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Preliminary Assessment of the Behaviour of Temporary Flood Barriers in Floods

CIE5050-09 Additional Graduation Work, Research Project (2022/23)

Delft University of Technology

PRELIMINARY ASSESSMENT OF THE BEHAVIOUR OF TEMPORARY FLOOD BARRIERS IN FLOODS

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Summary

Due to an extraordinary precipitation event in July 2021, the Dutch government want to utilise the temporary flood barriers to reduce the impact caused by a flash flood event in the future. As a result, Water Board Limburg, Flood Proof Holland and Delft University of Technology made an agreement to conduct a physical experiment in Roermond on May 2023 to test the functionality of the temporary flood barriers in different spatial conditions.

This report aims to provide a comprehensive understanding of the temporary flood barriers and their performance in spatial variability before the experiment. To achieve this, available information on various barriers has been summarised to make a valid argument for the comparison of different barriers.

The first part of this report provides an overview of worldwide available barriers with their corresponding physical concepts explained, while more detailed information is given on those tested in Flood Proof Holland. The report then presents a theoretical hypothesis based on the calculation of the resisting force of the barriers. The findings reveal that most of the tested barriers can withstand a water level of 50 cm on asphalt, concrete, sand, and grass. However, BoxBarrier and BoxWall(Waterschot) show exceptions when subpressure is taken into account.

The report also includes a comprehensive outline of a physical experiment that will be conducted in May 2023, which provides a detailed description of the experiment, as well as preliminary assessment criteria. These criteria include logistics, failure mechanisms, spatial conditions, and additional requirements from the water board, and will be used to assess the performance of the temporary flood barriers. Additionally, an ideal monitoring plan utilising video camera, tracer fluid, and RBR-Diver has been proposed for the experiment.

Lastly, the report features a discussion of a preliminary test conducted on February 15th 2023 in Flood Proof Holland, to evaluate the effectiveness of the designed monitoring approach. The test proved that the proposed monitoring plan was successful and emphasised the significance of proper equipment inspection, anchoring, and quality control of materials for the temporary flood barriers.

Contents

1. Introduction

The rise in extreme water events due to climate change has significantly increased the frequency of floods. However, flood protection systems designed for short return periods may not be adequate to protect against emergency flooding (Slomp, 2012), as flash floods can occur unpredictably anywhere and anytime (Gaume et al., 2009). As a result, there is an increasing demand for temporary flood barriers. The primary purpose of using temporary flood barriers is to prevent or delay flooding to provide safety in the hinterland. These temporary structures should be mobilised and flexible during emergencies (Ogunyoye et al., 2002). When adopting these barriers, the labour-intensive construction time should be compared on efficiency with sandbags, which is the traditional method currently used to delay the arrival of flood waves.

It is known that flooding can spread to various areas, including low-lying cities or basins. Also, temporary flood barriers can be used to delay the arrival of floods in an emergency, thus reducing damage. However, despite their potential benefits, failures of these temporary flood protection systems can occur, including functional, structural, and operational failures, as illustrated in Figure 1. It may be easy to identify functional and operational failures through observation, but there is little experimental or theoretical data available to define the structural failure of these barriers, for example, their strengths and weaknesses under different spatial conditions. In addition, when deploying barriers on various surface conditions, such as streets, standard asphalt, grass, sand, or rocky surfaces, the resisting force can be affected by different friction factors, making it challenging to determine the strengths and weaknesses of these barriers.

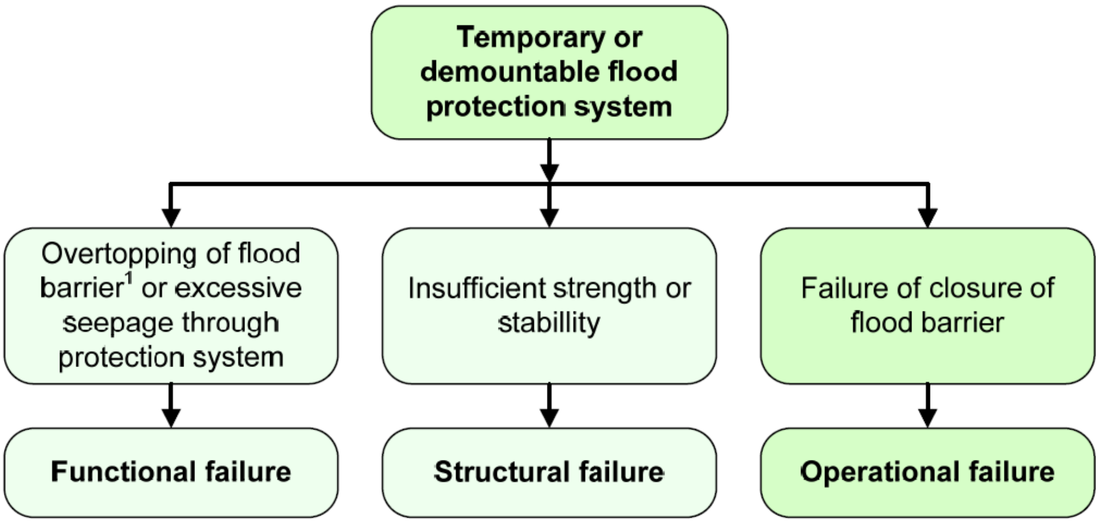


Figure 1 Fault tree for a temporary or demountable flood protection system (Ogunyoye et al., 2002)

Besides, in the summer of 2021, a flooding event occurred in the Netherlands, as shown in Figure 2. It was estimated that the heavy precipitation caused the Meuse River near Eijsden and some tributaries in Limburg exceeding their design return period, leading to damage larger than the flooding event in 1993 and 1995, estimated to 350 to 600 million euros (Rongen et al., 2021). The Water Board Limburg recognised the severity of the situation and concluded that temporary flood barriers would be necessary for future events to minimise damage. To determine the most suitable options in terms of cost and functionality, a tender was announced, with the physical experiment in May to identify appropriate barriers. At the request of the water board, a monitoring system has been developed to observe specific areas of potential failure.

Figure 2 Example of flooding area in Roermond during the event, scale 1:2500 m (Waterschapshuis)

The objective of this report is to outline the experimental setup for testing temporary flood barriers at the Roermond test field in May. This involves a theoretical analysis of the structural failure of the barriers by calculating their resisting force, as well as incorporating all aspects of an experiment protocol provided by the water board.

2. General description of Temporary Flood Barriers

This chapter will provide a classification of differents temporary flood barriers available in the world. After that, detail information about the barriers which tested in Flood Proof Holland and their physical principal concepts will be concluded. At the end of the chapter, a simple calculation of the resisting force of the barriers will be presented based on the required water level of 0.5 m specified by the Water Board Limburg.

2.1 Classification of Temporary Flood Barrier

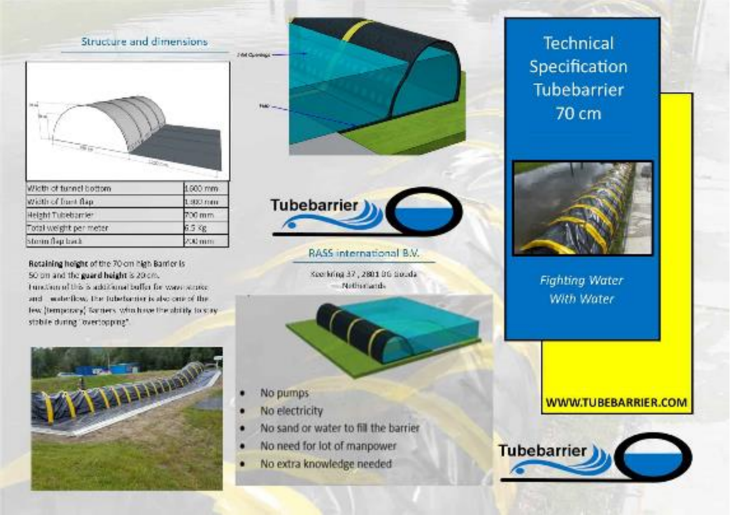
The temporary flood barriers can be categorised into four main types: Tube Shape Barrier, Filled Container Barrier, Free-standing Barrier and Frame Barrier. Each type has further subdivisions based on the filling material and mechanisms. A table has been created to illustrate the classification of the barriers. However, there are many types of temporary flood barriers available worldwide. This report will focus on the temporary barriers currently being investigated at TU Delft, which are indicated by a blue tick.

Table 1 Classification of temporary flood barriers according to the categorisation provided by the Environment Agency (Ogunyoye et al., 2002)

Temporary Flood Barrier			
Filled Container		Tube Shape	
Filled with water or aggregate (optional for some systems) Permeable or impermeable material Bottom seal formed by flexibility and weight of aggregate Ogunyoye et al, 2002		External tube, typically waterproof geosynthetic material Overturning is prevented by internal resistant or external anchoring Ogunyoye et al, 2002	
Permeable	Impermeable	Air Filled	Water Filled
Hesco Barrier	BoxBarrier ✓	TubeWall	TubeBarrier ✓ Mobile Dike ✓ SlamDam ✓
Free-standing		Frame	
Reinforced waterproof flexible or rigid structure Tension straps or solid membranes Skirt weighted with sand bags or similar Long sleeve to provide stability and reduce seepage Ogunyoye et al, 2002		Weighting for fabric wind resistance. Waterproof fabric over frame or other rigid material fixed to the frame Metal support frame Skirt weighted or anchored Long sleeve to provide stability and reduce seepage Ogunyoye et al, 2002	
Flexible	Rigid	Flexible	Rigid
Flex Wall	BoxWall ✓ H-Wall ✓	PortaDam	Geodesign Barrier

2.2 Tubebarrier

The tubebarrier system contains two parts, including the tube and the slab, as shown in Figure 3. For stability, the tube itself is supported by tension bars; meanwhile, the tip of the slab is anchored at the ground to avoid piping. This system is designed for the long length protection close to a water source, and it is not easy to transport for a long distance. Therefore, each component is 10 m long and it is compressed into a storage box. When deploying the tubebarrier, zipper at the edge of the element can be used to connect each other. As water is coming, the inlet openings at the front of the tube allow water to flow inside. Eventually, the inside water balances out with the outside water level, stabilising the system.



Width of tunnel bottom	1600 mm
Width of front flap	[illegible]
Height Tubebarrier	700 mm
Total weight per meter	6.5 Kg
Storm flap back	200 mm

Retaining height of the 70 cm high Barrier is 50 cm and the **guard height** is 20 cm. Function of this is additional buffer for wave stroke and waterflow. The Tubebarrier is also one of the few (temporary) barriers who have the ability to stay stabile during "overtopping".

Keerkring 37 , 2801 DG Gouda
Netherlands

- No pumps
- No electricity
- No sand or water to fill the barrier
- No need for lot of manpower
- No extra knowledge needed

Figure 3 Schematisation of Tubebarrier (Tubebarrier, 2015)

2.3 BoxBarrier

The principle behind the boxbarrier system is quite simple. It contains three main components: the box with the rubber strip at the bottom, the lid and the rubber spacer. Each box has a dimension L: 90 cm W: 63.5 cm H: 60 cm as shown in Figure 4, so it can be against the water level for 0.5 m. When adopting the boxbarrier, these barriers need to be filled with enough water to gain enough weight for the barrier to compensate for the floodwater. On the other hand, the rubber strip ensures the Boxbarrier can be used on top of the rough surface. Based on this information, the advantage of this barrier is that it is easy to assemble by attaching the barriers with rubber spacers and easy to transport. Also, people can walk on top of it as an escape route. However, it is proven that the boxbarriers cannot be overtopped according to the experiment mentioned in Chapter 7.

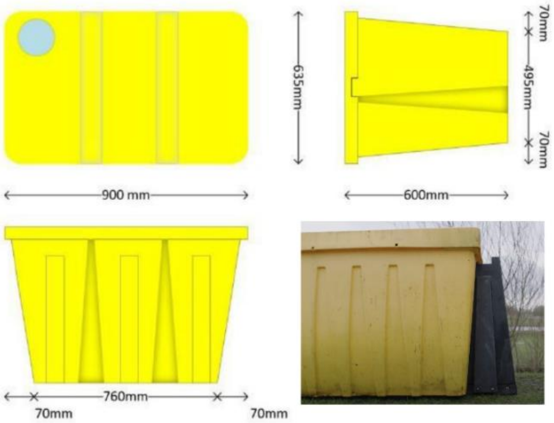


Figure 4 Schematisation of Tubebarrier (Scheel, 2021)

2.4 Mobile Dikes (Mobiele Dijk in Dutch)

This mobile dike is also known as the water-filled tube barrier. The core is made of 2 to 3 hoses, and each hose will be filled with water from the flooding area to provide enough weight to act as a foundation. A patented net around the hoses will absorb and distribute the impact load through the whole barrier. During the construction, the sealing tarpaulin with chains will be placed on top of the core to reduce leakage loss. This system can retain the water level up to 2.6 m high as demonstrated by Figure 5. For transportation, a set of wheels is designed to unroll the dike to a specific location.

Figure 5 Schematisation of Mobile Dikes (Mobiele Dijken, 2016)

2.5 SlamDam

The principal mechanism of SlamDam barrier is the same as the water-filled tube barrier, similar to Mobile Dikes. This system is made of one single tube, which has the prototype dimensions of 164 cm wide and 67 cm high, 50 cm for the retaining water level as illustrated by Figure 6. The total length of one element is 500 cm, which can be compressed into a plastic storage box with the size (80 × 60 × 42 cm) for transportation. The entire system must be filled with water to stabilise the impact load. On top of the tube, there are four inlet openings. By using a water pump, water can flow through them and store inside the barrier.

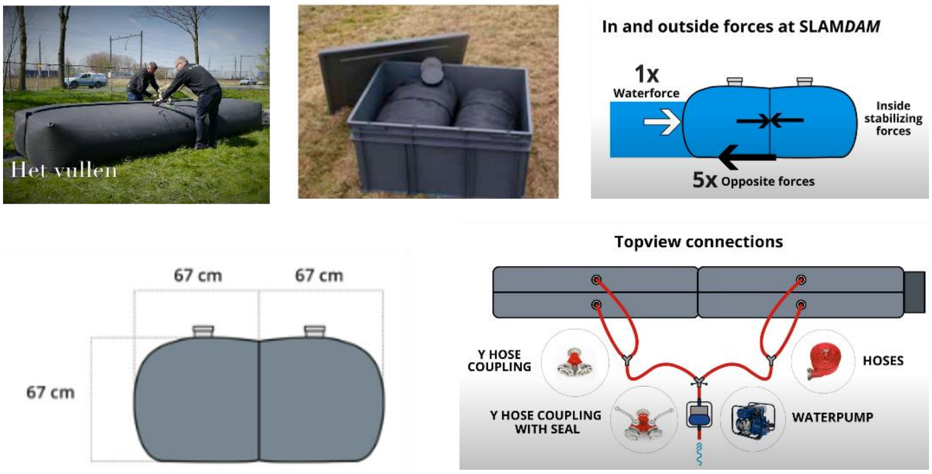


Figure 6 Schematisation of SlamDam (SlamDam, 2016)

2.6 Boxwall (Waterschot in Dutch)

The Boxwall barrier can be defined as a rigid free-standing barrier, which means that no frame is necessary to support the structure. Usually, each element with self-anchoring can connect to form a continuous barrier. When there is flooding, the weight of water on top of the horizontal part of the barrier will provide enough stability to let the barrier attach to the ground surface to prevent sliding. Prefabricated material connectors will be used if a change in the direction of barriers is required. The typical dimensions of Boxwall barrier are 70.5 cm wide and 62.8 cm high as shown in Figure 7, so the retaining water level is 50 cm.

The base section of the boxwall is pressed firmly against the ground by the weight of the flood water. There is a pair of cellular rubber soles on the underside to provide a reliable grip on the road.

Beneath the front edge of the boxwall is a sealing strip made of cellular rubber. This keeps the leakage of water at the bottom to a minimum.

The anchoring force is proportional to the difference in water pressure between the upper and lower side of the boxwall. A system of drainage channels on the lower side diverts the leaking water, so that no counter pressure arises.

The rear wall dams the flood water. The water's pressure is absorbed by a couple of large bulges, which also act as drainage channels.

Figure 7 Schematisation of Boxwall (Waterschot, 2023)

2.7 H-Wall

The H-Wall barrier is also one of the rigid free-standing barriers. It contains three components: the single rigid element, tension straps, and wrapping foil. For stability, the weight of water over the front leading edge and the tension straps will support the whole barrier. With the combination of wrapping foil and sandbags, water cannot flow underneath the barrier. On the other hand, each element has a dimension of 122 cm wide and 90 cm high as illustrated by Figure 8, and the retaining water level is around 80 cm.

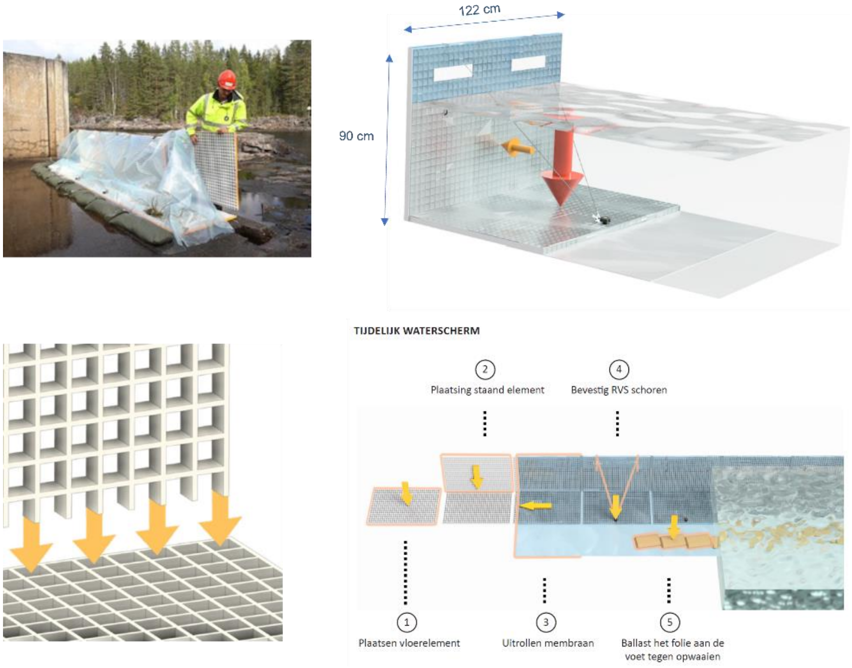


Figure 8 Schematisation of H-Wall (Altena, 2022)

2.8 Resisting Force

As mentioned before, the performance of temporary flood barriers can be affected by various failure mechanisms, which can be categorised into functional, structural, and operational failures (Ogunyoye et al., 2002). This report will focus on the structural failure mechanism and the calculation of the resisting force of sliding. This is because the type and characteristics of the surface layer with different frictions play a significant role in the spatial conditions. However, it is important to know that excessive stress on the material can also lead to the collapse of the structure due to inadequate strength, as well as deformation, which can result in structural failure. In cases where the material is too weak for the structure, for instance, if the structure is made of steel, it is not expected to deform, but if it is made of soft plastic, the structure can deform under load.

Since the total of the horizontal forces acting on the barrier will be transferred to the subsoil. The friction force of the subsoil should resist the resulting total acting horizontal force, otherwise it will slide aside (Molenaar, 2016). Based on this concept, the stability of the temporary flood barriers can be determined. The condition for horizontal stability is shown in the equation Eq 1 below.

$$\underbrace{\sum F_H}_{\textbf{Total Horizontal Force}} < \underbrace{f \cdot \sum F_V}_{\textbf{Friction Force}} \tag{Eq 1}$$

Where, f is the dimensionless friction coefficient, $\sum F_H$ is the sum of all horizontal forces [N] and $\sum F_V$ is the sum of all vertical forces [N]. By integrating the pressure over the area acting on the barriers, the total horizontal force can be obtained as equation Eq 2.

$$F_H = \int_A p dA \tag{Eq 2}$$

Where, A is the total surface area [m^2], p is the hydrostatic water pressure [N/m^2]. p can be computed by the following equation Eq 3,

$$p = \rho_w g h \tag{Eq 3}$$

In which, h is the water depth [m], g is the acceleration due to gravity [m/s^2], ρ_w is density of water [kg/m^3]. Besides, a difference in water level across a barrier can cause a flow beneath the barrier when the waterproofing at the bottom of a barrier is insufficient. It can lead to a linear change in water pressure along the path directly beneath the structure, which causes a discontinuity in the upward pressure known as subpressure F_s (Molenaar, 2016). Therefore, the computation of the total vertical force can be determined by utilizing the following equation Eq 4, which considers various components including the subpressure F_s [N], the hydrostatic pressure [N/m^2], and the total weight of the barrier W [N].

$$F_v = \int_A p dA + W - F_s \tag{Eq 4}$$

For comparison, a standard water depth (h) of 50 cm used in Eq 3 was assumed as the retaining water level for all temporary flood barriers being evaluated with the specifications set by Water Board Limburg. This water level is the height that the water board must address during the majority of emergency situations. To provide a visual representation of the loading distribution for each barrier, a loading distribution diagram was generated in Figure 9. This diagram illustrates the distribution of the applied load across the entire length of the barrier.

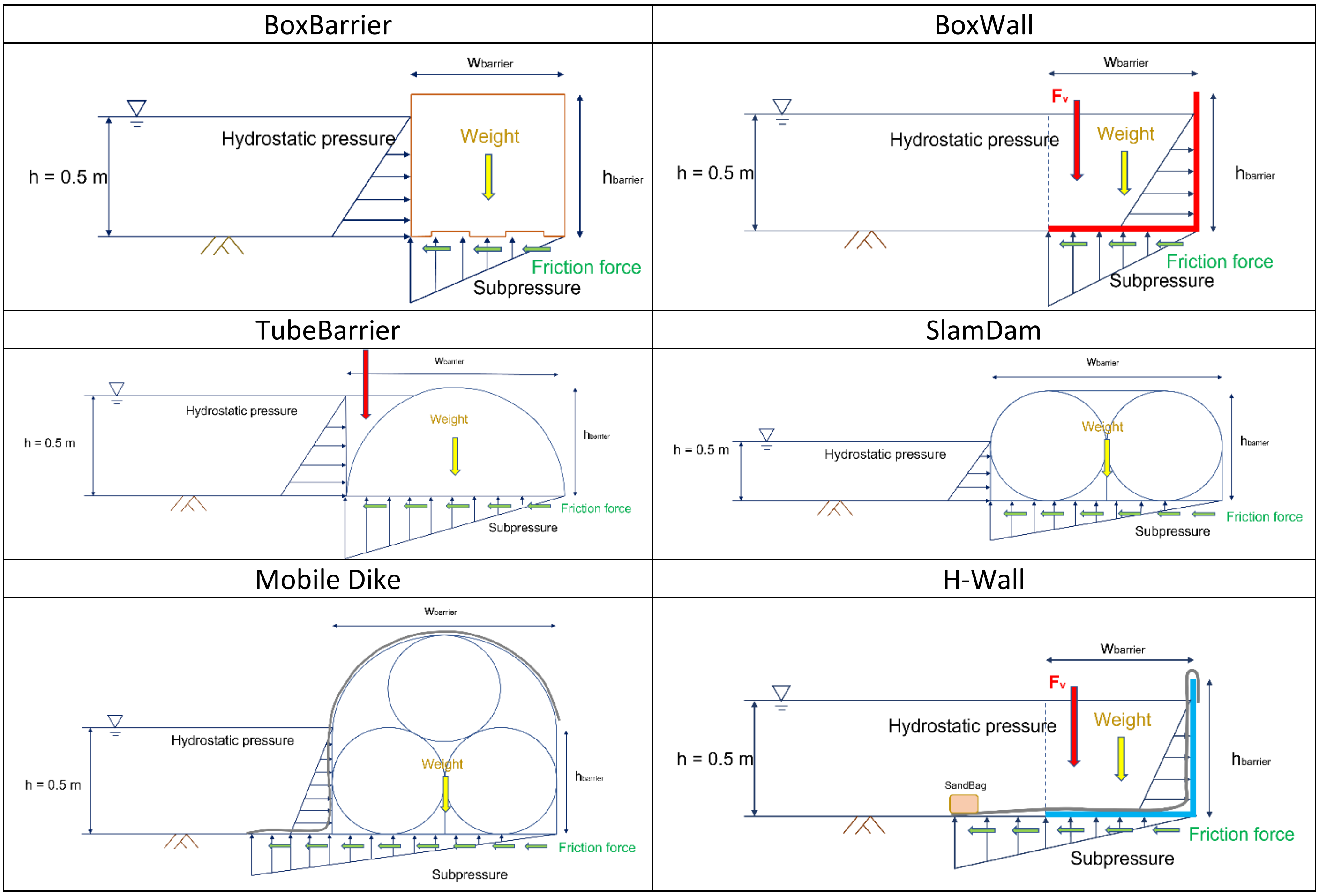


Figure 9 Loading Distribution Diagram

Next, an analysis of all the forces acting on the temporary flood barriers tested in Flood Proof Holland will be provided. In this case, four different spatial conditions have been considered, including concrete layer, asphalt layer, sandy layer, and grass layer. To determine the friction coefficient, it is crucial to consider the material of the barriers. Therefore, a detailed definition of the various materials used for the barriers is necessary. The information gathered has been summarised and presented in the form of a table for better clarity and understanding, as shown in Table 2.

Table 2 Corresponding material of different barriers.

Barriers	BoxBarrier	TubeBarrier	Mobile Dike	SlamDam	BoxWall	H-Wall
Material	Rubber	Polypropylene	Polypropylene	Rubber	Rubber	Reinforced PVC

In addition, when calculating the vertical forces acting on temporary flood barriers, it is important to account for the worst-case scenario with the maximum subpressure due to water flow underneath, which can significantly impact the resisting force. The friction coefficient is an important parameter that affects the calculation of resisting force and can be obtained from literature reviews. Table 3 presents the relevant studies used in this report regarding the friction coefficient of various materials on different surfaces.

Table 3 Summary of friction coefficient data for various materials and different surfaces

Marterial \ Surface	Concrete	Asphalt	Sand	Grass
Rubber	0.68 (Regents Physics Friction, 2017)	0.67 (Regents Physics Friction, 2017)	0.40 (Sharkawy et al., 2017)	0.35 (Elert, 2021)
Polypropylene	0.56 (Klipalo et al., 2022)	0.54 (Klipalo et al., 2022)	0.50 (Klipalo et al., 2022)	0.67 (Klipalo et al., 2022)
Reinforced PVC	0.65 (Smeijers, 2023)	0.78 (Smeijers, 2023)	0.58 (Vaid et al., 1995)	1.52 (Smeijers, 2023)

The assumption of the friction coefficient between rubber and sand was based on the research on rubber's sliding on a sand-contaminated floor (Sharkawy et al., 2017), and the determination of the friction coefficient for rubber on concrete and asphalt was derived from the study on the coefficient of friction conducted by Regents Physics Friction in 2017. Similarly, the investigation conducted by Elert in 2021 provided insights into the friction coefficient for rubber on grass. In addition, the interaction between polypropylene material suitable for flood defence and various surface areas has been investigated by a full-scale interface friction test (Klipalo et al., 2022), and the resulting data is presented in the second row of Table 3, while the values of the friction coefficient of reinforced PVC with concrete, asphalt and grass have been extracted by the experimental investigation of H-wall stability (Smeijers, 2023). Furthermore, the experiments on the interface friction of geomembranes and granular filters (Vaid et al., 1995) provided valuable data on the friction angle between the reinforced PVC and the subsoil. This information allows for the calculation of the friction coefficient using the following equation:

$$f = \tan(\delta) \qquad \text{(Eq 5)}$$

Where, δ is the friction angle between structure and subsoil [°]. Once the subpressure and friction coefficient have been taken into consideration, the resisting force calculations can be presented, which shown in Table 4.

Table 4 Result of resisting force of different barriers in various spatial conditions

BoxBarrier		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.68	0.67	0.40	0.35
Including Subpressure	$F_{subpressure}$ [N]	1402	1402	1402	1402
	$F_{vertical}$ [N]	2042	2042	2042	2042
	Fiction [N]	1388	1368	817	715
	$F_{horizontal}$ [N]	1104	1104	1104	1104
	Safety Factor	1.26	1.24	**0.74**	**0.65**
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	3443	3443	3443	3443
	Fiction [N]	2341	2307	1377	1205
	$F_{horizontal}$ [N]	1104	1104	1104	1104
	Safety Factor	2.12	2.09	1.25	1.09
TubeBarrier		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.56	0.54	0.50	0.67
Including Subpressure	$F_{subpressure}$ [N]	39240	39240	39240	39240
	$F_{vertical}$ [N]	34067	34067	34067	34067
	Fiction [N]	19078	18396	17034	22825
	$F_{horizontal}$ [N]	12263	12263	12263	12263
	Safety Factor	1.56	1.50	1.39	1.86
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	73307	73307	73307	73307
	Fiction [N]	41052	39586	36654	49116
	$F_{horizontal}$ [N]	12263	12263	12263	12263
	Safety Factor	3.35	3.23	2.99	4.01
MobileDike		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.56	0.54	0.50	0.67
Including Subpressure	$F_{subpressure}$ [N]	58860	58860	58860	58860
	$F_{vertical}$ [N]	74556	74556	74556	74556
	Fiction [N]	41751	40260	37278	49953
	$F_{horizontal}$ [N]	24525	24525	24525	24525
	Safety Factor	1.70	1.64	1.52	2.04
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	133416	133416	133416	133416
	Fiction [N]	74713	72045	66708	89389
	$F_{horizontal}$ [N]	24525	24525	24525	24525
	Safety Factor	3.05	2.94	2.72	3.64
SlamDam		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.68	0.67	0.40	0.35
Including Subpressure	$F_{subpressure}$ [N]	16432	16432	16432	16432
	$F_{vertical}$ [N]	18472	18472	18472	18472
	Fiction [N]	12561	12376	7389	6465
	$F_{horizontal}$ [N]	6131	6131	6131	6131
	Safety Factor	2.05	2.02	1.21	1.05
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	34904	34904	34904	34904
	Fiction [N]	23735	23386	13962	12216
	$F_{horizontal}$ [N]	6131	6131	6131	6131
	Safety Factor	3.87	3.81	2.28	1.99
BoxWall		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.68	0.67	0.40	0.35
Including Subpressure	$F_{subpressure}$ [N]	1176	1176	1176	1176
	$F_{vertical}$ [N]	1233	1233	1233	1233
	Fiction [N]	838	826	493	431
	$F_{horizontal}$ [N]	865	865	865	865
	Safety Factor	**0.97**	**0.96**	**0.57**	**0.50**
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	2408	2408	2408	2408
	Fiction [N]	1638	1614	963	843
	$F_{horizontal}$ [N]	865	865	865	865
	Safety Factor	1.89	1.87	1.11	**0.98**
H-Wall		Concrete	Asphlat	Sand	Grass
	Friction Coefficient	0.65	0.78	0.58	1.52
Including Subpressure	$F_{subpressure}$ [N]	5386	5386	5386	5386
	$F_{vertical}$ [N]	5709	5709	5709	5709
	Fiction [N]	3711	4453	3311	8678
	$F_{horizontal}$ [N]	1496	1496	1496	1496
	Safety Factor	2.48	2.98	2.21	5.80
Excluding Subpressure	$F_{subpressure}$ [N]	0	0	0	0
	$F_{vertical}$ [N]	11095	11095	11095	11095
	Fiction [N]	7212	8654	6435	16865
	$F_{horizontal}$ [N]	1496	1496	1496	1496
	Safety Factor	4.82	5.78	4.30	11.27

The calculation results indicate that all barriers can resist a water level of 50 cm. However, some exceptions exist when considering the subpressure, specifically with the BoxBarrier and BoxWall. Based on this theoretical hypothesis, BoxBarrier cannot withstand the total horizontal forces on sand and grass layers due to insufficient weight and low friction coefficient, leading to instability. Similarly, BoxWall cannot resist the 50 cm water pressure on all surface layers under subpressure, even on the grass surface without subpressure. The vertical components of BoxWall, including the weight of the barrier and water, are not enough to provide stability against the total horizontal force. It suggests that friction coefficient, subpressure, and barrier length significantly affect the results. Further analysis may be necessary to fully understand the factors contributing to the differences in barrier performance.

3. Motivation for Physical Experiment in May

A brief description of the motivation for testing the temporary flood barriers will be elaborated in this chapter. Moreover, this part will conclude by describing the study area, the requirements, and the objective for the physical experiment from the water board.

3.1 Study Area

The Dutch province of Limburg is located in the south of the Netherlands, near the border of Belgium and Germany. More than one million people live in this historical region and the total surface area is estimated as 2209 km^2 (Mappr, 2022). The elevation of Limburg is quite different compared to the other provinces in the Netherlands, characterised by relatively hilly terrain. Apart from this, the mainstream flow through this province is the Meuse River, which is fed mostly by rainwater. Along the Meuse River, three main tributaries can be found in Limburg, including Geul River, Geleenbeek River and Roer River, as shown in Figure 10. Due to its specific geographical condition, when there is an extraordinary precipitation event in the upstream part of Meuse River, this results in unpredictable damage for the towns along the river.

In the previous chapter, it was mentioned that physical experiments on the stability and performance of temporary flood barriers will be examined in Roermond. The reason for selecting the test side in this city can be divided into two parts. On the one hand, Roermond is located at the interaction of Meuse River and Roer River in the province of Limburg. Since testing the temporary flood barriers requires a large amount of water, it is an excellent position to set the test site in this place. Additionally, this city is surrounded by many streams, lakes, and canals. As a consequence, flooding is a significant problem for the city of Roermond. During this test, the functionality of temporary flood barriers in street conditions will be observed and evaluated.

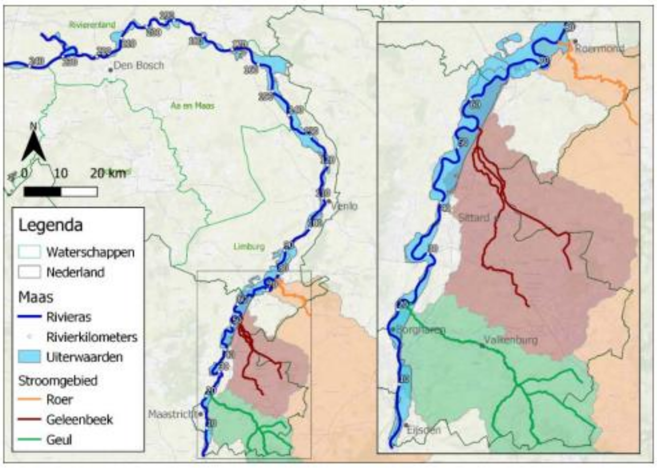


Figure 10 Flooding Map and Subcatchment of Meuse Flooding Event (Hoogwater, 2021)

3.2 Physical Experiment Requirements

The objective of this experiment is to assess the functionality, structural stability and operation efficiency of the temporary flood barrier (Waterschap Limburg, 2023). The main scope of the test is to verify the ability of the barriers to resist a 50 cm water level and guide the flow through bendings and steps. In this experiment, monitoring equipment is set up to detect whether the barrier is functioning and working according to the requirements of the water board, with the cooperation of TU Delft and AccessHub company.

It is known that this experiment is only open for tenderers who have placed a complete bid and reached a minimum score of "Good" for the K1 Plan of Action announced by the water board. In order to secure valid participation, qualified tenderers must provide the resources and materials needed for the experiment in a timely manner. During the experiment, tenderers must undergo the installation and assembly operations under the supervision and control of Water Board Limburg. The resources and materials used in the experiment must align with the proposed solutions, and all spare materials have to be declared. In addition, the presence of tenderers during their testing is mandatory. For the arrangement, each tenderer is expected to proceed with the schedule in one day, including build-up, test and tear-down. During the assembly, a maximum of 5 people is limited to participate in the whole process, and tenderers can ask for three people from the water board if they cannot reach the maximum number of people.

4. Experiment Description

The exact location of the test site is near the northwest direction of Burgemeester Höppenerlaan roundabout in Roermond. Next to the site, there is a river called the Roer. To ensure a sufficient water supply for the test, the water will be pumped directly from the river.

4.1 Boundary Conditions

Before establishing the experiment site, the primary function of this area was to serve as a space for pet owners to engage in dog-walking activities. Grass is widely spread over this region as shown in Figure 11. In the middle of the basin, there is a ditch for releasing the water pressure at the hinterland. During the test, the water from the pump can flow back to the Roer River through the ditch.

Figure 11 Test site exact location in Roermond

In the test framework established by the water board, the execution is structured to incorporate two different test lanes, including a paved lane and an unpaved lane as demonstrated by Figure 12. For The first test, the temporary flood barriers are involved to test for water-steering capacity with respect to longitudinal flow and the ability of overtopping on a hard surface. The second is focused on evaluating the water resistance (50 cm water retaining) of the flood barriers on a natural substrate.

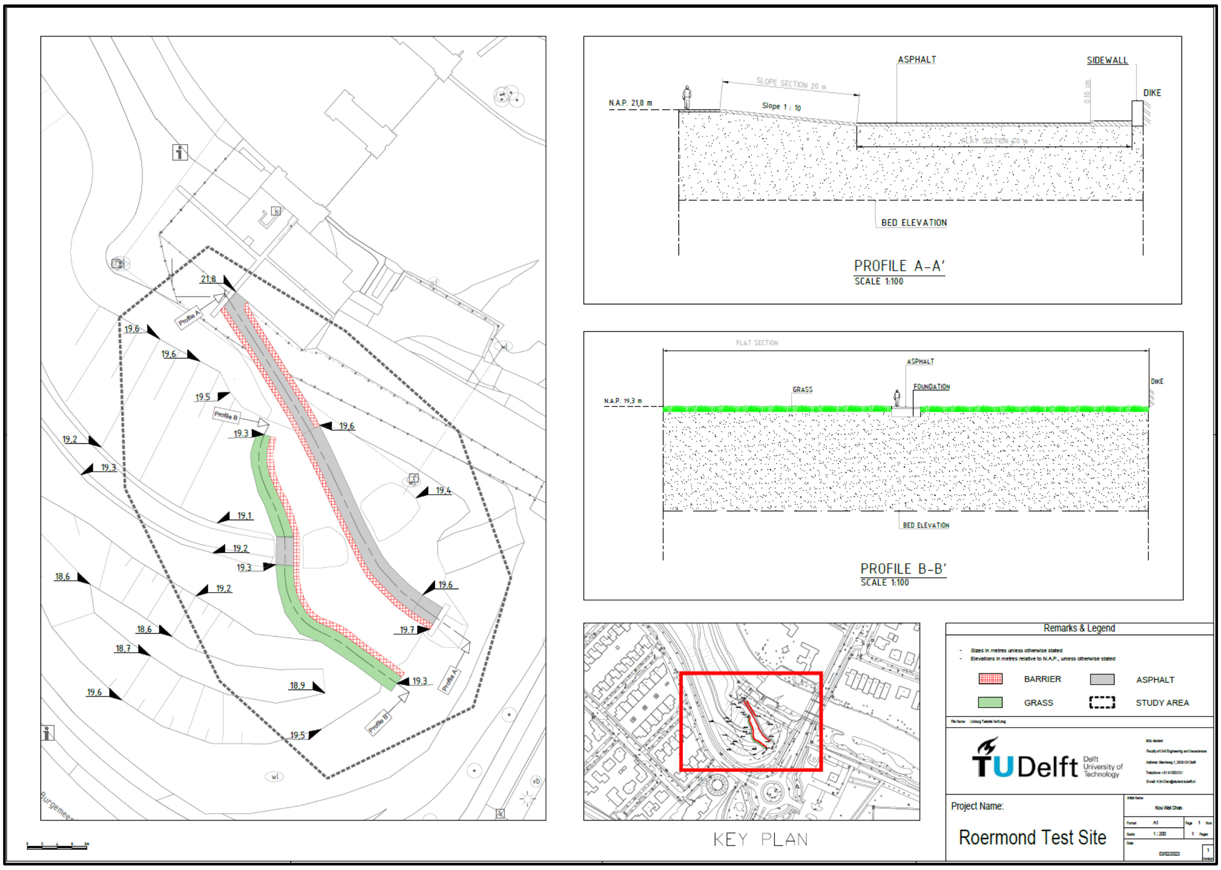


Figure 12 Detail presentation of the test layout

4.2 Illustration of Test 1

As stated before, Test 1 will focus on the water steering capacity and overtopping ability of the temporary flood barriers. This will be done on a fully enclosed pavement with a width of 3 m. In order to guide the flow of water, the barriers will be deployed as S-bend shape with a minimum interval of 1 m or a maximum of 1.5 m on the slope section. The entire length of the slope is approximately 20 m with an inclination of 10 degrees. This information can be seen in Figure 14. At the top of the slope, the water stream is introduced from the Roer River through a 12-inch hose by using a pump provided by Water Board Limburg, which has a maximum flow rate of 1500 m^3/hour, as shown in Figure 13.

Figure 13 Hose and Pump provide by Water Board Limburg

To assess the capacity of overtopping, the barriers will also be implemented on the flat section after the slope. This section will end with a straight wall, and the distance measured from the end of the slope to the wall is about 40 m. This brings the total length of the pavement to around 55 m. Before the side wall, there is a curb. That means the temporary flood barrier needs to encounter the overtopping with a curb height difference. The schematisation of test 1 can be seen from the profile A-A' in Figure 12.

The performance of the barrier is evaluated by measuring the displacement and the connections between its elements. The barrier is considered successful if it can remain watertight up to a maximum of 0.3 m and the interconnection remains stable despite displacement. Measurements are conducted at the backside of the barrier before the test and marked using pickets up to the edge of asphalt. Following the test, the measurements are repeated. If the barrier fails, it is assessed as rejection.

Figure 14 Actual View of the enclosed pavement, scale 1:50 cm

4.3 Illustration of Test 2

The main objective of test 2 is to evaluate the stability of the temporary flood barrier at a required retaining water level of 50 cm and assess the underflow through observations of water leakage. One or more types of barriers, each having a minimum length of 25 m, will be constructed simultaneously from the same supplier on a levelled soil body with grass. The duration of this test is defined as the time needed to fill the basin constructed by the barrier from test lane 1 with overtopping water until the water level of 50 cm is reached on test lane 2, lasting at least one hour. The schematisation of test 2 can be seen from the profile B-B' in Figure 15.

Figure 15 Actual View of the unpaved lane, scale 1:50 cm

5. Table of Quantified Measures

Water Board Limburg has established 14 evaluation criteria to evaluate the effectiveness and efficiency of the temporary flood barriers. These criteria are designed to assess several aspects of the barriers, including their stability, durability, water-stopping capability, and resistance to longitudinal flow as well as overtopping. The evaluation procedure aims to provide a fully understanding of the barriers' overall performance, ensuring that they meet the required standards and regulations for flood control and protection. Below shows the criteria provided by the water board.

Table 5 Evaluation Criteria provided by Water Board Limburg.

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.

Based on the established criteria by Water Board Limburg, as well as measurements from the Hedwige-Prosperpolder test (Damen, 2022) and reference to the reliability of flood protection system (Ogunyoye et al., 2002), a multi-criteria analysis can be conducted with quantifiable measures. This semi-analytical approach provides a thorough and objective assessment, enabling decision-makers to make informed judgements on the effectiveness and suitability of the system (Nijkamp et al., 1977).

By using multiple criteria, the analysis can identify the weaknesses and strengths of barriers, allowing for improvements and modifications to enhance their efficacy and resilience. The table used for this analysis has four objectives: logistics, failure mechanism, surface, and extra. Water Board Limburg needs to decide the importance of each objective by giving them a weight between 1 to 3. The largest weight will show the most important objective. The weight will be decided after a discussion and meeting with the water board and experts before May.

Table 6 represents the multiple-criteria analysis. Where, each barrier will be given a symbol based on the performance of the physical experiment during the process. The meaning of these symbols and the rating method (Table 5) is shown below,

- ⇨ $Negative\ impact\ on\ objective \quad (value: -1)$

o ⇨ $No\ change\ in\ objective \quad (value: \ \ 0\ )$

+ ⇨ $Positive\ impact\ on\ objective \quad (value: +1)$

Table 6 Rating Method of objectives

Category	Objective	Rating Method
Logistics	User Friendly (easy to operate)	Rating from the questionnaire by users
	Can be transported by only one people	More than 1 people will be indicated as -
	No extra transport effort (vehicle)	With vehicle will be indicated as -
	Simplicity (easy to know how it works)	Rating from the questionnaire by users
	No extra supply effort (filling method)	With extra supply effort will be indicated as -
	No extra component needed (connection)	With extra components will be indicated as -
	Resilience (when barrier suddenly breaks)	Cannot recover the gap will be indicated as -
	Total set up time	Set up time exceeds 30 mins will be indicated as -
	Can be stored	Without storage method will be indicated as -
	Can be repaired	Cannot repair the broken barrier will be indicated as -
	Reusable	Cannot reuse all components will be indicated as -
Failure Mechanism	Water-stopping capability	Fail will be indicated as -
	Stability (hydrodynamic)	Fail will be indicated as -
	Resistance of underflow	Fail will be indicated as -
	Resistance of overtopping	Fail will be indicated as -
	Ability of steering water	Fail will be indicated as -
	Retaining water capability (1 hr)	Fail will be indicated as -
	Resistance of human weight (walk)	Fail because of the human weight will be indicated as -
	Connectivity (Curb & Side Wall)	Cannot connect will be indicated as -
	Resistance of buoyancy	Fail will be indicated as -
	Capability of slope	Cannot use on the slope will be indicated as -
	Resistance of bearing capacity	Fail will be indicated as -
	Leakage control	Acceptable leakage as o; No leakage as +; Fail as -
	Displacement control	Moves (max 30cm) but remains stable as o; No movement as + ; Fail as -
Surface	Capability used on Asphalt	Fail will be indicated as -
	Capability used on Concrete	Fail will be indicated as -
	Capability used on Sand	Fail will be indicated as -
	Capability used on Grass	Fail will be indicated as -
	Capability used on Clay	Fail will be indicated as -
Extra	Length (minimum 25 m)	Less than 25 m will be indicated as -
	Walkability	Adult with normal weight cannot walk on top of it as -

Each symbol in the analysis represents a specific value that is utilised to calculate the total score of the barrier being tested. The weight of the different objectives is multiplied by the corresponding symbol value, and then these resulting values are summed to obtain the total score of the barrier.

Table 7 Muti-criteria analysis for the physical experiment in May (The types of barriers are for example)

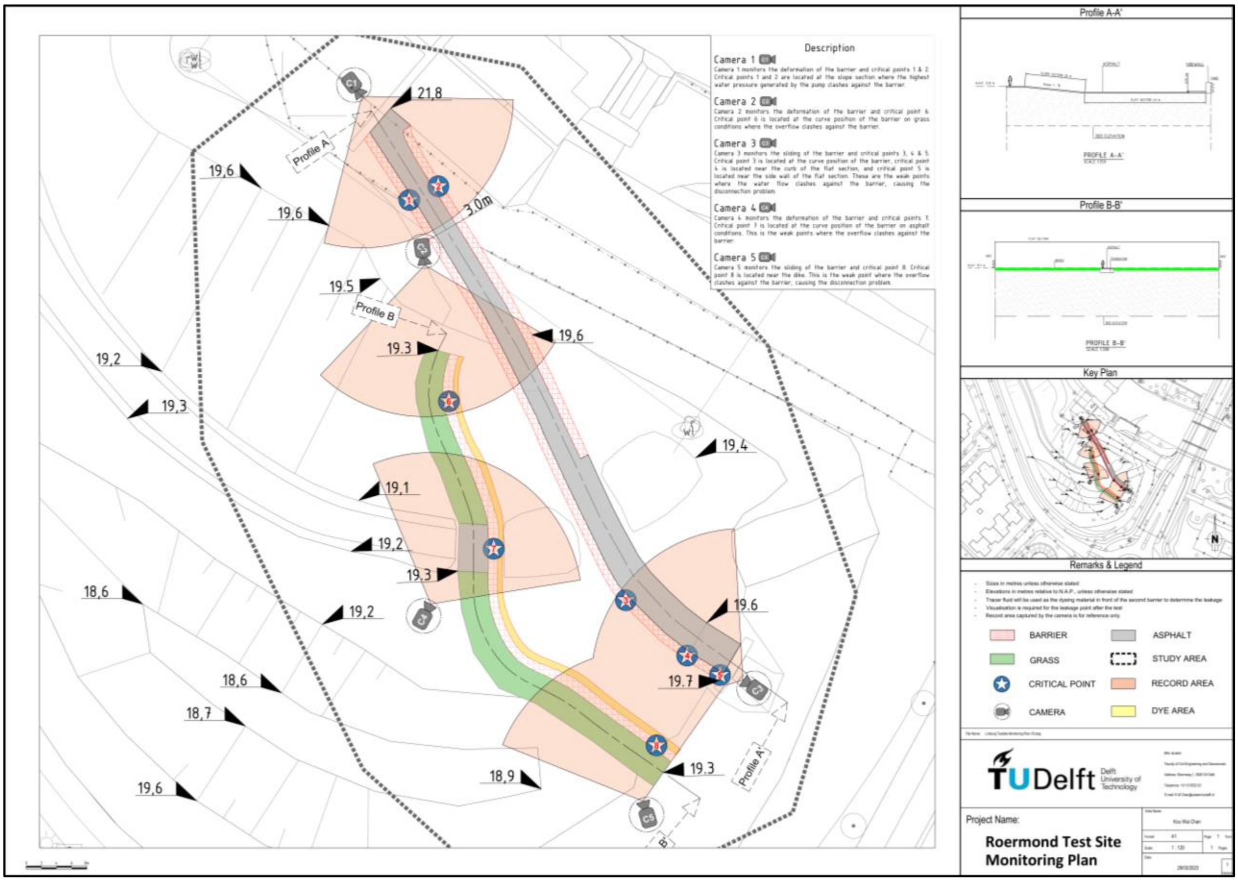
Objectives/Concepts		Weight	Temporary Flood Barrier (Here is for example, it should be based on tender)					
			BoxBarrier	Mobile Dike	SlamDam	TubeBarrier	BoxWall	H-Wall
Logistics	User Friendly (easy to operate)							
	Can be transported by only one people							
	No extra transport effort (vehicle)							
	Simplicity (easy to know how it works)							
	No extra supply effort (filling method)							
	No extra component needed (connection)							
	Resilience (when barrier suddenly broke)							
	Total set up time							
	Can be stored							
	Can be repaired							
	Reusable							
Failure Mechanism	Water-stopping capability							
	Stability (hydrodynamic)							
	Resistance of underflow							
	Resistance of overtopping							
	Ability of steering water							
	Retaining water capability (1 hr)							
	Resistance of human weight (walk)							
	Connectivity (Curb & Side Wall)							
	Resistance of buoyancy							
	Capability of slope							
	Resistance of bearing capacity							
	Leakage control							
	Displacement control							
Surface	Capability used on Asphalt							
	Capability used on Concrete							
	Capability used on Sand							
	Capability used on Grass							
	Capability used on Clay							
Extra	Length (minimum 25 m)							
	Walkability							
Total Score								

6. Introduction to Monitoring Plan

A monitoring system has been developed to evaluate the performance of the tested barrier by monitoring the failure mechanism among all criteria provided by the water board. This monitoring includes systems for recording and detecting changes in the barrier dimensions, such as changes in water level, as well as displacement and deformation of the systems due to water flow. In addition, a timestamp has been implemented to record the time at which various events occur during the test, for example, when the barrier is finished to install and when it starts to deform or move.

6.1 Video Camera

For the upcoming test, 5 TBD video cameras provided by the AccessHub company will be strategically positioned to monitor critical points along the barrier as shown in the Figure 16. Each camera will capture specific parameters including the water level, leakage events, deformation, and displacement, providing valuable data for analysis.



Description

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

Camera 2
Camera 2 monitors the deformation of the barrier and critical point 6. Critical point 6 is located at the curve position of the barrier on grass conditions where the overflow clashes against the barrier.

Camera 3
Camera 3 monitors the sliding of the barrier and critical points 3, 4 & 5. Critical point 3 is located at the curve position of the barrier, critical point 4 is located near the curb of the flat section, and critical point 5 is located near the side wall of the flat section. 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 and critical points 7. Critical point 7 is located at the curve position of the barrier on asphalt conditions. This is the weak points where the overflow clashes against the barrier.

Camera 5
Camera 5 monitors the sliding of the barrier and critical point 8. Critical point 8 is located near the dike. This is the weak point where the overflow clashes against the barrier, causing the disconnection problem.

Remarks & Legend

- Sizes in metres unless otherwise stated
- Elevations in metres relative to N.A.P., unless otherwise stated
- Tracer fluid will be used as the dyeing material in front of the second barrier to determine the leakage
- Visualisation is required for the leakage point after the test
- Record area captured by the camera is for reference only

Figure 16 Detail Expression of the monitoring system layout

- Camera 1: Monitors the deformation of the barrier and critical points 1 and 2, which are located at the slope section where the highest water pressure generated by the pump clashes against the barrier.
- Camera 2: Monitors the deformation of the barrier and critical point 6, which is located at the curve position of the barrier on grass conditions where the overflow clashes against the barrier.
- Camera 3: Monitors the sliding of the barrier and critical points 3, 4, and 5. Critical point 3 is located at the curve position of the barrier, critical point 4 is located near the curb of the flat section, and critical point 5 is located near the side wall of the flat section. These are the weak points where the water flow clashes against the barrier, causing the disconnection problem.

- Camera 4: Monitors the deformation of the barrier and critical point 7, which is located at the curve position of the barrier on asphalt conditions. This is another weak point where the overflow clashes against the barrier.
- Camera 5: Monitors the sliding of the barrier and critical point 8, which is located near the dike. This is also a weak point where the overflow clashes against the barrier, causing the disconnection problem.

6.2 Tracer Fluid

Many dyes have been used as hydrological tracers; the most prominent are probably Fluorescein/Uranine. The selection of a specific dye as a tracer depends on a variety of factors including the purpose of the experiment, the physical and chemical characteristics of the medium, and the method of tracer detection. (Flury et al., 2003). In the upcoming physical experiment, Uranine may be selected as a tracer to detect the leakage points, thereby providing clear and reliable results for the analysis, as shown in Figure 17. From previous experiments, it has been observed that after testing the performance of the barriers, visualisation is required to determine the exact leakage location. However, this can be challenging in flood conditions where the water is muddy and contains sand, making it difficult to identify the exact point. The use of uranine as a tracer will help to overcome this challenge and ensure accurate identification of whether the barrier has a leakage problem.

During the test, the tracer fluid will be put in front of the second test lane. When flood water is coming, it is expected to observe the leakage point in different spatial conditions. Through the observation, a comparison of the leakage problem between grass and asphalt layers, and valuable insights into the effectiveness of different barriers can be obtained.

Figure 17 Adaption of Uranine in real situation

6.3 RBR-Diver

In order to accurately monitor the changes in water pressure during the experiment, a small depth recorder will be utilized, as depicted in Figure 18. This particular device is well-suited to the task because it offers flexible measurement schedules and standard sampling. The data collected by the logger can be easily exported to various analysis tools such as Matlab, Excel, OceanDataView, or text files. Once the data has been collected, based on the data set, a plot can be generated to show the changes in water pressure over time. This plot will then be compared to the deformation graph of the barrier provided by AccessHub, allowing for a comprehensive and accurate understanding of the stability. This sophisticated monitoring equipment will make the test results more precise and informative.

Figure 18 RBRsolo^3 logger information (RBR, 2021)

7. Preliminary test in Flood Proof Holland

A preliminary test was conducted on February 15th 2023 at Flood Proof Holland to better prepare for the upcoming physical experiment in May. The main objective of this test was to verify the effectiveness of the monitoring plan, which is similar to the plan for the upcoming test in Roermond, by monitoring the water-steering capacity, retaining water capability and overtopping. Before providing details on the test, this report will provide a brief overview of Flood Proof Holland.

7.1 Flood Proof Holland

Flood Proof Holland in Figure 19 is a research facility located in the TU Delft Campus in Netherlands that serves as a testing and showcase location for semi-full-scale temporary flood defences which are innovative, modular, and flexible (Kreijns et al., 2018). Its primary purpose is to enable the testing and optimisation of these innovations, which is critical because they are intended to be used during emergencies. The facility features various testing areas, including a wave flume and several basins, that enable researchers to simulate and study different flood scenarios. (VPdelta, 2022) In addition, Flood Proof Holland provides access to advanced measurement equipment and data analysis tools, which are essential for conducting accurate and reliable experiments. By conducting experiments and tests at Flood Proof Holland, researchers and engineers can gain valuable insights and improve the design and functionality of these flood defences, ultimately enhancing their reliability and effectiveness in protecting against flooding.

Figure 19 Test Field of Flood Proof Holland

7.2 Description of The Preliminary Test

Two tests were conducted at Flood Proof Holland to evaluate the water-steering and overtopping capacity of the box barrier and the retaining water capacity of the H-Wall. Both tests involved placing the barriers on a concrete layer and utilising cameras to record the performance of the barriers. Uranine was also used as the tracer liquid to detect leakage problems of the barrier during the test for H-Wall.

In the first experiment as indicated in Figure 20, the boxbarrier was placed at an angle of 15 degrees with respect to the incoming flow to observe its ability to withstand water flow from the valve. The position of the boxbarrier and the angle at which it was placed were chosen to reflect a realistic scenario in which the barrier would be deployed in the field. Additionally, a wifi camera was mounted on a wooden pole to monitor any deformations during the test. To ensure that the water trapped from the boxbarrier was allowed to escape, a gap was created. As the test progressed and water levels in the basin rose, an overtopping event assume to occur.

Figure 20 Preliminary Test of BoxBarrier

In the second experiment as illustrated in Figure 21, the H-Wall was positioned horizontally across a small basin to assess its retaining water capacity, and a wifi camera was set up to record the test. When the valve was opened, water from the polder reached the barrier inside. Tracer liquid was also added to the water to detect any leakage. The test was conducted for a duration of 30 minutes to simulate a real-life flood emergency scenario, and the barrier was required to maintain a minimum water level of at least 50 cm during the time.

Figure 21 Preliminary Test of H-Wall

7.3 Result of The Preliminary Test

During the water-steering capacity test, the boxbarrier appeared to be initially effective in withstanding water flow, since the barriers remained stable and did not experience any noticeable movement. As the water level continued to increase, no deformation was observed on either side of the barrier. However, when the water level reached the same height as the boxbarrier before, overturning began to occur. The last barrier began to experience deformation, resulting in floating. Due to the interlocking rubber strip design, water began to flow under the second barrier, causing all the barriers to float. This resulted in a rotation of the box barriers, leading to all of them overturning, as shown in Figure 22. As a result, the ability of the boxbarrier to withstand overtopping was compromised, and the experiment failed.

Figure 22 Overturning event of BoxBarrier

The H-Wall performed satisfactorily during the water retention capacity test, remaining stable and without any noticeable movement even under high water pressure. At the beginning of the test, small leaks were initially detected through the Uranine. As the water levels continued to rise, the leaks did not worsen, which was deemed acceptable. However, when the water level reached 50 cm, the entire barrier began to bend, and the tension strap vibrated significantly. Despite this, the barrier continued to function well. To determine its maximum capacity, the valve was opened, and the water level was raised to 70 cm. At this point, one of the cables failed. Some leakage points were also observed on the barriers. But surprisingly, it remained stable for the whole 30 minutes. Information can be observed in Figure 23.

Figure 23 Water retention capacity test of H-Wall

8. Discussion about Failure Mechanism

By combining the results of the preliminary test in Flood Proof Holland and the resisting force calculated in Chapter 2, it was found that the BoxBarrier and H-Wall are capable of withstanding hydrostatic pressures on a concrete floor. However, the calculation of the water pressure on the inner side of the barrier was not considered in this case, raising questions about the reliability of the barriers in real-life situations. Before reaching the overtopping conditions, the BoxBarrier had already failed due to two reasons. Firstly, the water pressure caused by the flow around the barrier added extra subpressure to the barriers. This extra subpressure, along with the original subpressure caused by the flood water, reduces the total vertical force of the barriers. Therefore, the water has room to flow underneath the gap of all barriers at the bottom, and this generates the uplift force of the barriers themselves, the barriers started to float. Secondly, the friction force was smaller than the total horizontal force, the barriers cannot resist the water pressure of the flood water, and they eventually overturn because of the higher subpressure on one side, as shown in Figure 24.

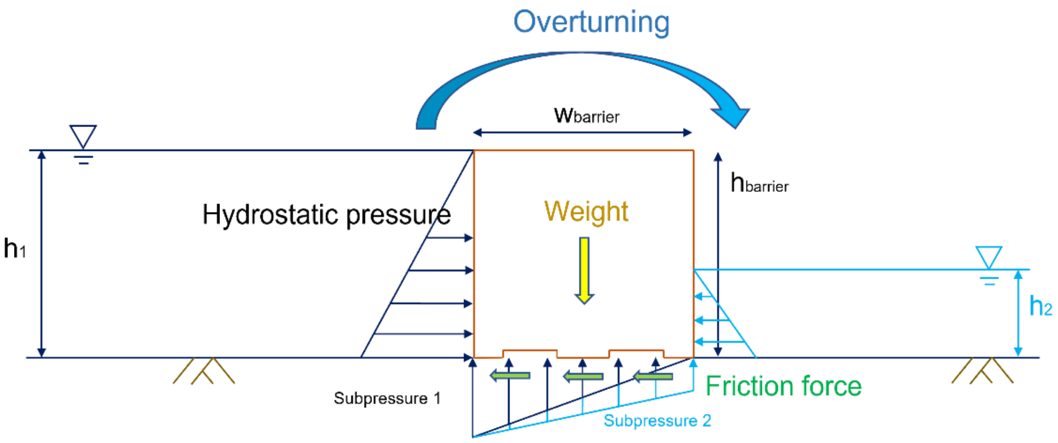


Figure 24 Schematisation of overtopping event

On the other hand, although some issues such as leakage and deformation were observed according to the test, the overall performance of H-Wall was satisfactory. Upon further investigation, it was found that the leakage problem was mainly due to the poor manufacturing of the foil, which had some abnormal openings at the same horizontal line. Causing the water to seep through, leading to the leakage. For the deformation issue, it was discovered that the tension strap of the deformation barrier was not properly anchored, leading to the deformation observed during the test.

One finding from the preliminary test was that Uranine tracer fluid effectively provided visible results. However, only a small amount of Uranine was used in the test to make the results more visible. Considering the area of the test site in Roermond is quite large, and a significant amount of pumping water will be involved in the actual flood scenario, this would require a huge amount of Uranine, which may not be practical for a full-scale test. This issue requires further discussion and consideration in future monitoring plans.

While the Wi-Fi connection and recording quality of camera were evaluated during the test, no in-depth analysis was performed for the present study. Additionally, the deformation graph provided by AccessHub is still ongoing, and no numerical results can be obtained yet. Furthermore, the RBR-Diver was not used in the test, which means there is no data to create the deformation diagram of the barriers. Therefore, a comparison between the barriers cannot be made in this test.

9. Conclusion

This report provides an introduction and preparatory study for the test in May 2023 which is being conducted in collaboration with Water Board Limburg. It includes an overview of the different types of flood barriers, an evaluation of their performance, a proposed monitoring plan, and the expected results from the calculation of the resisting force of each barrier. This report is intended to serve as a foundation for further investigation.

The preliminary test, conducted at Flood Proof Holland, provided valuable insights into the reliability and effectiveness of the proposed monitoring plan, which includes the use of cameras and tracer fluids. The test also highlighted the importance of proper equipment inspection, anchoring, and quality control of materials such as foil and rubber strips.

Based on the results of the physical experiment in May 2023, a multi-criteria table can be developed to aid all participants in understanding the physical principles underlying each barrier. Furthermore, the findings can be used by the company to improve the design of their temporary flood barriers, leading to better designs in the future and reduced damage caused by flash flood events.

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