 13:01 the pump is turned off. In the graph you can see an immediate large decrease of the water level.
- At 13:06 culvert 1 is opened, which results in an increase of the water flow from the asphalt lane to the grass lane. This explains the small increase in the water level around 13:06. Around 13:09 this increase reaches its peak, after which the water level starts to decrease further. The water level does not return to 0 m because the not all the water flows away after the pump is turned off.

Day 2 of the tests:
In the second graph of Figure 17 it can be observed that the water level first rises to approximately 0.40 meters, then to approximately 0.62 meters, and then decreases again. There are severable

notable observations in the graph that can be explained by looking at the video footage from camera 2 and camera 4.

- At 11:30 the pump is turned on, you can see an immediate rise of the water level to approximately 0.05 m. This is the result of leakage from the Boxwall to the grass lane. At 11:39 the asphalt lane is completely filled with water and overtopping starts. From that moment on, the grass lane starts to fill with water. You can see that after the start of the overtopping, the water level starts to rise very quickly.
- At 11:45 culvert 2 is opened, which is why the water level stops rising and stays constant for some time.
- At 11:54 culvert 2 is opened again, this explains why the water level does not continue to rise but remains relatively constant.
- At 12:27 the water level in the grass lane is so high that the Boxwall crashes. As a result, the water level immediately increases.
- At 12:30 culvert 2 is opened, which causes a small stop of the rising of the water level. After this moment the water level starts to increase again.
- At 12:43 the pump is turned off, in the graph you can see an immediate decrease of the water level. At 12:49 culvert 2 is opened, which causes a larger decrease of the water level. The water level does not return to 0 m because the not all the water flows away after the pump is turned off.

5.2 Water level data analysis from the cameras

The videos from camera 2 and camera 4 are analysed. Both cameras are aimed at a water level scale so that the water level can be observed anytime during the test. The water level scales are situated on the grass lane, the water level scale from camera 2 is situated closer to the pump than the water level scale from camera 4. For the exact position of the cameras and the water level scales, see Appendix C. In order to make a graph of the water level plotted against the time, the water level is observed every five minutes and this information is put in a table. From this table a graph can be made. In Figure 18 two graphs of the water level variation monitored by camera 2 can be seen.

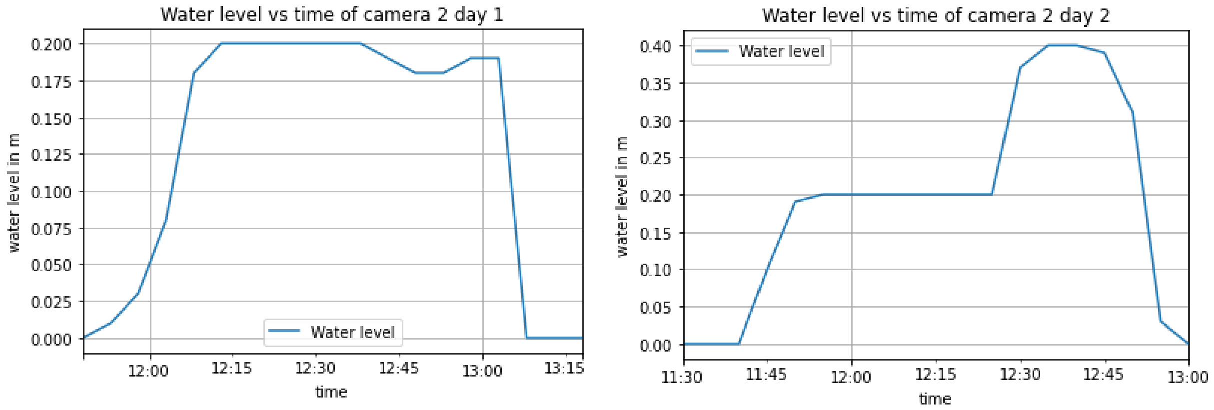


Figure 18: Water level vs time monitored by camera 2 during the tests on the 10th and 11th of May 2023

In Figure 19 two graphs of the water level variation monitored by camera 4 can be seen.

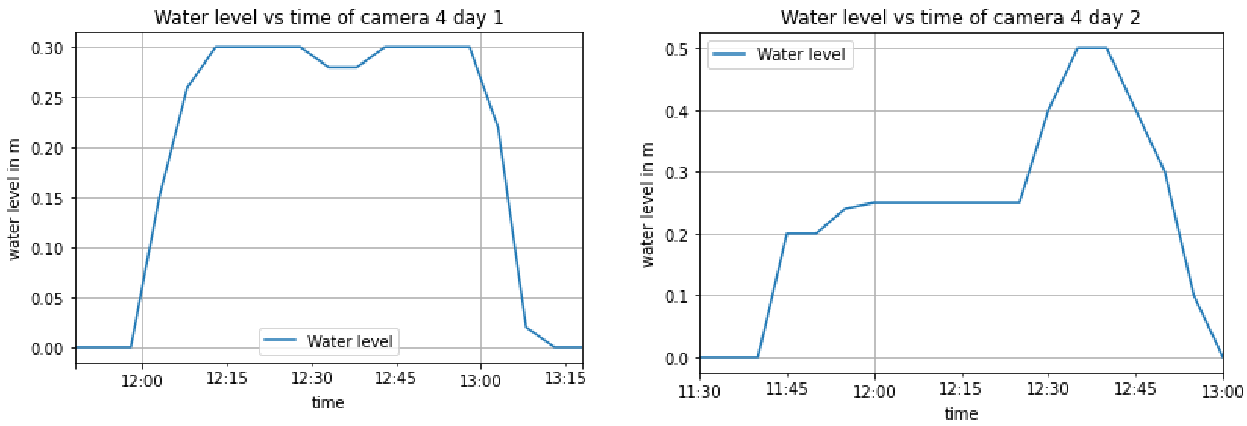


Figure 19: Water level vs time monitored by camera 4 during the tests on the 10th and 11th of May 2023

5.3 Comparison between the two different ways of measuring the water level

The graphs made by analysing the data from camera 2 and camera 4 resemble the graphs made by analysing the data from the diver. The diver measures the water level every second, while the graphs from the cameras only have information about the water level every five minutes. As a result, the diver's graphs are much more precise than the graphs from the cameras and the small variations in Figure 17 are not visible in Figure 18 and 19.

Another difference between the graphs is the maximum water level. The diver measures a maximum water level of approximately 0.45 m for day 1 and 0.62 m for day 2. Camera 2 measures a maximum water level of 0.20 m for day 1 and 0.40 m for day 2, camera 4 measures a maximum water level of 0.30 m for day 1 and 0.50 m for day 2. The reason for this difference is that the grass lane has a variation in elevation and the two water level scales and diver are situated on different locations on the grass lane. In Figure 20 the location of the water level scales and the diver can be seen. The water level scale from camera 4 is situated closer to the diver than the water level scale from camera 2. This is why the maximum water level in the graph from camera 4 resembles more with the graph from the diver.

Figure 20: Location of the water level scales and the diver

Measuring the water level using divers and water level scales has different advantages and disadvantages. The advantage of the diver is that the measurements are very precise. The disadvantage is that you have to wait until the end of the test before you get the data. The advantage of the water level scales is that you can measure the water level anytime during the test. Disadvantages are that the measurements are not very precise and measurement errors are easily made.

6. Conclusion and recommendations

In this report three different temporary flood barriers are investigated: Mobile Dike, Boxwall and Geodesign Barrier. These three types were tested on a test site in Roermond on the 10th and 11th of May 2023. This report answered the research question of how video analysis can be used as a new monitoring tool for the behaviour of temporary flood barriers.

The first sub-question was about the investigation of the failure mechanisms of the three temporary flood barriers. Two situations had to be analysed, the situation with and without water present. The Mobile Dike is stable in both situations, this was also the case during the tests in Roermond. For the Boxwall and Geodesign Barrier, the two situations resulted in different outcomes. The Boxwall and Geodesign Barrier are not stable when water is not present, the flood barriers are stable when water is present. This was not what happened during the tests in Roermond, there the Boxwall and Geodesign Barrier remained stable with and without water present. In the stability calculations the wind force for the design of structures is used, this is a very large wind force that does not happen very often. During the tests there was a much smaller wind force, which explains why the flood barriers remained stable.

The second sub-question was about how a 5G monitoring system can be used to assess the stability of the temporary flood barriers. In this report is focused on detecting the water level during the tests in Roermond, because the water level affects the stability of the temporary flood barriers. During the tests, the water level is detected in two ways: with water level scales and with divers. Graphs are made of the water level plotted against the time. The graphs from the water level scale data resemble the graphs from the diver data, but the graphs from the diver data are much more precise. These graphs contain small variations in the water level that cannot be seen in the graphs from the water level scale data. A disadvantage of using the diver is that you have to wait until the end of the test before you get the data. The use of water level scales allows you to read the water level anytime during the test.

Video analysis can be effectively used as a new monitoring tool for the behaviour of temporary flood barriers. In this report is focused on water level monitoring, but video analysis can also be used to detect deformation, displacement or damage of the temporary flood barriers. In this report, it has been found that the use of divers provides more precise water level detection compared to video analysis of the water level scales. For further research, video processing techniques in Python can be used to improve the accuracy of the water level detection in the video analysis. By measuring the water level in each frame of the video, a more precise graph of the water level over time can be obtained. Another possibility for further research is to use video analysis for the investigation of deformations, displacements and damages of the temporary flood barriers. Video analysis can also be used to detect the water level before the temporary flood barriers are installed. If the water level exceeds a certain value, a signal can be given indicating a flood and the need to install the temporary flood barriers.

References

Damen, K. (2022). *Functioneren van tijdelijke waterkeringen*.

Geodesign Barriers Ltd. (n.d.). *Flood Barriers*.

Gutierrez, A. M. J. A., Chan, A. C., Del Pilar, E., Mansilla, M. M. Z., & Tee, M. L. (n.d.). *Developing a Localized Disaster Risk Management Framework with an Introduced Optimal Flood Barrier in the Philippines*.

Haase, J. (2021). *The design of temporary flood damage mitigating measures*.

Hydro Response. (n.d.). *Geodesign Barriers*.

KNMI. (n.d.). *Daggegevens van het weer in Nederland*.

Massolle, C., Lankenau, L., & Koppe, B. (2018). Emergency Flood Control: Practice-Oriented Test Series for the Use of Sandbag Replacement Systems . *Geosciences*, *8*(12).

Mobiele Dijken Nederland BV. (n.d.). *Mobiele Dijken Nederland BV*.

Mobiele Dijken Nederland BV. (2016). *Het Systeem*.

NOAQ Flood Protection AB. (n.d.). *NOAQ Flood Fighting System*.

Ogunyoye, F., & van Heereveld, M. (2002). *Temporary and Demountable Flood Protection*.

Omnexus. (n.d.). *Plastics & Elastomers*.

ProQuest. (2014). *Purchase a total of 10000 meters +25% of mobile dam system for flood protection*.

Rijkswaterstaat. (2022, July 11). *Een jaar na het hoogwater in Limburg*.

Smeijers S. (2023). *H-wall*.

The Engineering ToolBox. (n.d.). *Young's Modulus, Tensile Strength and Yield Strength Values for some Materials* .

Voorendt, M. (2023). *Manual Hydraulic Structures*.

Waterschot. (n.d.-a). *Hoe werkt het waterschot?*

Waterschot. (n.d.-b). *Veelgestelde vragen over onze waterschotten*.

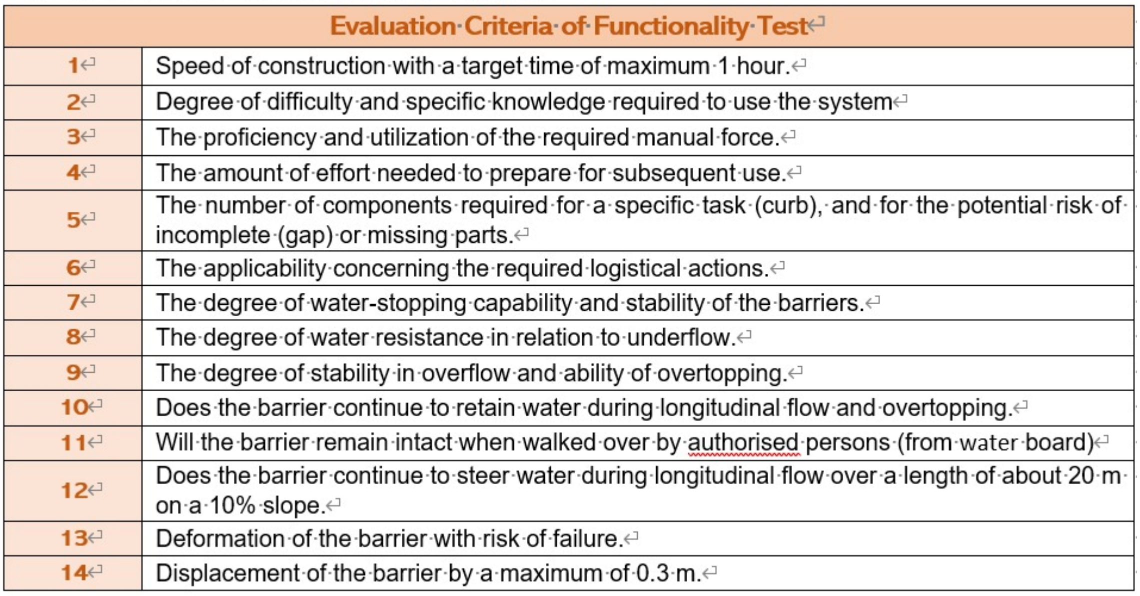
WIKI-noodmaatregelen. (n.d.). *Hoe om te gaan met zandzakken*.

Appendix A: Planning

Table 4 Planning

Week	Activities	Deadlines
1 (24 April – 28 April)	Write work plan, literature study Mobile Dike, Boxwall and Geodesign Barrier	
2 (1 May – 5 May)	Preparations for the measurements	Monday 1 May – Literacy 2 assignment Monday 1 May – submitting work plan
3 (8 May – 12 May)	Measurements on the test field location	
4 (15 May – 19 May)	Analysis of the data, forming objective – writing interim report and preparing interim presentation	
5 (22 May – 26 May)	Studying measurements from the test field location	Monday 22 May – submitting interim report Wednesday 24 May – interim presentations and peer review
6 (29 May – 2 June)	Studying measurements from the test field location and answering the research questions Write ethics essay	Friday 2 June – upload ethics essay
7 (5 June – 9 June)	Studying measurements from the test field location and answering the research questions	
8 (12 June – 16 June)	Writing conclusions and recommendations Preparing elevator pitch ethics essay	Wednesday 14 June – elevator pitch ethics essay
9 (19 June – 23 June)	Finalizing final report and preparing final presentation	Friday 23 June – submitting final report
10 (26 June – 30 June)	Preparing final presentation	Tuesday 27 June – final presentations

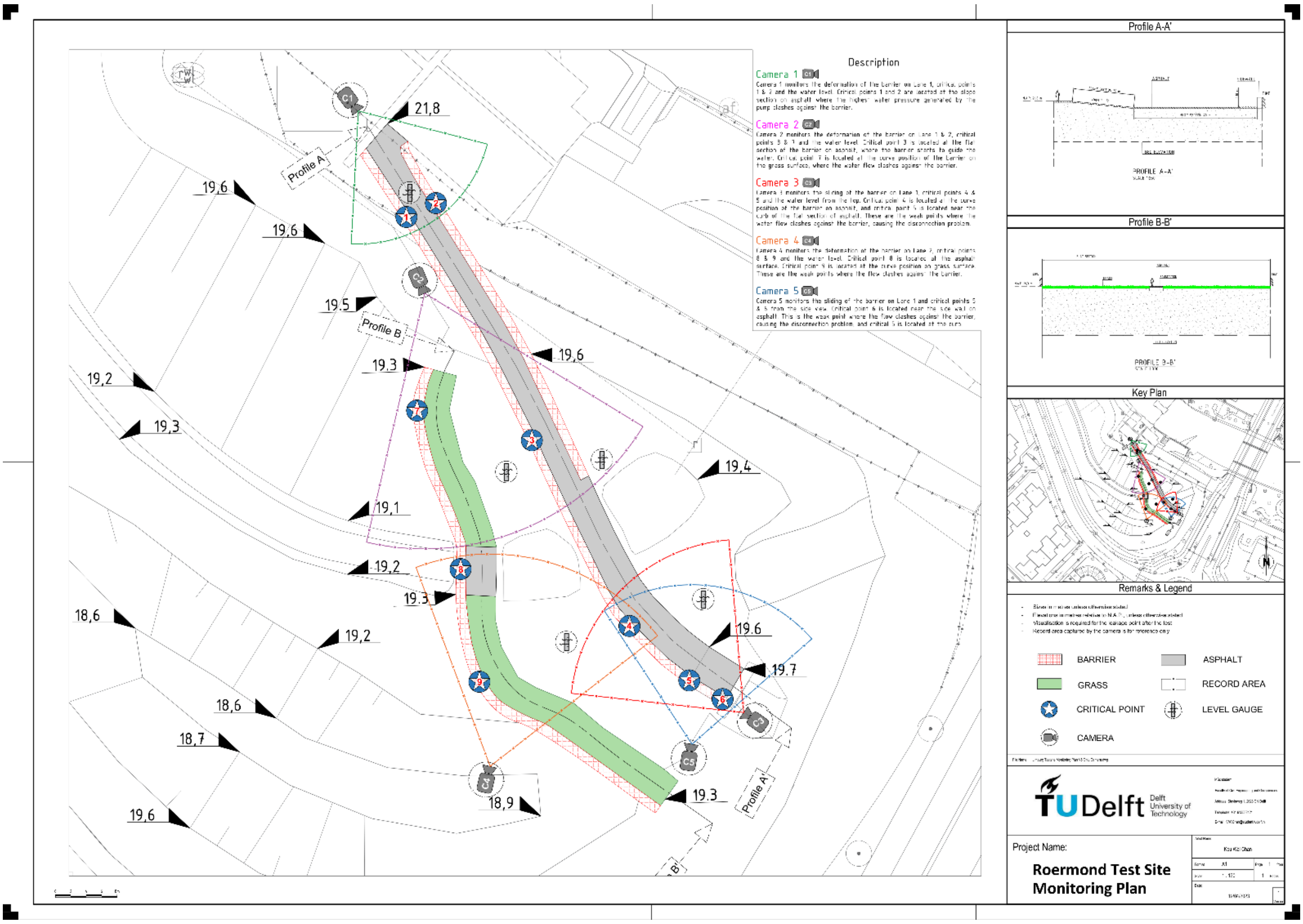
Appendix B: Evaluation Criteria



Evaluation Criteria of Functionality Test	
1	Speed of construction with a target time of maximum 1 hour.
2	Degree of difficulty and specific knowledge required to use the system
3	The proficiency and utilization of the required manual force.
4	The amount of effort needed to prepare for subsequent use.
5	The number of components required for a specific task (curb), and for the potential risk of incomplete (gap) or missing parts.
6	The applicability concerning the required logistical actions.
7	The degree of water-stopping capability and stability of the barriers.
8	The degree of water resistance in relation to underflow.
9	The degree of stability in overflow and ability of overtopping.
10	Does the barrier continue to retain water during longitudinal flow and overtopping.
11	Will the barrier remain intact when walked over by authorised persons (from water board)
12	Does the barrier continue to steer water during longitudinal flow over a length of about 20 m on a 10% slope.
13	Deformation of the barrier with risk of failure.
14	Displacement of the barrier by a maximum of 0.3 m.

Figure 21: Evaluation Criteria

Appendix C: Roermond test site monitoring plan



Description

Camera 1

Camera 1 monitors the deformation of the barrier on Lane 1, critical points 1 & 2 and the water level. Critical points 1 and 2 are located at the slope section on asphalt where the highest water pressure generated by the pump clashes against the barrier.

Camera 2

Camera 2 monitors the deformation of the barrier on Lane 1 & 2, critical points 3 & 7 and the water level. Critical point 3 is located at the flat section of the barrier on asphalt, where the barrier starts to guide the water. Critical point 7 is located at the curve position of the barrier on the grass surface, where the water flow clashes against the barrier.

Camera 3

Camera 3 monitors the sliding of the barrier on Lane 1, critical points 4 & 5 and the water level from the top. Critical point 4 is located at the curve position of the barrier on asphalt, and critical point 5 is located near the curb of the flat section of asphalt. These are the weak points where the water flow clashes against the barrier, causing the disconnection problem.

Camera 4

Camera 4 monitors the deformation of the barrier on Lane 2, critical points 8 & 9 and the water level. Critical point 8 is located at the asphalt surface. Critical point 9 is located at the curve position on grass surface. These are the weak points where the flow clashes against the barrier.

Camera 5

Camera 5 monitors the sliding of the barrier on Lane 1 and critical points 5 & 6 from the side view. Critical point 6 is located near the side wall on asphalt. This is the weak point where the flow clashes against the barrier, causing the disconnection problem, and critical 5 is located at the curb.

Remarks & Legend

- Sizes in metres unless otherwise stated
- Elevations in metres relative to N.A.P., unless otherwise stated
- Visualisation is required for the leakage point after the test
- Record area captured by the camera is for reference only

Figure 22: Roermond test site monitoring plan

Appendix D: Calculations of the failure mechanisms for the Mobile Dike

The failure mechanism that needs to be taken into account for the Mobile Dike is horizontal stability. The situation where the water is present and the situation where the water is not present will be discussed.

The horizontal stability can be calculated with the following equation (Voorendt, 2023):

$$\sum H < f * \sum V$$

where:

$\sum H$	[kN]	=	the total horizontal forces
f	[-]	=	the dimensionless friction coefficient
$\sum V$	[kN]	=	the total vertical forces

In Figure 23 a sketch of the two situations can be seen.

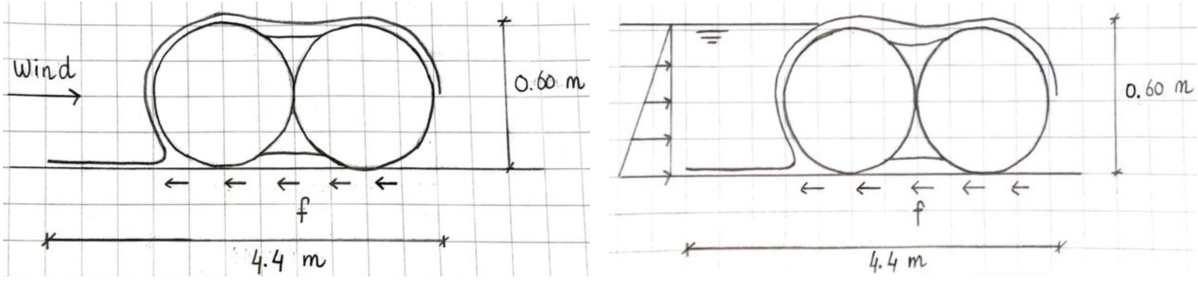


Figure 23: Sketch of the Mobile Dike with no water present (left) and with water present (right)

Water is not present:

Horizontal forces:

Water is not present, so the only horizontal force is the wind force. The Mobile Dike has dimensions of *h* < 50 m and *h/b* < 5, therefore the wind load equation simplifies to (Voorendt, 2023):

$$p_{rep} = C_{dim} * C_{index} * p_w \text{ [kN/m}^2\text{]}$$

where:

p_{rep}	[kN/m^2]	=	wind load as a result of wind pressure, suction, friction and over- or underpressure
C_{dim}	[-]	=	factor for the dimensions of the structure
C_{index}	[-]	=	wind type factor
p_w	[kN/m^2]	=	peak velocity pressure, depending on the height and location of the structure

C_{dim} can be obtained from Table 2-4 from the Manual Hydraulic Structures (Voorendt, 2023). For h = 0.60 m and b = 4.4 m we get C_{dim} = 1.00.

C_{index} = 0.8 (Voorendt, 2023)

p_w can be obtained from Table 2-3 from the Manual Hydraulic Structures (Voorendt, 2023). For $h \leq 2$ m we get p_w = 0.64.

p_{rep} can be calculated as follows:

$$p_{rep} = C_{dim} * C_{index} * p_w = 1.00 * 0.8 * 0.64 = 0.512\ kN/m^2$$

Multiply with the height of the Mobile Dike:

$$p_{rep} = 0.512 * 0.60 = 0.307\ kN/m = 307\ N/m$$

Vertical forces:

The only vertical force that needs to be taken into account is the self-weight of the Mobile Dike. The self-weight when the Mobile Dike is filled with water is 17500 kg/30 m (D. Bon, personal communication, May 26, 2023). This is equal to:

$$\frac{17500}{30} = 583\ kg/m = 583 * 9.81 = 5723\ N/m$$

Friction coefficient:
The friction coefficient depends on the soil type on which the water barrier is situated. Smeijers (2023) determined the friction coefficients of temporary flood barriers on different ground surfaces. The friction coefficient for temporary flood barriers on asphalt is $f = 0.76$ and on grass is $f = 0.64$. The Mobile Dike is situated on grass, therefore the value for the friction coefficient is $f = 0.64$.

Now the horizontal stability can be calculated:

$$\sum H < f * \sum V$$

$$f * \sum V = 0.64 * 5723 \ = 3663\ N/m$$

$$\sum H = 307\ N/m$$

307 N/m < 3663 N/m, therefore there is horizontal stability.

Water is present:
Horizontal forces:
Instead of the wind force, there is a hydrostatic force. The hydrostatic force can be calculated with the following equation:

$$F = \frac{1}{2} * \rho_w * g * h^2$$

where:

F [N/m] = hydrostatic force
ρ_w [kg/m^3] = density of water ($\rho_w = 1000$)
g [m/s^2] = acceleration due to gravity = 9.81 m/s^2
h [m] = water level

$$F = \frac{1}{2} * \rho_w * g * h^2 = \frac{1}{2} * 1000 * 9.81 * 0.60^2 = 1766\ N/m$$

Vertical forces:
The vertical force is the same as in the situation where there is no water present. The self-weight of the Mobile Dike is equal to 5723 N/m.

Now the horizontal stability can be calculated:

$$\sum H < f * \sum V$$

$$f * \sum V = 0.64 * 5723 \ = 3663\ N/m$$

$$\sum H = 1766\ N/m$$

1766 N/m < 3654 N/m, therefore there is horizontal stability.

Appendix E: Calculations of the failure mechanisms for the Boxwall

There are two possible failure mechanisms that need to be taken into account for the Boxwall: horizontal stability and rotational stability.

Horizontal stability:
For the horizontal stability, the situation where water is present and the situation where water is not present will be discussed.

The horizontal stability can be calculated with the following equation:

$$\sum H < f * \sum V$$

In Figure 24 a sketch of the two situations can be seen.

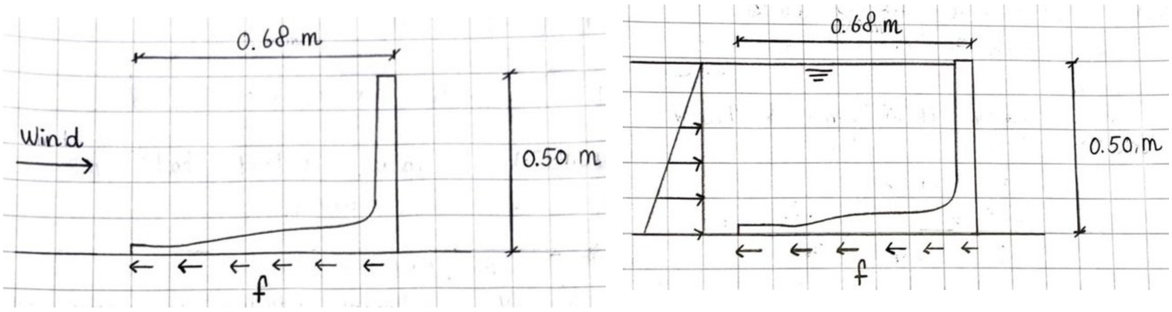


Figure 24: Sketch of the Boxwall with no water present (left) and with water present (right)

Water is not present:
Horizontal forces:
Water is not present, so the only horizontal force is the wind force. The Boxwall has dimensions of *h* < 50 m and *h/b* < 5, therefore the wind load equation simplifies to:

$$p_{rep} = C_{dim} * C_{index} * p_w \text{ [kN/m}^2\text{]}$$

C_{dim} can be obtained from Table 2-4 from the Manual Hydraulic Structures (Voorendt, 2023). For h = 0.50 m and b = 0.68 m we get C_{dim} = 1.00.
C_{index} = 0.8 (Voorendt, 2023)
p_w can be obtained from Table 2-3 from the Manual Hydraulic Structures (Voorendt, 2023). For $h \leq 2$ m we get p_w = 0.64.
p_{rep} can be calculated as follows:

$$p_{rep} = C_{dim} * C_{index} * p_w = 1.00 * 0.8 * 0.64 = 0.512\ kN/m^2$$

Multiply with the height of the Boxwall:

$$p_{rep} = 0.512 * 0.50 = 0.256\ kN/m = 256\ N/m$$

Vertical forces:
The only vertical force that needs to be taken into account is the self-weight of the Boxwall. The self-weight is 6.2 kg per box (Waterschot, n.d.-b). The length of one box is 0.98 m, therefore the self-weight is equal to:

$$\frac{6.2}{0.98} = 6.33\ kg/m = 6.33 * 9.81 = 62.1\ N/m$$

Friction coefficient:
The friction coefficient depends on the soil type on which the water barrier is situated. Smeijers (2023) determined the friction coefficients of temporary flood barriers on different ground surfaces. The friction coefficient for temporary flood barriers on asphalt is *f* = 0.76 and on grass is *f* = 0.64. The Boxwall is situated on asphalt, therefore the value for the friction coefficient is *f* = 0.76.

Now the horizontal stability can be calculated:

$\sum H < f * \sum V$
$f * \sum V = 0.76 * 62.1 = 47.2\ N/m$
$\sum H = 256\ N/m$

256 N/m > 47.2 N/m, therefore there is no horizontal stability when there is a wind force of p_{rep} = 256 N/m. This wind force is used for the design of structures, therefore this is a very large wind force that does not happen very often. On the day the Boxwall was tested, a wind speed of 4.0 m/s has been measured at weather station Ell, which is located 15 km away from Roermond (KNMI, n.d.). The wind speed in m/s can be converted to N/m using the following formula:

$F = area * \rho_{air} * (wind\ speed)^2$

where:

F [N] = wind force
$area$ [m^2] = surface area on which the wind force acts

$F = 0.50 * 1229 * 4.0^2 * 10^{-3} = 9.8\ N/m$

A wind force of 9.8 N/m is a much smaller force than p_{rep} = 256 N/m. This explains why the flood barrier was horizontally stable during the tests, unlike what is predicted by the horizontal stability calculation. To ensure horizontal stability when there is a wind force of 256 N/m, the weight of the Boxwall will need to be significantly increased. However, a great advantage of the Boxwall is that it is very easy and quick to set up, and this is due to its lightweight construction. Another option to ensure horizontal stability when there are higher wind forces, is to increase the friction coefficient. This can be done by placing more rubber at the bottom of the Boxwall.

Water is present:

Horizontal forces:

Instead of the wind force, there is a hydrostatic force. The hydrostatic force can be calculated with the following equation:

$F = \frac{1}{2} * \rho_w * g * h^2$
$F = \frac{1}{2} * \rho_w * g * h^2 = \frac{1}{2} * 1000 * 9.81 * 0.5^2 = 1226\ N/m$

Vertical forces:

In addition to the self-weight of the Boxwall, there is also the weight of the water. The weight of the water can be calculated with the following equation:

$W = \rho_w * V * g$

where:

W [N/m] = weight of the water
ρ_w [kg/m^3] = density of water (ρ_w = 1000)
V [m^3] = volume of the water
g [m/s^2] = acceleration due to gravity = 9.81 m/s^2

The thickness of the Boxwall is approximately 5 cm, therefore the volume of the water above the Boxwall has dimensions of $b \approx 0.63$ m and $h \approx 0.45$ m. The weight of the water can be calculated as follows:

$W = \rho_w * V * g = 1000 * 0.63 * 0.45 * 9.81 = 2781\ N/m$

The self-weight of the Boxwall stays the same:

$W = 62.1\ N/m$

The total vertical forces can be calculated:

$\sum V = 2781 + 62.1 = 2843\ N/m$

Now the horizontal stability can be calculated:

$\sum H < f * \sum V$
$f * \sum V = 0.76 * 2843 = 2161\ N/m$
$\sum H = 1226\ N/m$

1226 N/m < 2161 N/m, therefore there is horizontal stability.

Rotational stability:
For the rotational stability two criteria must be met. First, the sum of the stabilising moments should be higher than the sum of the de-stabilising moments. Second, there have to be zero tensional stresses at the bottom of the Boxwall.

The first criterium can be checked with the following equation:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

where:

$|M_{stabilising}|$ [Nm] = the absolute value of the sum of the stabilising moments about the rotational point P

$|M_{de-stabilising}|$ [Nm] = the absolute value of the sum of the de-stabilising moments about the rotational point P

The situation where water is present and the situation where water is not present will be discussed.

In Figure 25 a sketch of the two situations can be seen.

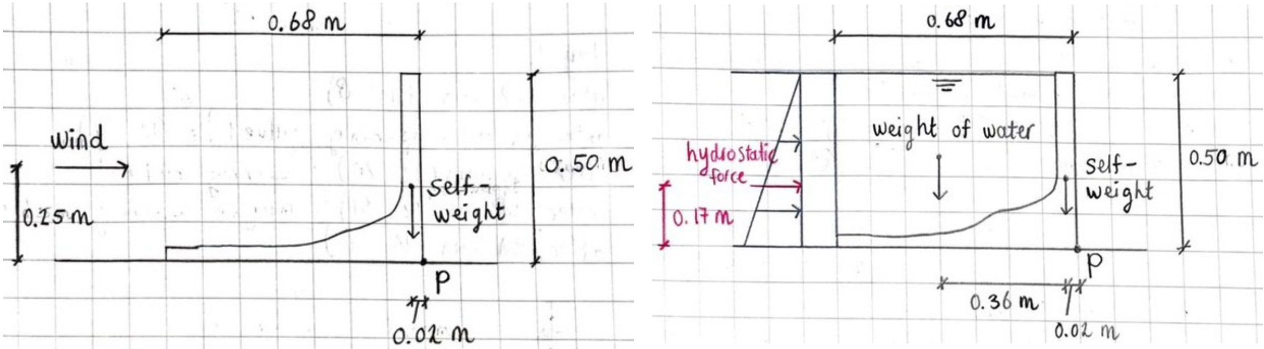


Figure 25: Sketch of the Boxwall for checking the stabilising and de-stabilising moments with no water present (left) and with water present (right)

Water is not present:
Stabilising forces:
The only stabilising force is the self-weight of the Boxwall. The self-weight is equal to 62.1 N/m. The moment due to the stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{stabilising}| = |M_{self-weight}| = |-62.1 * 0.02| = 1.2\ Nm/m$$

De-stabilising forces:
The only de-stabilising force is the wind force. The wind force is equal to p_{rep} = 256 N/m.
The moment due to the de-stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{de-stabilising\}} = |M_{wind}| = |256 * 0.25| = 64.0\ Nm/m$$

Now the first criterium can be checked:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

$1.2\ Nm/m < 64.0\ Nm/m$ therefore the de-stabilising moments are larger than the stabilising moments and the first criterium for rotational stability is not met. As a result, the Boxwall will tip over when there is a wind force of p_{rep} = 256 N/m.

Water is present:
Stabilising forces:
In addition to the self-weight of the Boxwall, there is also the weight of the water. The weight of the water is equal to W = 2781 N/m. The moment due to the self-weight stays the same and is equal to

$M_{self\text{-}weight}$ = -1.2 Nm/m. The moment due to the weight of the water can be calculated as follows (clockwise is considered positive):

$$M_{weight\ of\ water} = -2781 * 0.38 = -1057\ Nm/m$$

The sum of the stabilising moments can be calculated:

$$|M_{stabilising}| = |M_{self-weight} + M_{weight\ of\ water}| = |-1.2 - 1057| = 1058\ Nm/m$$

De-stabilising forces:
The only de-stabilising force is the hydrostatic force. The hydrostatic force is equal to *F* = 1226 N/m.
The moment due to the de-stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{de-stabilising}| = |M_{hydrostatic}| = |1226 * 0.17| = 208\ Nm/m$$

Now the first criterium can be checked:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

$1058\ Nm/m > 208\ Nm/m$ therefore the stabilising moments are larger than the de-stabilising moments and the first criterium for rotational stability is met.

The second criterium can be calculated with the following equation (Voorendt, 2023):

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6} b$$

where:

e_R [m] = distance from the middle of the structure (K) to the application point of the resulting force and the bottom line of the structure
$\sum V$ [N] = total vertical forces
$\sum M$ [Nm] = total of the acting moments around point K, halfway the width
b [m] = width of the structure

The situation where water is present and the situation where water is not present will be discussed.

In Figure 26 a sketch of the two situations can be seen.

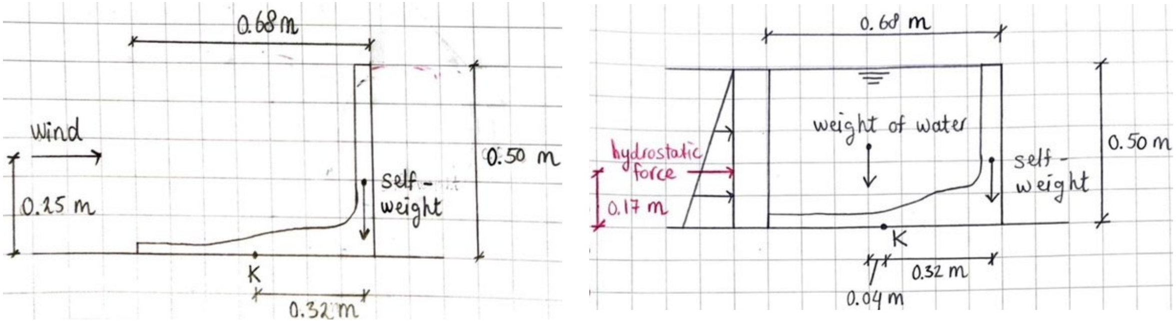


Figure 26: Sketch of the Boxwall for checking the tensional stresses at the bottom with no water present (left) and with water present (right)

Water is not present:
Horizontal forces:
Water is not present, so the only horizontal force is the wind force. The wind force is equal to p_{rep} = 256 N/m.
The moment due to the horizontal forces can be calculated as follows (clockwise is considered positive):

$$M_{wind} = 256 * 0.25 = 64.0\ Nm/m$$

Vertical forces:

The only vertical force that needs to be taken into account is the self-weight of the Boxwall. The self-weight is equal to 62.1 N/m.
The moment due to the vertical forces can be calculated as follows (clockwise is considered positive):

$$M_{self-weight} = 62.1 * 0.32 = 19.9\ Nm/m$$

The total of the acting moments can be calculated as follows:

$$\sum M = M_{wind} + M_{self-weight} = 64.0 + 19.9 = 83.9\ Nm/m$$

The total vertical forces are equal to:

$$\sum V = 62.1\ N/m$$

Now the second criterium can be checked:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6} b$$

$$\frac{\sum M}{\sum V} = \frac{83.9}{62.1} = 1.4\ m$$

$$\frac{1}{6} b = \frac{1}{6} * 0.68 = 0.11\ m$$

$1.4\ m > 0.11\ m$ therefore there are tensional stresses at the bottom of the Boxwall and the second criterium for rotational stability is not met. Tensional stresses are a problem when concrete is used in the structure, because concrete has a very weak tensile strength. The Boxwall is made from polypropylene (Waterschot, n.d.-b), and polypropylene has a high tensile strength (Omnexus, n.d.), therefore the tensional stresses at the bottom of the Boxwall do not have a significant effect on the rotational stability.

Water is present:
Horizontal forces:
Instead of the wind force, there is a hydrostatic force. The hydrostatic force is equal to *F* = 1226 N/m. The moment due to the horizontal forces can be calculated as follows (clockwise is considered positive):

$$M_{hydrostatic} = 1226 * 0.17 = 208\ Nm/m$$

Vertical forces:
In addition to the self-weight of the Boxwall, there is also the weight of the water. The weight of the water is equal to *W* = 2781 N/m. The self-weight of the Boxwall stays the same and is equal to *W* = 62.1 N/m. The moment due to the vertical forces can be calculated as follows (clockwise is considered positive):

$$M_{vertical} = M_{self-weight} + M_{water} = 62.1 * 0.32 - 2781 * 0.04 = -91.3\ Nm/m$$

The total of the acting moments can be calculated as follows:

$$\sum M = M_{hydrostatic} + M_{vertical} = 208 - 91.3 = 117\ Nm/m$$

The total vertical forces are equal to:

$$\sum V = 62.1 + 2781 = 2843\ N/m$$

Now the second criterium can be checked:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6} b$$

$$\frac{\sum M}{\sum V} = \frac{117}{2843} = 0.04\ m$$

$$\frac{1}{6} b = \frac{1}{6} * 0.68 = 0.11\ m$$

$0.04\ m < 0.11\ m$ therefore there are no tensional stresses at the bottom of the Boxwall and the second criterium for rotational stability is met.

In conclusion, the first and second criterium are not met for the situation where water is not present, therefore there is no rotational stability in this situation. The first and second criterium are met for the situation where water is present, therefore there is rotational stability in this situation. In the calculations where the water is not present, a wind force of 256 N/m is used, while during the tests there was a wind force of 9.8 N/m. This explains why the flood barrier was rotationally stable during the tests, unlike what is predicted by the first and second criterium for rotational stability.

Appendix F: Calculations of the failure mechanisms for the Geodesign Barrier

There are two possible failure mechanisms that need to be taken into account for the Geodesign Barrier: horizontal stability and rotational stability.

Horizontal stability:
For the horizontal stability, the situation where water is present and the situation where water is not present will be discussed.

The horizontal stability can be calculated with the following equation:

$$\sum H < f * \sum V$$

In Figure 27 a sketch of the two situations can be seen.

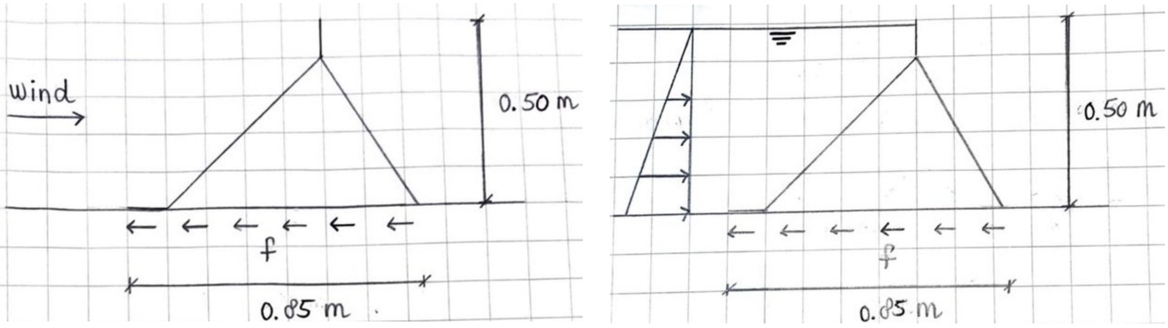


Figure 27: Sketch of the Geodesign Barrier with no water present (left) and with water present (right)

Water is not present:
Horizontal forces:
Water is not present, so the only horizontal force is the wind force. The Geodesign Barrier has dimensions of h < 50 m and h/b < 5, therefore the wind load equation simplifies to:

$$p_{rep} = C_{dim} * C_{index} * p_w \text{ [kN/m}^2\text{]}$$

C_{dim} can be obtained from Table 2-4 from the Manual Hydraulic Structures (Voorendt, 2023). For h = 0.50 m and b = 0.85 m we get C_{dim} = 1.00.
C_{index} = 0.8 (Voorendt, 2023)
p_w can be obtained from Table 2-3 from the Manual Hydraulic Structures (Voorendt, 2023). For $h \leq 2$ m we get p_w = 0.64.
p_{rep} can be calculated as follows:

$$p_{rep} = C_{dim} * C_{index} * p_w = 1.00 * 0.8 * 0.64 = 0.512\ kN/m^2$$

Multiply with the height of the Geodesign Barrier:

$$p_{rep} = 0.512 * 0.50 = 0.256\ kN/m = 256\ N/m$$

Vertical forces:
The only vertical force that needs to be taken into account is the self-weight of the Geodesign Barrier. The self-weight is 15 kg/m (D. Bon, personal communication, May 26, 2023) and this is equal to:

$$15 * 9.81 = 147\ N/m$$

Friction coefficient:
The friction coefficient depends on the soil type on which the water barrier is situated. Smeijers (2023) determined the friction coefficients of temporary flood barriers on different ground surfaces. The friction coefficient for temporary flood barriers on asphalt is f = 0.76 and on grass is f = 0.64. The Geodesign Barrier is situated on both asphalt and grass. The barrier has to be stable in both situations, so the most unfavourable situation will be analysed, therefore f = 0.64 is used.

Now the horizontal stability can be calculated:

$$\sum H < f * \sum V$$

$$f * \sum V = 0.64 * 147 = 94.2\ N/m$$

$$\sum H = 256\ N/m$$

256 N/m > 94.2 N/m, therefore there is no horizontal stability when there is a wind force of p_{rep} = 256 N/m. This wind force is used for the design of structures, therefore this is a very large wind force that does not happen very often. On the day the Geodesign Barrier was tested, a wind speed of 6.0 m/s has been measured at weather station Ell, which is located 15 km away from Roermond (KNMI, n.d.). The wind speed in m/s can be converted to N/m using the following formula:

$$F = area * \rho_{air} * (wind\ speed)^2$$

$$F = 0.50 * 1229 * 6.0^2 * 10^{-3} = 22\ N/m$$

A wind force of 22 N/m is a much smaller force than p_{rep} = 256 N/m. This explains why the flood barrier was horizontally stable during the tests, unlike what is predicted by the horizontal stability calculation. To ensure horizontal stability when there is a wind force of 256 N/m, the weight of the Geodesign Barrier will need to be significantly increased. A disadvantage of this is that it becomes more difficult to set up the flood barrier. Another option to ensure horizontal stability when there are higher wind forces, is to increase the friction coefficient. This can be done by placing more rubber at the bottom of the Geodesign Barrier.

Water is present:

Horizontal forces:

Instead of the wind force, there is a hydrostatic force. The hydrostatic force can be calculated with the following equation:

$$F = \frac{1}{2} * \rho_w * g * h^2$$

$$F = \frac{1}{2} * \rho_w * g * h^2 = \frac{1}{2} * 1000 * 9.81 * 0.50^2 = 1226\ N/m$$

Vertical forces:

In addition to the self-weight of the Geodesign Barrier, there is also the weight of the water. The weight of the water can be calculated with the following equation:

$$W = \rho_w * V * g$$

The volume of the water above the Geodesign Barrier is a square minus a triangle, see the sketch in Figure 28.

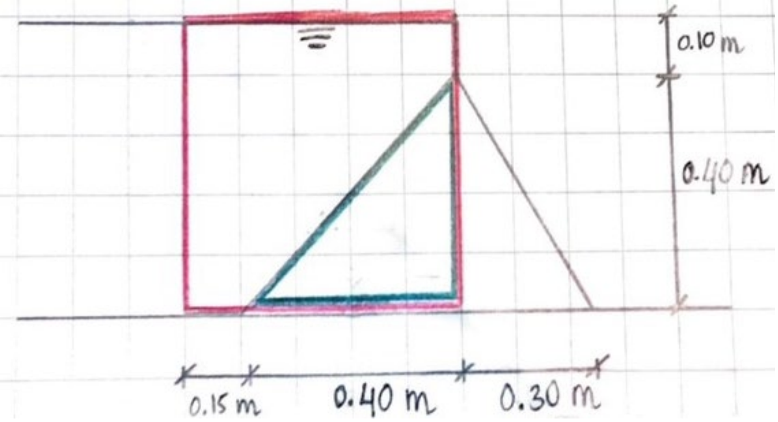


Figure 28: Sketch of the weight of the water above the Geodesign Barrier

The volume can be calculated as follows:

$$0.55 * 0.50 - \frac{1}{2} * 0.40 * 0.40 = 0.195\ m^3/m$$

The weight of the water can be calculated as follows:

$$W = \rho_w * V * g = 1000 * 0.195 * 9.81 = 1913\ N/m$$

The self-weight of the Geodesign Barrier stays the same:

$$W = 147\ N/m$$

The total vertical forces can be calculated:

$$\sum V = 1913 + 147 = 2060\ N/m$$

Now the horizontal stability can be calculated:

$$\sum H < f * \sum V$$

$$f * \sum V = 0.64 * 2060 = 1318\ N/m$$

$$\sum H = 1226\ N/m$$

1226 N/m < 1318 N/m, therefore there is horizontal stability.

Rotational stability:
For the rotational stability two criteria must be met. First, the sum of the stabilising moments should be higher than the sum of the de-stabilising moments. Second, there have to be zero tensional stresses at the bottom of the Boxwall.

The first criterium can be checked with the following equation:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

The situation where water is present and the situation where water is not present will be discussed.

In Figure 29 a sketch of the two situations can be seen.

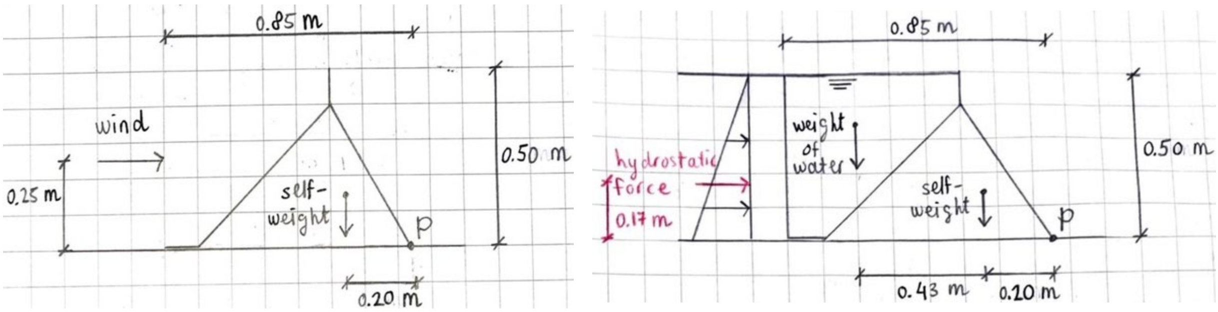


Figure 29: Sketch of the Geodesign Barrier for checking the stabilising and de-stabilising moments with no water present (left) and with water present (right)

Water is not present:
Stabilising forces:
The only stabilising force is the self-weight of the Geodesign Barrier. The self-weight is equal to 147 N/m. The moment due to the stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{stabilising}| = |M_{self-weight}| = |-147 * 0.20| = 29.4\ Nm/m$$

De-stabilising forces:
The only de-stabilising force is the wind force. The wind force is equal to p_{rep} = 256 N/m.
The moment due to the de-stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{de-stabilising\}} = |M_{wind}| = |256 * 0.25| = 64.0\ Nm/m$$

Now the first criterium can be checked:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

$29.4\ Nm/m < 64.0\ Nm/m$ therefore the de-stabilising moments are larger than the stabilising moments and the first criterium for rotational stability is not met. As a result, the Geodesign Barrier will tip over when there is a wind force of p_{rep} = 256 N/m.

Water is present:

Stabilising forces:

In addition to the self-weight of the Geodesign Barrier, there is also the weight of the water. The weight of the water is equal to W = 1913 N/m. The moment due to the self-weight stays the same and is equal to $M_{self\text{-}weight}$ = -29.4 Nm/m. The moment due to the weight of the water can be calculated as follows (clockwise is considered positive):

$$M_{weight\ of\ water} = -1913 * 0.63 = -1205\ Nm/m$$

The sum of the stabilising moments can be calculated:

$$|M_{stabilising}| = |M_{self-weight} + M_{weight\ of\ water}| = |-29.4 - 1205| = 1234\ Nm/m$$

De-stabilising forces:

The only de-stabilising force is the hydrostatic force. The hydrostatic force is equal to F = 1226 N/m. The moment due to the de-stabilising forces can be calculated as follows (clockwise is considered positive):

$$|M_{de-stabilising}| = |M_{hydrostatic}| = |1226 * 0.17| = 208\ Nm/m$$

Now the first criterium can be checked:

$$|M_{stabilising}| > |M_{de-stabilising}|$$

$1234\ Nm/m > 208\ Nm/m$ therefore the stabilising moments are larger than the de-stabilising moments and the first criterium for rotational stability is met.

The second criterium can be calculated with the following equation:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6} b$$

The situation where water is present and the situation where water is not present will be discussed.

In Figure 30 a sketch of the two situations can be seen.

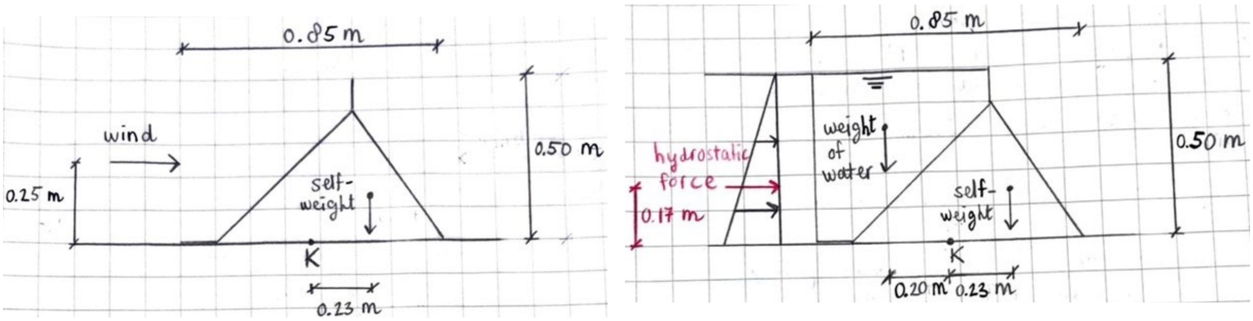


Figure 30: Sketch of the Geodesign Barrier for checking the tensional stresses at the bottom with no water present (left) and with water present (right)

Water is not present:

Horizontal forces:

Water is not present, so the only horizontal force is the wind force. The wind force is equal to p_{rep} = 256 N/m.

The moment due to the horizontal forces can be calculated as follows (clockwise is considered positive):

$$M_{wind} = 256 * 0.25 = 64.0\ Nm/m$$

Vertical forces:

The only vertical force that needs to be taken into account is the self-weight of the Geodesign Barrier. The self-weight is equal to 147 N/m.

The moment due to the vertical forces can be calculated as follows (clockwise is considered positive):

$$M_{self-weight} = 147 * 0.23 = 33.8\ Nm/m$$

The total of the acting moments can be calculated as follows:

$$\sum M = M_{wind} + M_{self-weight} = 64.0 + 33.8 = 97.8\ Nm/m$$

The total vertical forces are equal to:

$$\sum V = 147\ N/m$$

Now the first criterium can be checked:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6}b$$

$$\frac{\sum M}{\sum V} = \frac{97.8}{147} = 0.67\ m$$

$$\frac{1}{6}b = \frac{1}{6} * 0.85 = 0.14\ m$$

$0.67\ m > 0.14\ m$, therefore there are tensional stresses at the bottom of the Geodesign Barrier and the first criterium for rotational stability is not met. Tensional stresses are a problem when concrete is used in the structure, because concrete has a very weak tensile strength. The Geodesign Barrier is made from steel (Hydro Response, n.d.), and steel has a high tensile strength (The Engineering ToolBox, n.d.), therefore the tensional stresses at the bottom of the Geodesign Barrier do not have a significant effect on the rotational stability.

Water is present:

Horizontal forces:

Instead of the wind force, there is a hydrostatic force. The hydrostatic force is equal to *F* = 1226 N/m. The moment due to the horizontal forces can be calculated as follows (clockwise is considered positive):

$$M_{hydrostatic} = 1226 * 0.17 = 208\ Nm/m$$

Vertical forces:

In addition to the self-weight of the Geodesign Barrier, there is also the weight of the water. The weight of the water is equal to *W* = 1913 N/m. The self-weight of the Geodesign Barrier stays the same and is equal to *W* = 147 N/m. The moment due to the vertical forces can be calculated as follows (clockwise is considered positive):

$$M_{vertical} = M_{self-weight} + M_{water} = 147 * 0.23 - 1913 * 0.20 = -349\ Nm/m$$

The total of the acting moments can be calculated as follows:

$$\sum M = M_{hydrostatic} + M_{horizontal} = 208 - 349 = -141\ Nm/m$$

The total vertical forces are equal to:

$$\sum V = 147 + 1913 = 2060\ N/m$$

Now the first criterium can be checked:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6}b$$

$$\frac{\sum M}{\sum V} = \frac{-141}{2060} = -0.07\ m$$

$$\frac{1}{6}b = \frac{1}{6} * 0.85 = 0.14\ m$$

$-0.07\ m < 0.14\ m$ therefore there are no tensional stresses at the bottom of the Geodesign Barrier and the second criterium for rotational stability is met.

In conclusion, the first and second criterium are not met for the situation where water is not present, therefore there is no rotational stability in this situation. The first and second criterium are met for the situation where water is present, therefore there is rotational stability in this situation. In the calculations where the water is not present, a wind force of 256 N/m is used, while during the tests there was a wind force of 22 N/m. This explains why the Geodesign Barrier was rotationally stable during the tests, unlike what is predicted by the first and second criterium for rotational stability.