

Movable water barrier for the 21st century

Master thesis main report



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September 15, 2009*

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PREFACE

This report signify the end of my Master study at the faculty of Civil Engineering and Geosciences. My degree of specialism is hydraulic structures, however, within this thesis I have tried to come up with a integrated preliminary design where I used my constructive background as a helpful tool. It was my personal objective to investigate some of the boundaries of my graduation field and not to make my thesis a repetition of the followed lectures. This thesis, which is for most parts a technology assessment, is therefore slightly different than can be expected from a hydraulic structure student.

My thanks goes out to the graduation-committee for feedback and making it possible to graduate. Special thanks to Ties Rijcken for introducing me in an early stage to the UOOC concept, making it possible to work with architect students, and for providing inspiration and energy (though, it wasn't always about my thesis). Also special thanks to Anna Dijk for making a good start of my thesis possible and introducing me with a different design method.

Delft, 9 September 2009

ABSTRACT

The second Delta-committee (September 2008) foresees difficulty in resolving flood safety issues for Rotterdam and Dordrecht if high river runoffs are still running through the New Waterway. A new safety issue, induced by climate changes, lies in the combination of closed sea defensives and relatively high river runoffs at the same time. A research proposal is made towards a Usually Open Occasionally Closed (UOOC) water-system around Rotterdam and Dordrecht.

This concept diverts high river runoffs during storm situations towards the Southern rural parts of the delta. Four large movable water barriers, located in the main waterways and navigation channels, are required within the UOOC concept.

This plan calls for an innovative barrier designs. First of all, the purpose of the movable barriers in combination with their required width is exceptional. Second, barrier designs are outdated and relatively new, light-weighted and maintenance low, materials are not applied. Third, the life-time of a structure is determined by social aspects. The UOOC barriers are located at the edge of urbanized areas and a multi functional structure could enhance benefits and social acceptance. Up till now, hydraulic structures are mainly mono functional structures.

Within this thesis the objective is to make an innovative design for one of the UOOC barriers. The design should be ready for the water problems of the 21st century, ready for a 21st century society and constructed by the latest materials.

This Master thesis discusses the locations, corresponding boundary conditions, required dimensions and the costs of the UOOC barriers. The location choice is made considering costs, technical, architectural and landscape values. Research is done to predict the operation-management of the new water-system and the equivalent water levels. Furthermore design starting points, loads and main requirements are presented.

It is found that the storage area in the Southern part of the delta has to be altered, in the sense of increased discharge capacities and/or increased normative design water levels, to cope with the incoming water flow. It is also found that a certain management strategy causes two barriers to have to cope with large negative water heads. The costs for all four barriers are estimated at €850M.

An objective of this thesis is to investigate an innovative barrier design; an 'open fabric' movable water barrier., which is in contradiction to a 'closed fabric' barrier like an inflatable dam. An 'open fabric' barrier can be seen as a parachute opened horizontal in the waterway. The thesis is a technology assessment of an 'open fabric' barrier and designing with synthetic materials to lower the barrier costs.

Insight is given in synthetic materials and these are compared with other construction materials. Steel performs less in endurance tests, is heavy and requires a lot maintenance. This makes steel less favourable for a movable water barrier as a construction material, considering costs and environmental aspects. It is found that ropes made from Dyneema® fibers and a fabric screen of PA (polyamide) are likely to provide the best performance and that they are more than suitable for a movable water barrier.

From the literature study it is clear that an 'open fabric' barrier is technical possible, especially nowadays with improved synthetic materials and the ability to predict the behaviour of fabric barriers with computer programs. However, a research towards the possibilities of different 'open fabric' barrier and a structural optimization is not found. One of the objectives of this thesis is to fill this gap of knowhow.

A fabric barrier is suitable for the UOOC concept because of the possible fast construction/installation and low maintenance costs, which is favourable because the barriers are located in the busiest waterways of the Netherlands.

Design issues concerning fabric water barriers and specific ‘open fabric’ barriers are discussed. There are several typical concerns and one of them is (of course) the dynamic behaviour of the screen and cables.

Different ‘open fabric’ design concepts are generated and discussed. A subdivision can be made in single, mattress, modular and stepped water barriers. Also the “spinnaker” barrier, design by Prof.dr.ir. J.K. Vrijling back in the ’80, is taken in consideration.

A preliminary design is made for the Merwede barrier because this barrier has to cope with the largest hydraulic loads and because the determined location makes it possible to design a water barrier with an integrated pedestrian bridge. A curve (horizontal plane) cable stayed bridge is proposed with a single screen attached to the deck over the entire waterway of 210m wide.

The screen diverts the hydraulic loads with ropes towards the deck and the abutments. It is stored under the deck and unfolds with the help of cables. It is lowered from the deck towards the water level, then the bottom of the screen and its lower cables are pulled down with help of hydraulic jacks at each abutment. This system can assumable provide a good controlled movement and even tuning of the barrier will the barrier is in operation is a possibility. Because the screen is connected to a relatively stiff structure it is expected that the dynamic behaviour of screen is good.

A small scale model test is recommended for the closing-system of the barrier and to test its dynamic behaviour.

After estimating the required strength and dimension of certain elements it is concluded that the structure is technical feasible. It is also conclude that the screen size and screen orientation determines the hydraulic loads that have to be diverted by the bridge structure. In a further design stages an optimization should be made considering the size of the screen, greater width induces smaller loads, and the required strength of the bridge structure.

The barrier life-cycle costs for 100 years are estimated on €190M and €34M for the bridge. The costs reduction of a movable water barrier for using fabric instead of a steel is for this design estimated well over 34%. The life-cycle costs of the screen are approximately 40% of the total life-cycle barrier costs. This indicates that optimization towards a small screen is found to be most effective. It is possible to design with a relatively small screen, because the screen is connected to a bridge. More detailed research is required to investigate the minimum screen size and the limitations of a ‘bridge+screen’ barrier.

Within this thesis it is stated that the design should be ‘flexible’ in order to take climatic changes, different social views and local ecological changes into account. Moreover, a 21st water barrier has not only a minimal impact at this moment, but also in the future. The feasibility of this objective is not established, however, a direction is given.

SHORT REFERENCES, TERMINALLY, TRADEMARKS AND USED ICONS

Short references:

AOR:	“Afsluitbaar Open Rijnmond” (Dutch); ‘Usually Open, Occasionally Closed’; UOOC (English)
AVV:	“Adviesdienst Verkeer en Vervoer”; consultive agency traffic and transport
HMPET:	High Molecular Polyester
LCP:	Liquid Crystal Polymer
M:	million; 1,000,000
NAP:	“Normaal Amsterdam Peil”; normal Amsterdam water level
NHW:	‘Normative High Water’ (English); MHW; “Maatgevend Hoog Water” (Dutch) (In the middle of the waterway without local effects.)
NPV:	‘Net Present Value’ (English); “Netto Contante Waarde”; NCW (Dutch)
PA:	polyamide
PE:	polyethylene
PET:	polyetheentereftalaat; is a polyester based plastic
PP:	polypropylene
RWS:	“Rijkswaterstaat”; “Ministerie van Verkeer en Waterstaat”; Ministry of Transport, Public Works and Water Management
SWS:	Safety factor for side wind (for determine the width of a navigation channel)
UHMPE:	Utra High Molecular Polyethylene
UHMPET:	Utra High Molecular Polyester
UOOC:	‘Usually Open, Occasionally Closed’ (English); “Afsluitbaar Open Rijnmond”; AOR (Dutch);
WsHD:	“Waterschap Hollandse Delta”; water-board around of Rotterdam and Dordrecht

Terminology:

“Europoort”:

The waterways New Meuse and Old Meuse are together the Europoort. Within this report Europoort stands for the Hartel and the Maeslant barrier that can close of the two waterways;

(water) Head:

Water difference over a water barrier;

Life-cycle costs:

All costs concerning a civil structure during construction, use and demolition;

Life-time:

Technical life-time/span of a construction;

“Maasvlakte”:

The first and second (planned) “Maasvlakte” are large port extension into sea;

Peak stresses:

Dynamic loads can cause peak stresses, but within this thesis they are not referred as ‘peak stresses’. If not explicit stated different in the report; ‘Peak stresses’ refers to (tensile) stresses in the screen induces by folding/buckling of the screen, in Dutch: “plooi”;

Reference rate / calculation interest NPV:

The calculation interest/percentage for the NPV life-time costs estimation. In Dutch: “discontovoet”;

“Rijkswaterstaat”:

Implementing body of the Ministry of Transport, Public Works and Water Management;

Screen:

The fabric and possible incorporated elements that form together the gate of the movable water barrier;

Sill:

Barrier threshold, in Dutch: “drempel”.

Trademarks:

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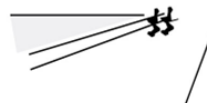
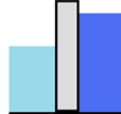
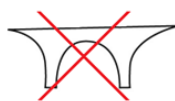
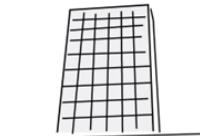
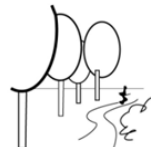
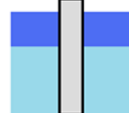
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Used icons:

Bridge	Buildings	Public space	Water head	Landmark
				
<i>pedestrian</i>	<i>residential</i>	<i>levees/dessolated</i>	<i>possitive</i>	
				
<i>no bridge desired</i>	<i>offices</i>	<i>forest / park</i>	<i>possitive and negative</i>	

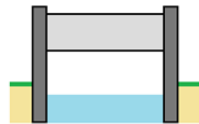
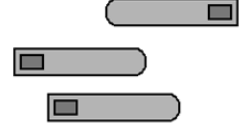
Visibility barrier	Navigation	Recreation	Load distribution	Movable barrier
				
<i>low</i>	<i>not busy</i>	<i>mast</i>	<i>vertical</i>	<i>open</i>
				
<i>medium</i>	<i>busy</i>	<i>no mast</i>	<i>horizontal</i>	<i>closed</i>
				
<i>high / ver. Lifting gate allowed</i>	<i>very busy</i>			

Figure 1: Used icons. (A. Dijk, F. van der Ziel)

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1 INTRODUCTION

In the Netherlands many weirs were constructed for navigation reasons during the first half of the 20th century. During the second half of the 20th century several storm surge barriers were built for flood protection against storm surges from sea. These sea defenses not only hold the sea water at bay but also trap river water behind them.

Due to the climate changes it is likely that the frequency of closure and the amount of water that will be trapped behind the sea barriers will increase. And because the current Rhine mouth is a densely urbanized economic center of the Netherlands, plans are in development to divert the river water, during closure of the sea barriers, into the (former) estuaries of the Rhine and Meuse delta. In these estuaries (surrounded by a rural landscape) the water can be stored until the storm surge has past and the river water can be spilled out into sea.

The second Delta-committee Veerman foresees difficulty in resolving flood safety issues for Rotterdam and Dordrecht (large cities along the current Rhine mouth) if high river runoffs are still running through the New Waterway within the upcoming 50 years. (Deltacommissie Veerman 2008)

One of the researches, concerning the water-system around Rotterdam and Dordrecht and one that is also recommended by the second Delta-committee, is the 'Usually open, Occasionally Closed' (UOOC) Rhine mouth. (Or in Dutch: "Afsluitbaar Open Rijnmond", (AOR)). This concept for the water-system around Rotterdam and the Drecht-cities diverts the river water towards the southern part of the delta. Four large movable water barriers, in the main waterways and navigation channels, are required within the current UOOC concept. The UOOC barriers will divert the high water wave from the rivers Lek, Waal and Meuse during storm surges and ensures a maximum water level (with probability of exceeding) for the urbanized areas behind the barriers.

The necessity to divert the river water into the South-West delta area finds its origin in the historic planning of the Dutch water-system. For instance: the Rhine mouth was located further to the North at Katwijk up until the year 1122. In 1821 the river-committee did not approve for the plans to close off the river Lek, where nowadays a maximum water flow for the Lek is suggested. And the river Waal was given an own southern river mouth by digging the "Nieuwe Merwede" around the year 1870. (Bosch en van der Ham, Twee Eeuwen Rijkswaterstaat 1998)

The Southern directed diversion of river water will be further enhanced at times when needed and more control of the entire water-system will be obtained with the movable water barriers in the UOOC. The concept provides a good perspective on the combination of functions like safety, fresh water supply, urban development and nature. (Deltacommissie Veerman 2008)

Water barriers are most likely constructed for an eternity; once placed, they will never be removed, at most replaced. However in time, they have to be improved to deal with new boundary conditions coming from its surroundings. In many occasions in the Netherlands this is (almost) impossible or far too expensive due to the spatial usage of the barrier itself and the spatial usage of the near surroundings of the barrier. This is the reason for constructing movable water barriers, like the Maeslant storm surges barrier at the entrance of Rotterdam port, instead of rising the levees in a dense urban area. (Verhagen 2007)

INTERMEZZO:

Spatial planning / urban development requires higher flood safety levels, and a lower flood probability leads to more investments / urban development. This is in short the spiral of land

value and the level of flood-protection where the Netherlands are confined in for many centuries.

In Amsterdam this has led to a socially environment where the water is 'tamed' to a great extent. Living along the water is social favored, however any hazard from the water is not accepted. Several channels were filled up and the water levels are under all circumstances maintained at certain levels. No dynamic behavior is left in the water-system which had far reaching consequences for the overall quality of the water and its direct surroundings. The decrease in water storage (invoked by both measures) gives problems at times of heavy rainfall and during dry seasons.

Rotterdam calls itself a dynamic city along the Meuse where commuters, ships and tides are flowing in and out. However the UOOC concept could be a step in the direction of Amsterdam, where the water was expelled out of the city many decades ago.

This is in contradiction to the wishes of politicians (from Rotterdam and Dordrecht) who speaks of embracing the water into the city. A lot of waterfront development can take place in the old harbours because the port activities are replaced towards the first and (planned) second "Maasvlakte" (port extension into sea). These spatial waterfront developments could break the spiral of increasing value and required flood protection, but just as (or even more) easily they could end up enhancing the spiral.

UOOC Rhine mouth will be a pro-active decision which have to be flexible and have to consider not only the technical and economic lifespan of the structures, but more important the social lifespan of the complete water-system as well. The later could be far shorter than the first two.

A 'no-regret scenario' which enables to change tactics in the future is required to minimize negative impacts of the water barriers (in social development, spatial planning and environmental sense).

However, in almost all cases the users and financiers of the barrier desire a design that is optimal for the boundary conditions at this moment to keep the impact and costs as low as possible. Looking beyond the moment and looking at the benefits for the entire society this optimal could be everything but favorable. (Verhagen 2007)

A 21st century water barrier design should acknowledge this and has to provide a 'flexible barrier' with a minimal of 'extra' costs and minimize the social impact at this moment and in the future. This should be possible to a greater extent for a movable water barrier than for a levee.

In addition one can say that the designs for (movable) weirs (retaining low river discharges) are outdated. Not only due to the fact that in the first half of the 20th century many weirs, and in the second half only storm surge barriers were constructed, but also because there are relatively new, strong and light-weighted materials available. For example synthetic fabrics that are scarcely applied and can have many benefits in opposed to steel and concrete. One of them is the flexibility of the material; in physical sense it has the possibility to divert loads without bending moments and it can be folded to decrease the required storage area, but also in time because the material has to be replaced every (approx.) thirty years. It might be possible to construct not only a 'no-regret-system', but a 'no-regret-structure' as well.

Another issue is that in the western part of the Netherlands multiple land use is seen as an improvement for the overall living quality. This is because the pressure on nature and rural landscape in this mainly urban part of the Netherlands is relatively high. By designing a barrier with multiple functions, presumably more social value can be obtained. This is something new in hydraulic engineering where most structures are designed for only one main function.

In the UOOC concept four large movable water barriers are proposed. Within this Master thesis these four barriers will be discussed, amongst others: the closing strategy, location, main boundary conditions and the costs. Not only technical issues will be addressed, but also environment, landscape and architectural aspects will be discussed to a certain degree. One UOOC barrier will be chosen for a first structural design.

For this barrier an innovative design is pursued. First of all this objective is given form due to the main function of the UOOC barriers: diverting a high river wave. This is for large movable barriers a new type of water barrier. Second, it is an objective to design with relatively new materials like synthetic fabric. Furthermore, an extra dimension is given by looking for a possible multifunctional land use / additional functions next to diverting river water.

For the movable water barrier a pre-choice is made for an 'open fabric' barrier type. (An 'open fabric' is also called a parachute dam. The barrier is the counterpart of a 'closed fabric' water barrier, such as an inflatable dam.) This is in contradiction with the civil engineering design methods, however, applying other design methods and 'reasoning back' will hopefully add to more insight and possibly innovation. Recommendations about the structural issues concerning the use of a synthetic fabric within a movable and 'open fabric' water barrier design and increasing the knowhow about applying such a fabric will be provided.

The feasibility of an 'open fabric' barrier for the UOOC Rhine mouth will be discussed and in the end a preliminary design for a movable water barrier for the 21st century will be obtained.

First of all the problem definition, objectives and scope are stated. In chapter three the project area and the water system are further described. After that the location, surrounding conditions and costs of the UOOC barriers are discussed. The general requirements, boundary conditions and assumptions are presented in the next chapter. In chapter six an explanation is given about the pre-choice for an 'open fabric' water barrier; subjects as closed vs. open, synthetic fabric vs. steel and concrete, the costs and the fabric selection are described. Next, the design specifications are given; the design starting points, the specific requirements, the loads and specific design concerns. In chapter eight several variants of an 'open fabric' barrier are discussed and compared. Subsequently the chosen variant is further designed in chapter nine. A preliminary structural design is presented with the main dimensions, strength calculations, construction method, costs and safety issues. In chapter ten recommendation and conclusions are presented.

2 PROBLEM, OBJECTIVE AND SCOPE

In this chapter the problem definition, the objective definition and the scope of this research are specified.

2.1 PROBLEM DEFINITION

Multiple reports about climate change indicate that more heavy rainfall, more frequent extreme river discharges and a rising sea level might be expected in the 21st century. For this reason a growing need can be anticipated for movable water barriers that divert high river discharges in delta areas like the Netherlands.

Furthermore one can say that the designs for (movable) weirs (retaining low river discharges) are outdated. In the first half of the 20th century many weirs, and in the second half only storm surge barriers were constructed. In addition, there are relatively new, strong and light-weighted materials available that are hardly used within barrier structures. For example synthetic fabrics that are scarcely applied and can have many benefits opposed to steel and concrete.

A third issue is that in the western part of the Netherlands multiple land use is seen as an improvement for the overall living quality. This is because the pressure on nature and rural landscape in this mainly urban part of the Netherlands is relatively high. By designing a barrier with multiple functions, presumably more social value can be obtained. This is something new in hydraulic engineering where most structures are designed for only one main function.

To summarise; there is a necessity for a new type of water barrier, promising new materials are scarcely applied and pressure on nature and rural areas invoke a tendency to multiple land use.

The main problem definition is therefore: what kind of movable water barrier fulfills the needs of society even under changing climate conditions and is constructed with promising new materials?

2.2 OBJECTIVE DEFINITION

2.2.1 MAIN OBJECTIVES

The main objective is to assess an innovative movable water barrier for the 21st century, that is beside technically, also economically feasible.

To achieve this objective, the innovative design will be:

- a. integrated in UOOC research: a movable water barrier that divert flood waves from the rivers and protects the main economic region in the Netherlands against flooding in the 21st century;
- b. combined with architecture: considering landscape values and increase the social value of the barrier by multiple land use.
- c. optimized with the newest materials: like synthetic fabric;

2.2.2 SUB-OBJECTIVES

1. Generate boundary conditions or weighted assumptions, to be able to design the movable barriers for the UOOC concept;
2. Provide recommendations about the location and design of the movable barriers for the UOOC concept, considering technical, economical, architectural and landscape issues;
3. Increasing knowhow about applying fabric in a movable barrier design;
4. Give insight and recommendations about the structural issues concerning the use of synthetic screens within a movable and 'open fabric' water barrier design; (See also section 2.3.3 Barrier design.)
5. Provide a possible solution to minimize the 'extra' costs with a 'flexible no-regret barrier', as mentioned in the introduction.

2.3 SCOPE

The scope of this Master thesis is indispensable because more than one specialization is involved and more than one problem is addressed. This research is done within the UOOC research, in combination (partly) with architecture and contains a research about 'open fabric' barriers. The subjects that will, or won't be discussed in this Master thesis are summed up in this section.

2.3.1 UOOC

- The locations of the four new barriers will be discussed considering technical and social aspects;
- The main requirements and boundary conditions of the barriers will be pointed out;
- The costs of the barriers will be estimated;
- One of the barriers within UOOC will be structural designed in the form of a fabric barrier;
- Salt intrusion problems within the Northern Delta will not be discussed in this master thesis;
- Desirable function for each barrier will be indicated and the general architectural possibilities will be addressed;
- Embedding of the barrier within the landscape will be discussed;
- The different possibilities for a 'barrier building' with extra functions, beside water retaining, will not be discussed. Only the combination of a water barrier and bridge function will be addressed.

2.3.2 BARRIER DESIGN

The emphasis of this design will be put on the structural design issues. To give more direction in this Master thesis a pre-chosen type of barrier will be investigated for the structural design: an 'open fabric' water barrier. (Contrary to an inflatable dam that is a closed fabric barrier.) This type of barrier fulfils the objective of an innovative water barrier optimized with the newest materials.

The scope for the barrier design:

- A technical innovation and optimization of a fabric barrier is aspired;
- Possibility and technical feasibility of an 'open fabric' barrier will be discussed;
- No attention will be given to the 'political introduction' of a new innovative structure like an 'open fabric' barrier;
- The applicability of an open fabric barrier within the UOOC Northern delta area will be discussed;
- Requirements, boundary and surrounding conditions forthcoming from the UOOC concept will be discussed;
- The life-time costs will be estimated on element level;

2.3.3 STRUCTURAL

- Calculations will be limited to simple models;
- Earthquakes, ice loads and ship collisions are not considered;
- Dynamic loading will not be calculated, they will be discussed and accounted for with safety factors;
- Main load distribution will be calculated;
- The strength of the screen and cables will be investigated and calculated for the required strength;
- Main elements of the barrier support structure will be designed for its required strength with compliance of technical standards;
- Erosion protection, guidance dolphins, and seepage screens will not be designed;

3 WATER-SYSTEM

In this chapter the project area and the water-system (current and future) of the Rhine and Meuse river mouth will be discussed.

3.1 PROJECT AREA

The project area is the Rhine and Meuse river mouth or in other words the Northern Delta area. This delta involves a complex water-system around the cities Rotterdam and Dordrecht. See also Figure 2.

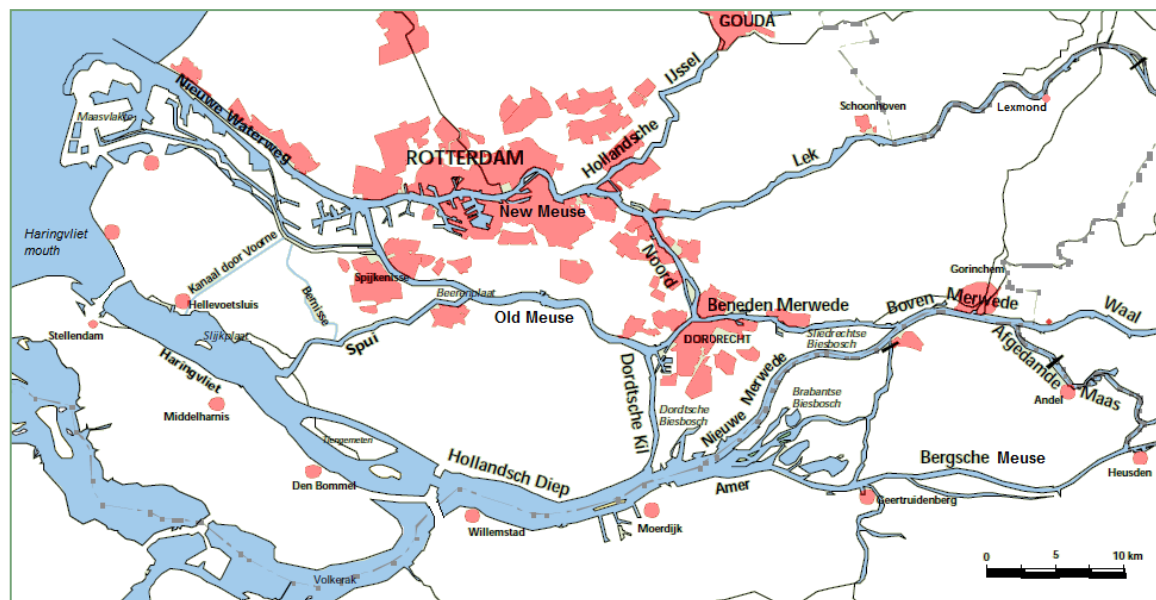


Figure 2: Project area; Rhine Meuse river mouth.

In the last 150 years this delta area has been changed to a great extent. In 1848 the new minister-president, J.R. Thorbecke, set up a river-committee which was the beginning of a range of large civil hydraulic works. Regulation and normalization of the main rivers and improvement of the river mouths were planned. The Meuse and Waal were separated and by construction of the “Nieuwe Merwede” (1850-1885) the Waal had her own connection with the North Sea. Also the river mouth from the Meuse was altered by the construction of the Bersche Meuse (1880 – 1904) and normalizing the Amer. For the shipping industry a direct connection between the port and the sea, the New Waterway, was constructed in 1868. (Wolters-Noordhoff 2007)(Bosch en van der Ham, Twee Eeuwen Rijkswaterstaat 1998)

Nowadays the Northern Delta is dominated by urban landscape and by the port of Rotterdam. This is the most important economic region of the Netherlands. Therefore inland navigation is one of the most important functions of the waterways around Rotterdam. The other main functions of the waterways are discharge of river water, water-storage, irrigation water, drinking water, recreation, nature and landscape value.

3.2 CURRENT WATER-SYSTEM

3.2.1 WATER MOVEMENT

The Rhine discharge (Lek and Waal) is several times greater than the discharge of the Meuse (Bergsche Meuse). In Figure 3 the average maximum discharges from the tidal flows and the residual discharges with direction are given. These residual discharges are the average flow over a tidal cycle divided by time and represents the river runoff through the different waterways.

In Figure 3 the discharges are given that are expected when the Haringvliet barrier is slightly opened. (See also paragraph 3.2.3 Flood protection.)

One can see that the average discharge of the Bergsche Meuse is similar to the Lek discharge and the discharge of the Waal is far greater. This difference is also during a flood wave on the rivers.

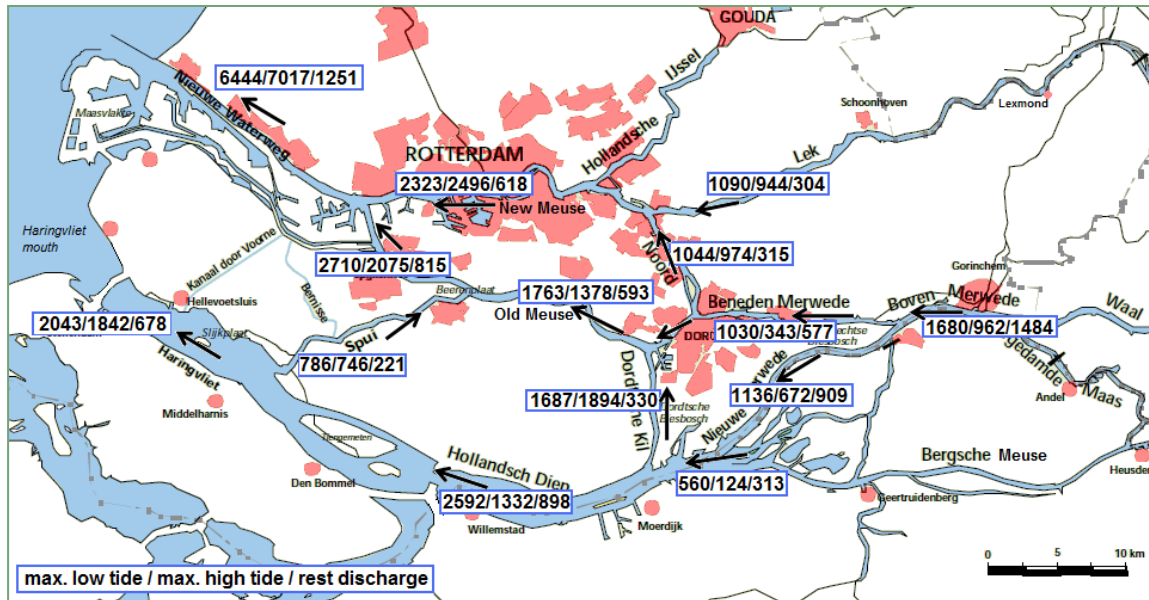


Figure 3: Water movement [m^3/s]. (RWS 'a' 1998) (WsHD 2007)

In normal condition most of the river water is discharged through the New Waterway. (Rest discharge.) During storm conditions however, the water-flow in the Spui and Dordtsche Kil are in the opposite direction; to the south. When the water levels in the Meuse are rising the Haringvliet will follow with a certain delay. Furthermore; the high water levels at the Haringvliet (after a small storm with open storm surge barriers) fall far slower than at the Meuse.

With closed storm surge barriers river water can pile up at the back of these barriers. For now the frequency and the amount of water of this event has little influence on the design water levels for the water retaining structures in the Northern Delta.

3.2.2 DIKE-AREAS AND SAFETY LEVELS

In Figure 4 the primary water barriers and polder or dike-areas (in Dutch called “dijkkringen”) with the maintained safety standards (probability of flooding the area/polder) are given. (A polder is an area that is protected by the primary water barriers like levees, dunes or high grounds.) Since the Maeslant and Hartel barrier are realised the safety standards of the dike-areas 17, 20 and 25 are decreased from 1/10000 to 1/4000 per year. (Waterschap Hollandse Delta) This means that the water retaining structure has to hold back a high water level that is exceeded once in 4000 year.

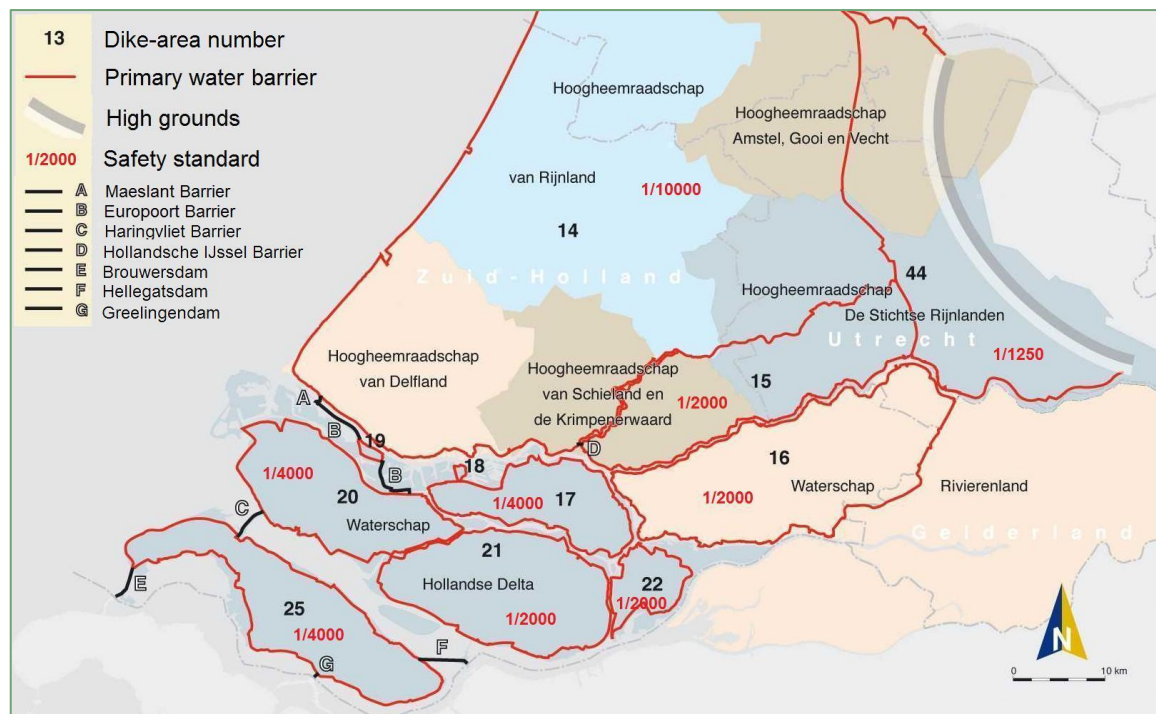


Figure 4: Dike areas and primary water barriers. (Provincie Zuid-Holland (adapted))

The Northern Delta is dominated by the sea. The influence of the sea, rivers and the Maeslant barrier are indicated in Figure 5 for several locations. (The Maeslant barrier is the main storm surge barrier for the Northern Delta and is located in the navigation channel (New Waterway) of the port of Rotterdam.) The diagrams indicate the percentage of influence on the design water levels for each location. The first column is the sea influence, second the river discharge and third the failure probability of the Maeslant barrier. (The probability that the barrier does not close when required.)

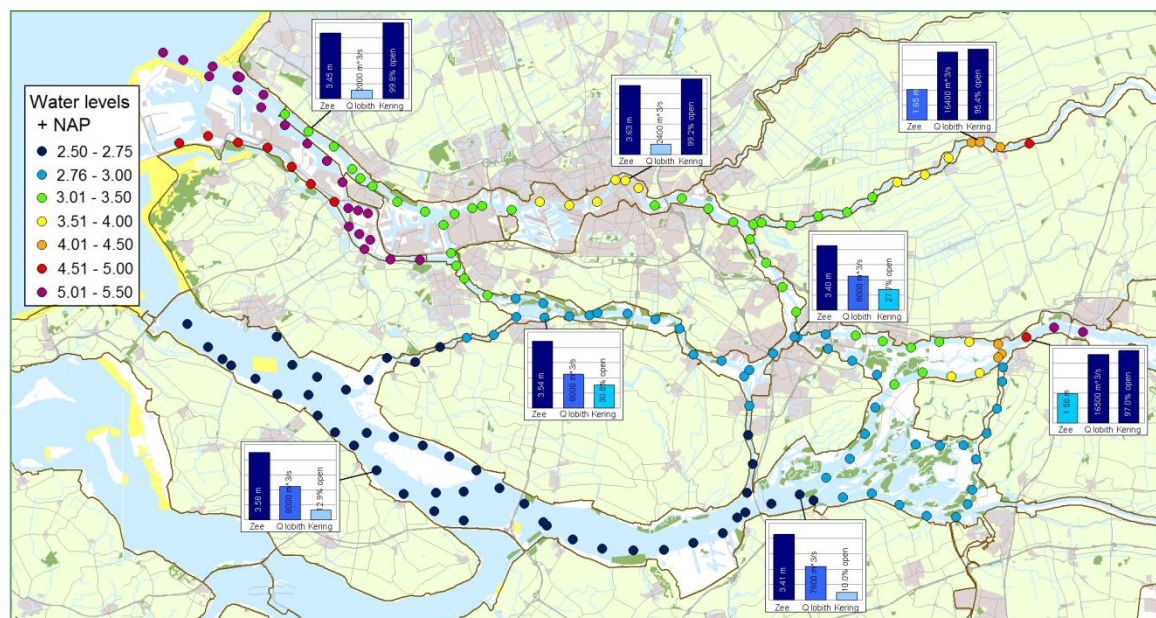


Figure 5: Current influence on the design water levels. (HKV | [lijn in water](#) 2009)

The design water levels are probabilistically calculated: this means that the probability of several events, with certain water levels, are calculated and taken together to determine the design

water level. These water levels combined with durations and local effects, like wave setup, determine the required height and strength of the water retaining structures.

It can be concluded that the Maeslant barrier has a large influence on the water retaining structures along the Meuse (city Rotterdam) and almost no influence for the structures along the Haringvliet. For the Drecht-cities the sea and rivers dominate the design levels.

Another conclusion can be drawn when looking at the colored dots (the design levels along the waterways with local effects); the design levels at the Meuse are higher than at the Haringvliet. This is not because the occurring water levels during a storm event are that much higher. This is because the design water levels at the Meuse are far more influenced by the probability of failure of the Maeslant barrier.

3.2.3 FLOOD PROTECTION

The Northern Delta is dominated by the sea, and beside the levees and dunes several storm surge barriers are build to increase safety against flooding. In Figure 6 the locations of these barriers are indicated and in Figure 7 pictures of these barriers are given.



Figure 6: Current water-system with water barriers. (RWS (adapted))



Figure 7: In order: Haringvliet, Maeslant, Hartel, Hollandsche IJssel and Heusdensch barrier.

The Hollandsche IJssel barrier was constructed in 1958 to reduce the maximum water levels on the “Hollandsche IJssel” river.

The Haringvliet was closed off in 1970 with a partially movable barrier to reduce the length of the coastline and the sea defenses (mostly levees). A fresh water lake was created (the Haringvliet) where river water can be stored and disposed if needed. At times of a low river discharge the barrier is closed to let the fresh water runoff through the New Waterway. This reduces salt intrusion in the urban port area. In 2010 the barrier will be slightly opened to let the tides in for ecological reasons. (RWS Website 2009)

Late 20st century storm surges threatened Rotterdam and the Drecht-cities. Within the urban area there was little room to strengthen or heighten the levees. Therefore the Europort

barriers, Maeslant and Hartel barrier, were constructed in 1997. The highest expected water levels with these storm surge barriers are about +2.9 m NAP at the Meuse in Rotterdam and +2.7m NAP at the Haringvliet.

The Heusdensch barrier (2001) reduces the water levels on the “Afgedamde Maas”. The water levels in this waterway are dominated by the sea and river discharges. Construction of the barrier was less expensive than strengthening the existing levees.

Nowadays a new program is executed to improve the river system in the Netherlands. In this program, ‘Room for the River’ (in Dutch: “Ruimte voor de Rivier”), no longer levees are heightened, but rivers are given literally more room, for instance by removing obstacles and lowering the floodplains. In the delta area two main projects are executed within ‘Room for the River’

The first one is the opening of the “Noordwaard polder”. The “Noordwaard” is located at the north of the “Biesbosch” against the Nieuwe Merwede river. An agriculture area that is partly going to be an environmental area again. An area that can also discharge a fraction of a flood wave that is running on the Merwede river. This way the maximum water levels upstream are lowered.

The second project is at a lake to the south of the Haringvliet; called Volkerak-Zoommeer. When the storm surge barriers are closed and in addition a flood wave on the rivers is threatening Rotterdam this lake can be used to temporally store river water. (This in addition to the existing available water-storage.) Consequently the maximum water levels can be reduced by approximately 0.2m. This is also more or less the expected increase of the water levels in the Northern Delta up to 2050. (Alkyon 2007)
(RvR website 2009)

For the Maeslant barrier the probability of failure (not closing when required) is far greater than expected. The intention was to have a safety standard of 1/10000. Currently the failure chance is at best 1/100. This probability should be lowered and a safety standard of 1/200 should be possible with some adjustments. (RWS 'e' 2006)

This lower safety standard has consequences for the levees behind the barrier. The current projects of levee strengthening (initiated by the second overall safety report of primary water defenses in 2006) are already dealing with this unexpected boundary condition.

3.2.4 NAVIGATION

One of the main function of the waterways in the North Delta area is vessel navigation. There are several classes for navigation and for each class a standard maximum ship size is defined. Also the standing mast route is going through the Northern Delta (waterways Dordtsche Kil and Noord).

In addition; at the Lek there are no drawbridges, at the Beneden Merwede there are and at this moment at the Spui and Dordtsche Kil there are no bridges.

For detailed information about vessel navigation see appendix B.

3.3 FUTURE WATER-SYSTEM (UOOC)

The climate is changing, sea levels rise and the maximum discharge of the rivers will increase. Besides that, the land is declining and the frequency of the flood waves will increase.

Sea level rise of approximately 0.25m in 2050 and 0.8m in 2100 must be expected for the Dutch coast. (These are averages values, the second Delta-committee gives a maximum value of 1.5 m sea level rise in 2100.) The maximum discharge from the Rhine at Lobith in 2050 is predicted at 16,000m³/s and in 2100 18,000m³/s. This gives respectively a discharge at the Waal of 10,200 and 11,350m³/s, and at the Lek: 3,350 and 3,350m³/s. The maximum discharge of the Meuse at Eijsdens resp. 4,200 and 4,600m³/s. (Deltacommissie Veerman 2008)

The current water-system, in combination with the current measures that are already taken and some water management adjustments, are robust enough to guarantee safety up to 2050. After 2050 several problems occur. (Alkyon 2007) (Deltacommissie Veerman 2008)

High river runoff on its own will not be a problem for the delta area. The capacity to discharge the water into sea is sufficient large. However problems can occur at times of extreme low discharges. This invokes, together with a higher sea level, salt intrusion.

Sea level rise causes the storm surge barriers to close more frequently. This inflicts hinder to vessel navigation. Additionally more salt infiltration will take place at lakes and polders and cause problems for irrigation and drinking water.

However it is likely that the main problem occurs when there is a relatively high river runoff and a storm surge at the same time. At this moment the probability for a critical situation when the sea defences are closed is once every 1400 years. (DHV 2009) Due to climate change this combination of events will occur more frequently.

It can be concluded that in the Northern Delta higher water levels will occur more frequently in the future. (Deltacommissie Veerman 2008)

3.3.1 UOOC CONCEPT

A possible solution for the risk of flooding by the combination of a high water wave and a storm surge is the concept of an 'Usually Open, Occasionally Closed' (UOOC) Northern Delta. (In Dutch: "Afsluitbaar Open Rijnmond" (AOR).) In Figure 8 this concept is illustrated. (Deltacommissie Veerman 2008)



Figure 8: UOOC concept. (TU Delft, HKV | lijn.in.water, Ties Rijcken)

In this concept the river water is diverted towards the Hollands Diep and Haringvliet. The fresh water will be temporally stored throughout the duration of the storm. It is assumed that four new barriers and a new waterway are required to divert the river water. The barriers will be located in the Spui, Dordtsche Kil, Beneden Merwede and the Lek. The Nieuwe Lek will be a natural wetland that only flows at times of high water runoffs.

Because there is a maximum water level (with a change of exceeding) guaranteed at the Rotterdam City; more waterfront development is possible. Development on the floodplains, on

the levees along the waterways and even on the waterways itself might be possible. These areas are economic high potential areas because of the port and dense urban landscape.

At this moment (beginning 2009) research is done by the TUDelft, HKV | [lijn in water](#) and Inbo to investigate the possibilities of this concept.

Numerous questions have to be answered about the water storage and the efficiency of the Nieuwe Lek. Perhaps a weir construction upstream is more efficient or the discharge of the Lek into the Northern Delta is not a problem at all. Furthermore: one of the conclusions could be that more safety can be guaranteed when a second storm surge barrier is constructed in the New Waterway. As indicated in this chapter, the Maeslant barrier is of immense importance to keep Rotterdam and the Drecht-cities from flooding.

However one of the main question for the UOOC concept is how large the influence of an event with relatively high river discharges in combination with a storm surge is on the water levels and safety. If UOOC will be applied the probability of flooding due to a combination of a surge and a relatively high water discharge is decreased, however, more safety against storm surges is not provided.

The frequency of this event is hard to predict. First of all, it is for now not clear for which discharge level the UOOC concept is relevant. Presumably a few times per year the discharge from the rivers is high enough to cause the UOOC barriers to close, presuming there is at the same time a storm surge (predicted). Additionally; surges occur mainly in autumn and winter, high river discharges occur from autumn up to spring. Furthermore it is predicted that in the year 2050 the Maeslant barrier will close once every five years. (RWS 'd' 2008) It can be assumed that the frequency of closing of the UOOC barriers is relatively low. (Smaller than 1/10 year.)

3.3.2 MANAGEMENT OF THE NEW WATER-SYSTEM

During the event of the combination of a relatively high water discharge and a storm surge several distinct situations can occur, presuming a certain management strategy of the system. This management system, in general: when closing which barrier, depends on timing, the sequence of occurrences and the level of discharge that is coming from the sea and rivers.

Sequence:

If a high water discharge from the rivers is predicted it can be wise to close the new barriers in the Spui, Dordtsche Kil and, if needed, the Beneden Merwede and discharge water into the sea to decrease the water level in the Haringvliet and Hollands Diep sufficiently enough to handle the incoming water discharge.

However this strategy is not wise when sea and water levels on the Meuse are already relatively high. The water flow from the Meuse towards the Haringvliet is then cut off and can induce, not only early closing, but also closing of the Europoort barriers (Maeslant and Hartel) when this was not required without the closed UOOC barriers. At this moment; closing of the Europoort for several hours can cost the Dutch economy millions of euro's and is therefore not desired. It is assumed that closing the Maeslant barrier is also in the future undesired. (However, this is under discussion because of the development of the second Maasvlakte. A large part of the harbour activities will be relocated at this new harbour side in front of the Maeslant barrier.)

This is also applicable the other way around. If there is a surge predicted that is just above the water level that means closing off the Europoort, the water levels on the Meuse could be lowered by diverting the river water to the Haringvliet by closing of the Lek and Beneden Merwede. Or even by lowering the water level on the Haringvliet before the surge levels rise and opening the Spui and Dordtsche Kill barriers again when the storm surge is occurring.

This means that there is no need to close the Europoort and no hazards for the port industry. However; there are hazards for the inland water transport. The need for navigation locks along the UOOC barriers will increase.

In appendix E.2 more elaborated closing sequences are presented.

Duration:

Beside the sequence also the duration plays an important role. A storm surge has a duration of more and less one day, whereas a high water wave on the rivers occurs for several days. When the sea barriers are opened after the storm a high water wave on the rivers is still passing the UOOC barriers. The maximum water-head is still acting on the barriers and the water level in the Meuse, behind the barrier is even declining with open Measlant barrier. If this is the case, then the barriers have to be opened very carefully and slowly under a maximum head difference. In appendix E.2 an option is presented where this challenging design issue for the UOOC barriers is possibly avoided.

The inland navigation is still threatened during the opening. In general; the time, that the new barriers are closed, is important for the inland navigation and determines the need for navigation locks. (See also appendix B navigation.)

Discharge:

The amount of river discharge that is required to invoke closure of the UOOC barriers is up till now unknown. The Europoort closes at a certain predicted maximum water level, due to a storm surge, at Rotterdam and or Dordrecht. (Resp. closure at +2.9 NAP and +2.7 NAP.) The barriers will only close when these water levels are predicted.

Water runoff from the rivers will increase the water levels in the Northern Delta. (+2.9 NAP and +2.7 NAP are not the maximum tolerated water levels to ensure safety.) No data is available about the current increase in water level (due to river discharge) or which amount of runoff can be stored causing no safety problems.

In appendix E.1 an estimation is made of the required storage capacity. From this data also the occurring water levels can be predicted.

Salt intrusion:

Also salt intrusion is a problem that must be addressed within the management of the system. This problem demands another approach and it is still a question if the UOOC barriers can play a role in the solution. Within this master thesis no special attention is given to this subject.

The different possibilities that are described for the future water management of the Northern Delta have to be investigated for each combination of different events on different time scales and is highly significant for the requirements and boundary conditions of the new proposed barriers. In the paragraph 4.3 assumptions, concerning the elaborated points from above, are made for the UOOC barriers.

4 REQUIREMENTS, BOUNDARY CONDITIONS AND ASSUMPTIONS

The general requirements, boundary conditions and assumptions related to the barriers in the UOOC research are stated in this chapter. (The requirements for the total new water-system are not stated.) The specified demands, boundary conditions and assumptions for the design of the movable water barrier will be stated in chapter 7.

4.1 GENERAL REQUIREMENTS

The general requirements for the movable water barriers in the UOOC concept are given for each function of a waterway.

4.1.1 FUNCTIONS NORTHERN DELTA WATER-SYSTEM

1. **Discharge:** water, ice and sediment;
2. **Irrigation and drinking water:** several inlets, for fresh water, are located along the waterways;
3. **Water storage:** several outlets discharge their water on the waterways, also some storage from relatively high river discharges;
4. **Navigation:** inland vessels and recreational vessels navigate on the waterways;
5. **Recreation:** several functions of recreation are located on and along the waterways: water sports and many cycling and walking trails;
6. **Nature:** several environmental areas are located along the waterways;
7. **Landscape:** the waterways have landscape values;
8. **Crossings:** there are several crossings over or under the waterways: bridges, tunnels, electric cables, etc.

4.1.2 FUNCTIONAL REQUIREMENTS

1. **Discharge:**
 - 1.1. The (future) discharge of water, ice and sediment through all the waterways has to be possible when the movable barriers are opened;
 - 1.2. The current-carrying profile and the shaping of the movable barriers may not cause stream accelerations, piling up water, erosion or sedimentation that interfere with the other functions of the waterways;
2. **Irrigation and drinking water:**

No direct requirements for the movable barriers. (There may be several for the total new water-system.)
3. **Storage:**

No direct requirements for the movable barriers. (There may be several for the total new water-system.)
4. **Navigation:**
 - 4.1. The waterways have to be accessible, when the movable barriers are opened, for the ascribed CEMT class; (See also appendix B.1.)
 - 4.2. Also vessels with exceptional sizes have to be accommodated in the Beneden Merwede and Dordtsche Kil; (Like crane vessels and sea pontoons.)
 - 4.3. When the movable barriers are opened navigation must be possible in both directions at the same time;
 - 4.4. During construction of the movable barriers one directional navigation should be possible;
 - 4.5. The movable barriers have to be visible for the vessel-traffic and easy approachable. Also sight beyond the barrier (5 times the standard vessel length) has to be good;
 - 4.6. Flow velocities have to be kept low. (For navigation channels under 0.5 m/s is desired, 1.0 m/s is maximum.) Furthermore it is preferred to have no lateral flows;
 - 4.7. Guaranteed draught on the main waterways (Lek, Beneden Merwede and Dordtsche Kil) is at least 4.0 m below the normative water level;

- 4.8. Depending on the closing frequencies of the new barriers, locks can be required in the main waterways (Lek, Beneden Merwede and Dordtsche Kil);
 5. **Recreation:**
 - 5.1. Changes to increase recreation along the waterways and the new barriers have to be taken into account; (One can think of; cycling and foot passage and a visitor-centre.)
 6. **Nature:**
 - 6.1. The total new water-system but also the barriers itself may not cause unacceptable damage to the ecological environment; (There are several areas, that are part of or along the waterways, that are Natura2000-areas.)
 - 6.2. The tide-movement in the waterways may not be altered when the movable barriers are opened;
 - 6.3. Fish have to be able to pass the movable barriers;
 7. **Landscape:**
 - 7.1. The barriers have to be incorporated in a responsible way within the landscape;
 8. **Crossings:**
 - 8.1. Existing crossings have to be maintained;
- (WsHD 2007)(RWS 'g' 1999) (RWS - ZL 2000)

4.1.3 INNOVATION

Within this Master thesis it is aimed to create and assess an innovative movable barrier design. The pre-choice for an 'open (synthetic) fabric' water barrier is an innovative starting point. (See for more elaboration chapter 6.) Furthermore, multifunctional land usage and integration within the landscape will be pointed out to increase the awareness that there are other optimizations possible within the design of a water barrier.

The innovation needs to be an improvement; providing the needed functions and dealing with the requirements in a better way. Moreover, the innovation needs to be less expensive than a conventional structure or enhance the value and benefits of the barrier and its surroundings in a more efficient way. In other words the innovation has to increase public benefits / usefulness or diminish public hazards to such an extent that the extra associated costs are small in comparison to conventional solutions.

4.2 BOUNDARY CONDITIONS

Safety:

Each movable barrier has to have a minimum safety-level and there for a maximum probability of failure that is equal to or smaller than the smallest of:

- a. the smallest safety standard of one of the dike-areas that the barrier connects;
- b. the required safety-level that gives adequate safety to meet the safety standards of the dike-areas of Rotterdam and Dordrecht.

This safety-level needs to be guaranteed for the next 100 years.

(WsHD 2007)

Life time:

The irreplaceable parts of the barrier needs to be designed for a minimal life-time of a 100 years.

4.3 GENERAL ASSUMPTIONS

The general assumptions are only briefly stated in this chapter. Elaboration and explanation of these assumptions are given in the following chapters of the main report and corresponding appendixes.

4.3.1 MANAGEMENT STRATEGY

In sections 3.3.2 and 5.2 some issues concerning the management of the UOOC water-system are addressed, and in appendix E elaboration and insight is given in relation to these issues.

From this appendix the following conclusions (mostly assumptions) are made:

- The current safety standards are maintained; (The Second Delta committee suggested an increase of a factor ten. (Deltacommissie Veerman 2008))
- The UOOC barriers are only used during the combined event of a storm surge and a high river runoff;
- Closure level of the Europoort in 2050 is not altered: +2.9 m NAP at Rotterdam and +2.7 NAP at Dordrecht;
- The closing frequency of the UOOC barriers lays between 1/10 and 1/15 years;
- The water basins Haringvliet, Hollands Diep and Volkerak-Zoommeer are used for water storage. The Northern basin (waterways around Rotterdam) is partly used for storage. Grevelingen and the Oosterschelde are not used because of environmental concerns;
- In the future, closing of the New Waterway with the Maeslant barrier is still undesired because of the enormous economic effects. If possible; delaying (or even preventing) the closure of the Europoort is preferred;
- 'Diverting river discharge beforehand' is a strategy to delay closure of the Europoort and is implemented;
- 'Lowering water levels beforehand' in the Haringvliet and Hollands Diep is a second strategy that is implemented;
- The NHW (Normative High Water) levels of the Haringvliet and Hollands Diep are increased (in the year 2050) with 0.5m up to +3.2m NAP;
- Leaking of the UOOC barriers is allowed up to several percentages of the River discharge, it is limited due to maximum water-levels in the Northern Delta area.

4.3.2 WATER LEVELS AND FLOWS

- The water storage on the Haringvliet and Hollands Diep causes higher water levels (on these waters) than can be expected without the UOOC concept;
- The Spui and Drecht barrier have to be able to diverted a negative head;
- There is no water head acting on the UOOC barriers during opening; (The possibility is, however, discussed in the movable barrier design.)
- The Nieuwe Lek ends in the Boven Merwede, east of Hardinxveld-Giessendam. Logical follows that the beginning of the Nieuwe Lek is near Lexmond and not further downstream; (Because of diminishing gradient (required potential energy) further downstream.)
- Constriction of the flow carrying profile of the waterways is limited to insure the discharge requirements. It is assumed that, when no center pillars are used that 40% reduction of the total width is possible. This way the sediment transport will be negligible influenced and causes no erosion or aggregation problems;
- Water levels in front of the Lexmond and Merwede barrier will pile up due to the incoming water flow; 1.0m setup is taken into account;
- Wind setup and wind setdown are taken in consideration, they are estimated at 0.5m at each side;
- The barriers do not have to endure severe wave loading. Waves up to 0.5m have to be diverted.

For elaboration of the water levels and flows assumptions see paragraph 5.2. Specific assumptions and figures of water levels and flows are given in appendix E and paragraphs 5.7 and 7.2.

4.3.3 NAVIGATION

- The shown tendency of the shipping navigation: decrease of passages and enlargement of the tonnage will probably proceed;
- There is no lock required in the waterway Spui;
- Only one lock in Dordtsche Kil or Beneden Merwede will be required;
- At the Lexmond barrier a local decrease of ship passage capacity should not be a problem. A two lane, each direction one, shipping passage is efficient enough;
- Local decreases of capacity in the Dordtsche Kil and Beneden Merwede should be avoided. This indicate that a 'four lane' shipping passage is necessary;
- Also in the future the standing mast route must be able to go through the Dordtsche Kil without any hazards;

For elaboration of the assumptions on vessel navigation see appendix B.

4.3.4 SOIL

- Soil that is able to resist serious loading / the bearing subgrade is located at -15 à -20m NAP; (WsHD 2007)

5 UOOC BARRIERS

In this chapter the four new barriers for the UOOC concept are discussed. Furthermore a pre-choice is made for synthetic fabric as construction material for the barriers.

5.1 BARRIER CATEGORIES

In the Netherlands, during the first half of the 20^e century, many weirs were constructed for navigation reasons. Movable barriers that closes at high water discharges, like in the UOOC, are never build within river systems. (With exception of locks or sluices that are closing off secondary waterways and spillways.)

During the second half of the 20^e century several storm surge barriers were constructed for protection against flooding from sea. These barriers not only hold the sea water at bay but also traps river water behind the barriers.

The barriers that are required within an Usually Open Occasionally Closed (UOOC) Rhine mouth, for in the 21^e century, are water barriers that are diverting a high water wave from the rivers Rhine (Lek and Waal) and Meuse.

In Table 1 four main groups of movable water barriers and their main purpose are given. The fourth group is a new group that is characterized for the UOOC barriers.

Locks, bypass and spillways constructions are not included in this overview. Spillways and bypass structures can be categorised as 'diversion works' and are therefore synonymous to a 'high water diverting barrier'. However the specific function and scale of the structures are dissimilar.

	SEA SIDE		RIVER SIDE	
	Storm surge barrier	(discharge) Sluice	Weir	High water diverting barrier
<i>Purpose</i>	retain storm at sea or lake	regulate discharge of water into sea or lake (and (small scale) high water barrier)	regulate river discharge or water level in rivers and waterways	diverting high water waves on rivers
<i>Closed</i>	few days / year	several weeks / year	several months / year	few days / year
<i>Types</i>	all kinds, except some typical weir designs	all kinds, except horizontal closed barriers	'underflow': ver. segment gate, visor gate, ... 'overflow': rolling gate, inflatable dam, ...	unknown
<i>Image</i>				-

Table 1: Movable water barriers indicated in four main categories.

A storm surge barrier closes of waterways to retain incoming tides and storm surges. A storm surge can be predicted several hours in advance; so the barriers have to close relatively fast. Furthermore the head difference, the force of the water, to retain is relatively high.

Sluices (not locks, although locks can also act as a spillway) regulate discharges and are adjusted all the time. They are generally closed during storm and dry summer periods.

A weir is most of the time closed and opens when high river discharges have to flow through. The gate of the barrier is most of the time in the water and under pressure. There is a difference in 'underflow' and 'overflow' weirs. Respectively regulate the discharge through or the water level in front of the barrier.

A 'high water diverting barrier' is a (movable) barrier that close of a waterway to divert the fresh river water into another waterway, like in the UOOC concept.

5.2 PROPOSED SYSTEM MANAGEMENT

In appendix E.2 three management strategies are discussed for the UOOC barrier: 'Lowering water levels beforehand', 'Diverting river water beforehand' and a combination of the two strategies. All water strategies are just for the high water event when a combination of high river discharge and a storm surge is happening. It is assumed that the UOOC barriers do not close when there is (only) a storm surge, nor when there is (only) a high river discharge occurring. It could be possible that the UOOC barriers are also suitable for increasing safety during one of these events, however, the UOOC research is not focussing on this aspect and within this thesis this is not investigated.

The first strategy (see Figure 9) rest on the idea to lower the water levels in the Haringvliet and Hollands Diep before the event of a high river runoff and a storm surge occurs. This way the storage capacity is increased, which is needed according the storage calculations in appendix E.1. (Within Figure 9, Figure 10 and Figure 11 only the UOOC barriers are drawn, the storm surge / sea barriers and the Hollandsche IJssel barrier are not drawn. The sketched situation is before the closure of these barriers.)

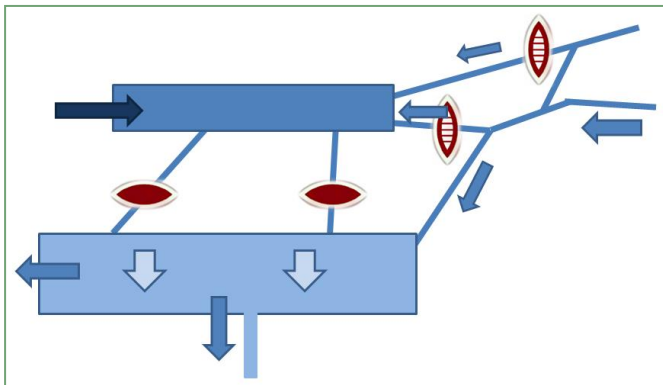


Figure 9: Lowering water level Southern basin before storm event.

The second strategy (see Figure 10) divers the high river runoff before the storm event occurs. This way the water levels at Rotterdam and Dordrecht are relatively kept low and closure of the sea barriers is delayed.

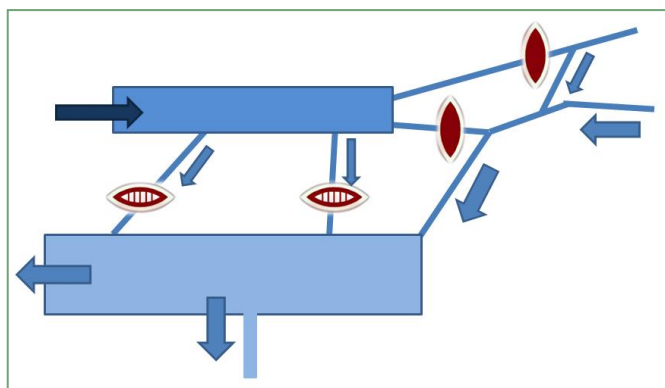


Figure 10: Avoiding high water wave flowing into the Northern basin.

In Figure 11 a combination is presented with some time steps. (Each step represents a tide cycle or approximately 12 hours).

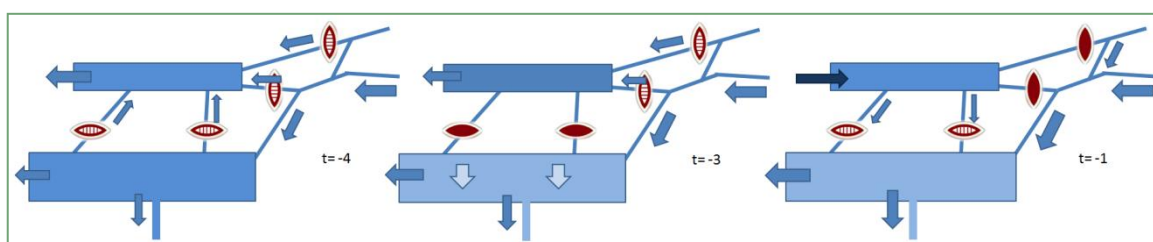


Figure 11: Combining management strategies.

In this combination the water levels in the storage basins are first lowered and when the high river runoff is there and the water is diverted away from the urban areas.

These strategies invokes certain boundary conditions for the UOOC barriers. The most pronounced, as assumed in chapter 4, it that the Spui and Drecht barrier are required to divert a large negative head (high water level at the Old Meuse, low at the Haringvliet).

5.3 UOOC ASSUMPTIONS ELABORATED

As pointed out in Table 1 the types of barriers that can be applied for a “high water diverting barrier” is unknown. Of course an indication can be made after some general requirements and desires are specified.

For the UOOC barriers the main requirements, boundary conditions and assumptions are given in chapter 4. Some of the assumptions will be elaborated and explained in this chapter:

- *It is assumed that the closing frequency of the UOOC barriers lays between 1/10 and 1/15 years;*

At this moment it is difficult, as indicated in section 3.3.2, to predict the closing frequency of the UOOC barriers. The closing frequency highly depends on the safety level that is required and the corresponding frequency of the event of a relatively high water wave and a storm surge. Assuming the UOOC concept is useful and looking at the future closing frequency of the Maeslant barrier a rough prediction is made.

- *It is assumed that the UOOC barriers are not required to be (completely) water tight. Leakage to a certain extent is allowed;*

There are more barriers in the Netherlands that are allowed to leak water to a certain extend. The main restrain is the capacity of water storage behind the barrier. This

indicates that the larger the water surface, available storage, behind the barrier the more leakage is allowed. For the UOOC holds that a large water surface is present behind the barriers. (Northern basin, waterways around Rotterdam.) In appendix E.1 it is assumed that several percentages of the river discharge is allowed to leak. This boundary condition gives more design freedom.

- *Increasing the discharge capacity towards sea;*

More discharge capacity enhance the positive effects of the UOOC concept. The two discussed strategies, 'Lowering water level beforehand' and 'Diverting river water beforehand', are more effective. However, the discharge capacity of the Haringvliet barrier is already (relatively) large, thus the relative-effect of further increase is not known.

If the discharge is large enough, it can be assumed that the UOOC barriers don't have to open with a water head acting on the barrier. (After the storm event the high water wave on the rivers is still present.) The closure time of the UOOC barriers are, however, increased.

This last assumption is highly debatable because of the unknown needed discharge capacity and because of the fact that keeping the UOOC barriers closed until the high water wave is passed is not a desired option for multiple reasons:

- Navigation on the waterways is not, or just marginally possible through the locks; (During a relatively high water wave inland navigation is presumably still possible.)
- The New Waterway is not available to discharge river water. It can be expected that the duration of the high water levels on the Haringvliet and Hollands Diep will increase. Consequently even further delaying the opening of the UOOC barriers and weakening the levees along these waters;
- The water depth in the Meuse could be too low (because of the tides);
- The water head difference over the barriers will increase;

Therefore: within the movable barrier design the possibility to open with a water head acting on the barrier will be discussed, but is not stated as a requirement.

- *The assumption that the Spui and Drecht barriers have to divert a negative head;*

To create more water storage on the Haringvliet and Hollands Diep the water level is lowered (or maintained low) when a closure of the UOOC barriers is predicted. ('Lowering the water levels beforehand' strategy.)

- *For navigation it is desired to keep a wide profile and a short construction time;*

Restriction in form of capacity decrease or temporarily closure of the waterways gives hazard to the shipping and transport industry and decrease the overall economy.

- *It is assumed that, when no center pillars are used, 40% reduction of the total width is possible to fulfill the discharge requirements;*

In the middle of the waterway the sediment transport capacity is the largest. A great part of the transport goes along the bottom of the waterway in the deepest parts. By applying no center pillars the sediment transport will be negligible influenced and causes no erosion or aggregation problems. If a center pillar is used additional width is required.

- *The barriers have to endure limited wave loading;*

The barriers are not located in front of a sea or lake where wave fronts can form.

5.4 SURROUNDING CONDITIONS

In this paragraph the surrounding conditions for each location are discussed. An overview is given about the chosen locations and the most important surrounding conditions per location are stated.

For an extensive elaboration on the different locations and issues see appendix C. In this appendix choice of a location is made for each new barrier within UOOC. Beside technical criteria and costs (regarding several locations for each new barrier), landscape and environmental criteria are also taken into account.

5.4.1 SPUI

In Figure 12 the Spui barrier is schematically drawn at the chosen location (location 2 in appendix C.2) and the (most important) surrounding conditions and desires/wishes are illustrated.

Because of environmental aspects the barrier at the Spui is located slightly more to the North than it would be when only the costs are considered. This choice has some negative consequences for the village nearby and have to be further investigated.

Due to the rural landscape it is desired to construct a barrier that has a minimal impact on the surroundings.

Navigation, some transport and recreational shipping, don't have a large influence on the barrier design. One of the main requirements is that the barrier has to divert the water in two directions.

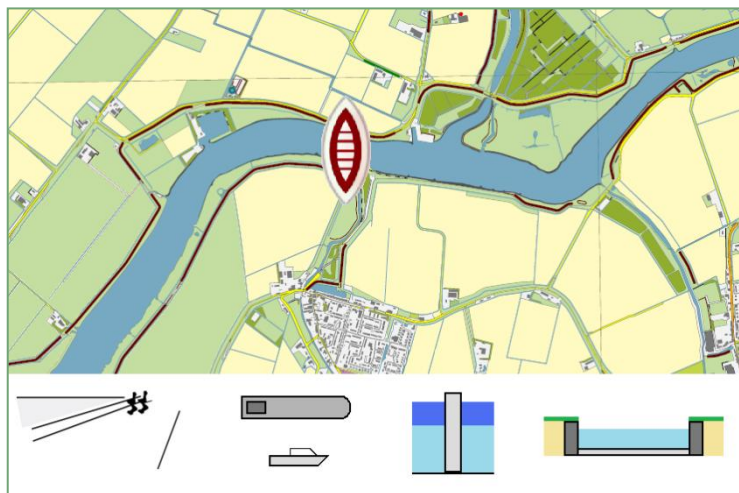


Figure 12: Spui barrier.

5.4.2 DORDTSCH KIL

For the Dordtsche Kil the barrier is located to the South of the two tunnels that cross the waterway (location 2 in appendix C.3). In Figure 13 the barrier location and the (most important) surrounding conditions and desires are illustrated. Further investigation is required about the available space for the barrier at this location. Foundation near and erosion protection on top of the rail tunnel could induce challenging design issues.

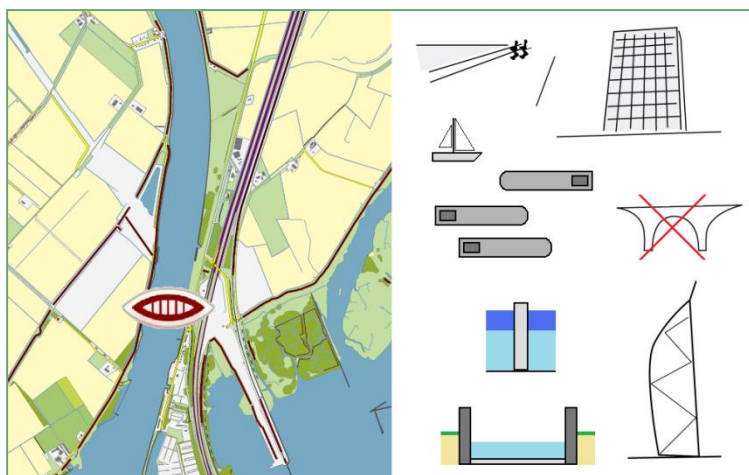


Figure 13: Dordtsche Kil barrier.

This location features a rural landscape that is crossed by water-, high- and rail-way traffic-lanes. Further to the North a rural landscape is present. Several harbours, houses and business parks are located and planned along the Dordtsche Kil.

The Dordtsche Kil is a busy navigation waterway. It is the inland water route from Port of Rotterdam to the port of Antwerp. Also the 'standing mast route' is going through the waterway. So no bridge or another construction that diminish the shipping capacity is desired.

Because it is a primary shipping waterway where several transport systems overlap each other the new barrier could be a landmark for the transport industry and for the trading spirit of the Netherlands.

5.4.3 BENEDEN MERWEDE

For the Beneden Merwede the chosen location (location 3 in appendix C.4), seen in Figure 14, is estimated to be the least expensive option.

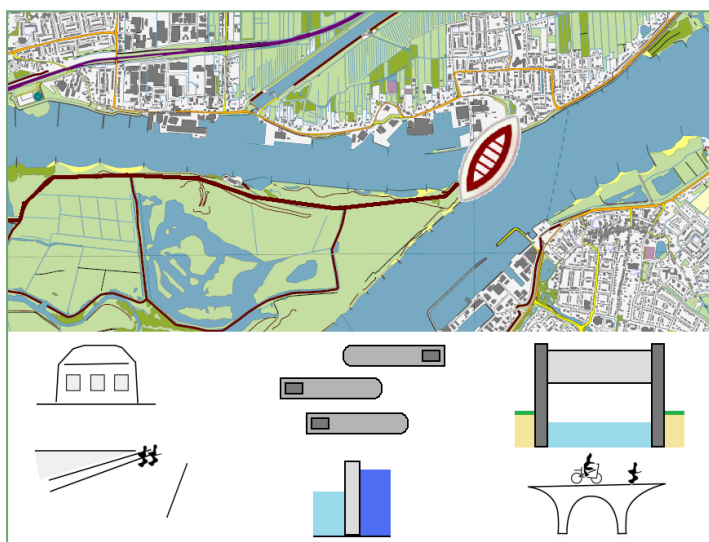


Figure 14: Merwede barrier.

This location is preferable due to the fact that there will be no need for strengthening and heightening of the levees in the dense urban waterfront at the North of the waterway. However a long connection dam, south of the waterway, through the "Dordrechtsche Biesbosch" is needed. It is perhaps possible to construct an ecological, environmental friendly, connection dam that diminish the impact on or even enhance the natural-values of this National Park. And

moreover; reduces the social impact of looking up to a relatively high levee at the other side of the Beneden Merwede.

The possibility that the barrier causes problems up stream due to piling up of the water in front of the barrier and the possible counter actions have to be investigated. Furthermore an investigation has to be made about the possibilities to connect the barrier at the north side. There is little space and space might has to be created.

The waterway is a busy inland water transport route to Germany. However there are several (movable)bridges crossing the waterway and there could be an option for a pedestrian and bicycle bridge for recreation purposes. This bridge will connect the urban area, largely houses and small industry, with the natural environment of “De Biesbosch”. This indicates that the barrier could be opened above water and combined with a bridge function. It is required that the bridge can open for standing mast and crane vessels considering the present drawbridges. It is unsure whether the barrier is required to divert water from both sides.

5.4.4 LEK

In Figure 15 the barrier location and the (most important) surrounding conditions and desires are illustrated.

The possible required width of the Nieuwe Lek is in range of the winter bed of the Lek. Probable even more because of the design plans to construct a green environmental river.

One barrier in the Lek and a sill construction in the Nieuwe Lek can be inadequate because the sill causes too much hindrance for the water wave. In that case a second barrier in the Nieuwe Lek is required that opens in times of high river runoffs.

Because of the rural landscape and natural values along the Lek, think of the floodplains that are no longer farmland because of the ‘Room for the River’ programme, the impact of the barrier should be as low as possible. A barrier that is most of the time invisible is preferred. However another option is constructing the barrier in line of the Visor weirs that are already located along the Lek.

Adding other functions to the barrier, beside the water-retaining function, is for natural reasons not further considered at this location.



Figure 15: Lexmond barrier.

There is transport and pleasure navigation along the waterway. There are several bridges along the waterway that are not suitable for standing mast vessels. It is assumed that also at this location no need is present for the possibility to pass the barrier with a standing mast.

The barrier has to divert high water from one side. However it is unclear if and how far the water level must be raised to get enough potential energy (gradient) for the Nieuwe Lek.

5.5 DIMENSIONS

The required width and depth of the barrier is dependent on the erosion / accretion and navigation requirements. In Table 2 the required width for different criteria and the required depth; sill height, are calculated. For elaboration on the table and used calculations methods see appendix D.

	WATERWAY			NAVIGATION			REQUIRED WIDTH		
	width [m]	min. / average water level m NAP	max. daily discharge [m ³ /s]	CEMT class /max. width /max. draught	required lanes /capacity	sill height NAP	erosion and accretion	navigation (capacity)	flow < 1.5 m/s (navigation)
Spui (2)	140	- 0.05 / 0.4	786	Va / 11.4 / 4.5	1x1	-5.1	84	57	96
Dordtsche Kil (2)	260	-0.1 / 0.5	1894	Vlc / 34.2 / 4.5	2x2	-5.1	156	268	225
Beneden Merwede (3)	230	-0.1 / 0.6	1030	Vlc / 34.2 / 4.5	2x2	-5.1	138	268	120
Lek (-)	250	0.2 / 0.8	1090	Vla / 22.8 / 4.5	3 lane	-4.8	150	142	130

Table 2: Dimensions UOOC barriers. (RWS 'a' 1998)(RWS 'b' 2007)(RWS 'g' 1999)(MVW waterstat 2009)(TUDelft; d'Angremond; Bezuyen; Van der Meulen 2003)

First of all some information is given about the waterways and the navigation on the waterways. The maximum discharge is the average maximum discharge of the ebb or flood tide. The frequency of occurrence is not clear, so the velocity criteria are only an (assumed maximum) indication for the required barrier width.

Second, some navigation figures are presented. The maximum draft is from a push-towing vessel and the required shipping lanes are estimated by looking at the present width, capacity and transport intensity. For this estimation and more details about the navigation on the four waterways see appendix B.

It has been stated that the available data is not reliable and specific enough to state a firm conclusion.

Assuming that Table 2 gives a representative image, it can be concluded that for the Drecht barrier (Dordtsche Kil) and the Merwede barrier the required navigation capacity is normative for the barrier width. The desired capacity / width even exceeds the current available capacity / width.

For the Spui barrier the velocity criteria is assumed to be normative. However added information about the discharges is required. (This is also required for the other waterways.) To lower the velocity (if this criteria is normative) also the sill depth can be lowered up to the present local depth.

Because of several weirs exist (with a gate width of 100 m) within the river system of the Lek, the sediment transport through the Lek is small for the most part of the year. However, the sediment transport at high water discharges is substantial. (RWS Website 2009) The new barrier at Lexmond should not block this sediment transport. And therefore it can be concluded that the

required width for the Lexmond barrier is prescribed by this sediment transport and thus by the erosion and accretion criteria.

5.6 COSTS UOOC BARRIERS

The construction costs of the four UOOC barriers are roughly estimated in appendix F with the help of existing movable water barriers. The costs lay in the range of 550 M up to 670 M euro's. (These are the construction and design costs, without maintenance and operation costs.)

When considering a life-cycle costs analysis, the required investment (at present time) for the construction, maintenance and operation of the barrier for the required life-time of 100 years, is around the 850 M. (From 700 M up to 1000 M.)

The difference are due to the rough estimation, the uncertainties about the design requirements and applying fabric or steel as a construction material. A fabric barrier is presumed to be less expensive, this hypothesis is addressed in appendix F and will be further investigated.

In chapter 5 some design issues are discussed. The costs of the UOOC barriers are also influenced by these unusual design issues.

It is assumed that the barriers don't have to be water tight, which reduces the costs. The barriers that have to be able to also withstand a (large) negative head are probably more expensive.

Also a comparison is made about the investment and the length of avoided levee alterations. If an investment is made for the UOOC barriers of 900 M euro's the length of avoided levee alteration must be around 350 km. Within this figure no distinction is made between urban and rural landscape. Because alteration in urban areas like the Northern Delta is very expensive, this investment is quite possible.

5.7 OVERVIEW UOOC BARRIERS

Here an overview of the UOOC barriers is given that is produced in appendix B throughout F and presented in this chapter. The location, costs and some requirements and wishes are presented in Figure 16. In Table 3 the main dimensions are stated.

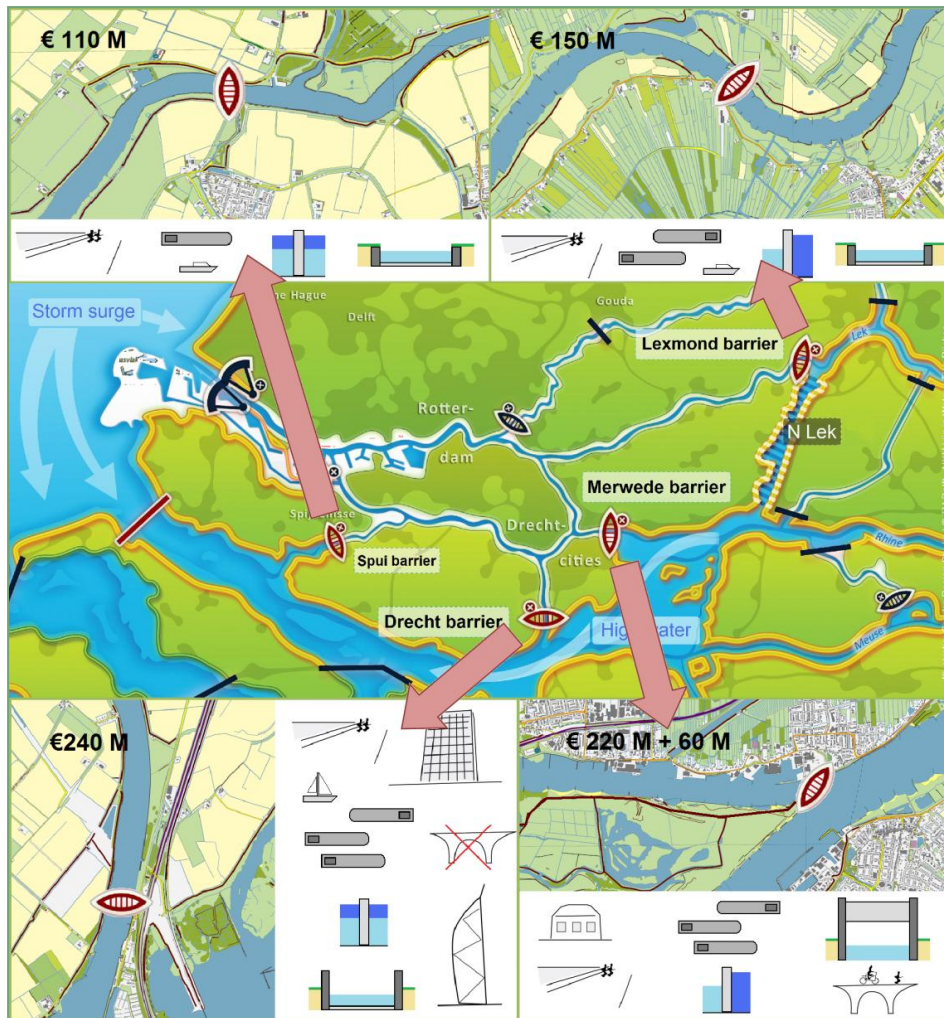


Figure 16: Overview location and costs UOOC barriers. (F. van der Ziel BSc)

The four selected location are indicated and the total costs are estimated at 760 M euro's. These limited costs are only true in the case that all the barriers are constructed with fabric, with a connection levee to the Merwede barrier and without a second (perhaps required) movable water barrier in the Nieuwe Lek near Lexmond.

	<i>sill depth ..m NAP</i>	<i>max. water level ..m NAP</i>	<i>min. Bridge height [m]</i>	<i>gate width [m]</i>	<i>gate height [m]</i>	<i>max. Head [m]</i>
Spui barrier	-5.1	+4.2	-	100	9.8	-3.8
Drecht barrier	-5.1	+4.2	-	240	9.8	-3.8
Merwede barrier	-5.1	+4.7	11.62 (movable) 13.06 (fixed)	210	10.3	+4.4
Lexmond barrier	-4.8	+4.9	15.54 (fixed)	120	10.2	+4.4

Table 3: Main dimensions UOOC barriers. (For sources see table 2 and for the actual figures see appendixes B, D and E.)

The maximum water level in Table 3 is the water at the barrier without waves. Wind setup and setdown, 'flow setup' and waves are accounted for in the gate height. (The gate heights are required when a vertical lifting/drop gate is used; waves are taken into account.) The maximum heads (water difference over the barrier) are for the Spui and Drecht barrier so called negative heads. During these (normative negative) heads the water levels at the Old Meuse are higher than at the Haringvliet and Hollands Diep. (Positive heads are directed in the opposite way.) All the figures are estimations and are described and or calculated in the appendixes B, C, D and E. The figures in Table 3 will be used for further design of the barriers.

6 'PRE-CHOICE' 'OPEN FABRIC' BARRIER

It is customary to fabricate the movable parts of hydraulic structures out of steel. However: steel gates, for example vertical drop gates, require a high level of maintenance. Because of this the life-cycle costs of such a barrier is relatively high. Therefore several developments are leading to structural designs with a low maintenance level. For example: special coatings, high strength concrete and fabric as building material.

In this chapter the 'pre-choice' for using (synthetic) fabric as building material is further explained. As already mentioned in chapter 5 it is presumed that a fabric barrier is less expensive than a steel barrier. In this chapter also some starting points concerning 'open fabric' barriers are presented.

By making this 'pre-choice' a different design method is used than followed by civil engineers and followed in the chapters above. The objectives, as stated in chapter 2, are to investigate the options of an 'open fabric' barrier (a technical assessment) and the possibility to implement this type of barrier within the UOOC concept.

6.1 'CLOSED' VS. 'OPEN'

In this Master thesis a pre-choice is made to investigate the possibilities for an 'open fabric' water barrier in general and specific for the UOOC research. The distinction 'open' is in contradiction with an inflatable dam (in Dutch: "balgstuw") that is a 'closed fabric' barrier.

In Figure 17 a photograph of the "balgstuw" at Ramspol, the Netherlands, is shown. In the photograph the barrier is closed and retains wave setup from the lakes: Ketelmeer and IJsselmeer.



Figure 17: Inflatable dam, the "balgstuw" at Ramspol, the Netherlands.

The fabric is stored in the sill under water and when required the bellow is inflated with water and air. This barrier deflects the water forces only by tensile stresses within the fabric. These forces are directed directly towards the foundation itself and not sideways through pillars or abutments. Because of this an inflatable dam is suitable for a low head over width ratio. This is desired for maintaining the discharge functions of the waterway and minimizing hinder for vessel navigation. Furthermore the design of the barrier can be easily adapted for also diverting a negative water head. For that case only the foundation must be adapted.

Because of the use of only tensile stresses the volume of material that is required is low. Furthermore; fabric is a relatively cheap and low weighted material that can cope with the high tensile stresses. Because of the low unit weight and the ease of connecting the fabric sheet to the foundation the construction time is short.

In addition the “balgstuw” needs little maintenance because there is no paint required and almost no movable parts present. This means less hazards for navigation (less frequent barges and other obstruction in the waterway for maintenance reasons) and viewer chemicals spilled in the local environment. In addition the operation costs are low mainly because of the low weight of the gate and the use of the available water pressure. (RWS & WL | Delft Hydraulics 2005)

The construction costs of a fabric inflatable barrier is 25% to 50% less expensive than a steel drop gate. When a life-cycle analysis for the costs of an inflatable barrier and a vertical steel drop gate are made this figure strongly depends on the life-time of the fabric. A fabric gate is twice as inexpensive as a steel gate, however the fabric needs to be replaced approximately every 30 years. The maintenance and replacement percentage of the total costs for a fabric barrier is higher than for a steel drop gate. However the inflatable barrier is still less expensive; approximately 30%. (WsHD 2007)

Some disadvantages are that an inflatable dam is in principle not suitable for discharge regulation (it is suitable for level regulation) and the fabric is sensitive for exposure to UV light and external damage like vessels, debris and vandalism.

An ‘open fabric’ barrier is like a parachute that is opened by the water flow and kept open (partly) by the hydraulic pressure. An inflatable dam is inflated and kept open due to a high air or water pressure inside the bellow.

The issues that are pointed out for the inflatable dam are very similar for an ‘open fabric’ barrier. In Figure 16 a sketch of a possible ‘open fabric’ water barrier is given.

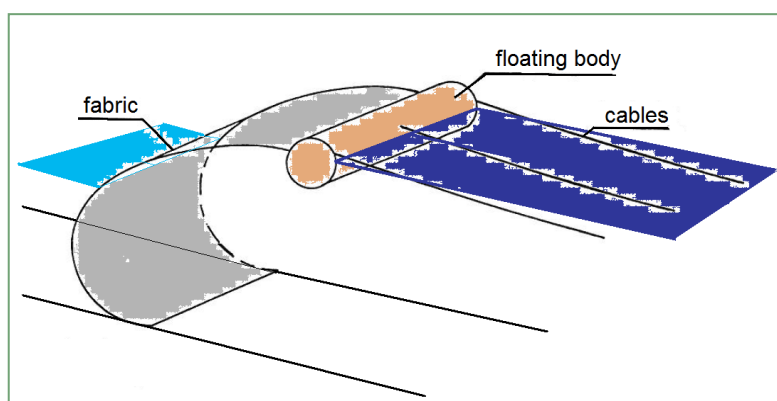


Figure 18: Possible 'open fabric' water barrier. (Knippels en Pechtold 1992)

Looking further at the design issues stated above it can be concluded that a fabric barrier can be suitable for the UOOC concept. This because of the fast construction time, leakage is allowed, there is no wave energy (dynamic loading) and the great width in combinations with the relatively low water head that has to be diverted.

However, if the barrier has to open with a water difference over the barrier and control the water discharge (this is not assumed but only discussed in this report) this design is less suitable. In addition: a negative head, which is assumed to be required, makes the design even more complex.

6.2 STEEL VS. SYNTHETIC MATERIALS

Steel has less strength, performs less in endurance tests, is heavy and requires a lot maintenance. This makes steel less favourable as a construction material for a movable water barrier.

Looking at cable-stayed and suspension bridges: more and more designs are made with synthetic cables. Light, high tensile strength, low maintenance and excellent fatigue performance are the main reasons. (See also Figure 19 endurance test.)

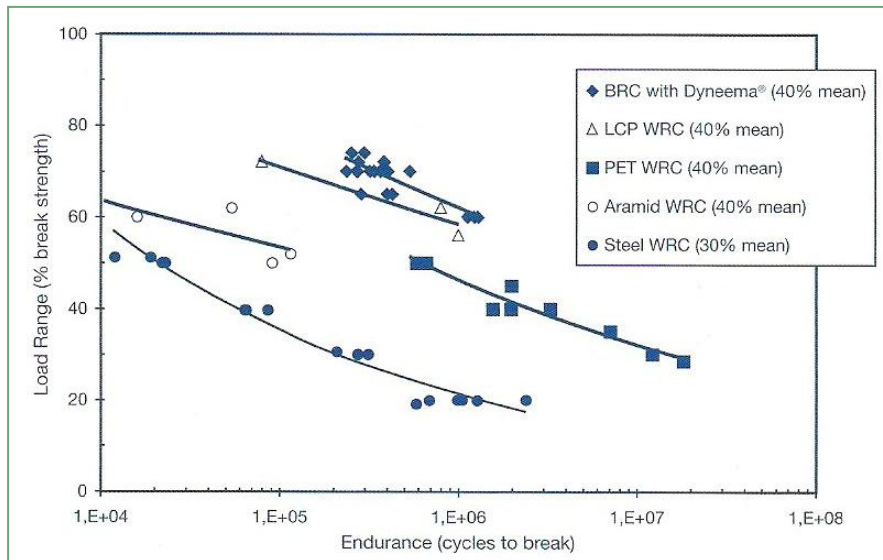


Figure 19: Tensile fatigue life compared. (DSM - Dyneema 2009)

High strength fibers perform especially good under tensile conditions. There are general synthetic fibers (PP, PA, PET and PE) and also high strength fibers like Stabilenka®, Kevlar®, Twaron®, Dyneema® and Vectran®.¹

In appendix G.1 comprehensive information is given about the fibers and their differences.

It has to be stated that the actual construction material will be a combination of a fiber and, if required, added materials like rubber and coatings. (For instance to increase UV and wear and tear resistance.)

6.3 COSTS OF A FABRIC BARRIER

The construction costs of the UOOC barriers are roughly estimated to be in the range of 550 M up to 700 M euro's. (These are the construction and design costs without maintenance and operation costs.) (See appendix F.)

When considering a life-cycle costs analysis, the required investment (at present time) for the construction, maintenance and operation of the barrier for the required life-time of 100 years, an extra 40% must be taken into account for a conservative construction like a vertical lifting gate. Considering an inflatable dam, like the "balgstuw", an extra 75% should be taken into account. This higher value is due to the fact that it is assumed that the fabric must be replaced every 30 years. Even considering these figures an inflatable dam can be 15% up to 50% less expensive.

The costs of the gate, or in this case the screen(fabric) of a movable water barrier is a substantial part of the total barrier costs.

For example: the screen of an inflatable water barrier with a width of 100m cost around 12M euro, however the total investment costs for 100 years is approximately 42M euro. For a vertical lifting case this is 28M to 64M. A large part of the costs for a 'fabric barrier' are placed further away in time and the investment costs are therefore lower than a conventional barrier.

¹ Stabilenka® is a registered trademark of Akzo Nobel. Dyneema® is a registered trademark of DSM. Kevlar® is a registered trademark of DuPont. Twaron® is a registered of Teijin. Vectran® is a registered trademark of Kuraray America, Inc.

The life-time of the fabric and the corresponding required life-time of the barrier have a great influence on the investment costs. The extra costs to extend the life-time with 20 years up to 120 years is, in the case of screen replacement every 30 year, minimal.

(WsHD 2007) (RWS & WL | Delft Hydraulics 2005)

In addition there is little to no experience in designing and constructing a large fabric water barrier, and therefore the ‘repetition-effect’ that normally decreases the costs is minimal.

However this can be seen as an opportunity to increase knowhow, for Dutch companies, about fabric barriers, especially due to the fact that there are four barriers required for a UOOC Rhine Mouth. Furthermore these barriers could be design and constructed in such way that they are adaptable in time.

6.4 FABRIC SELECTION

In appendix G.1 a comparison is made and more detailed information is given about the fibers that are selected to be the best for the ‘open fabric’ movable water barrier.

6.4.1 SCREEN

For the screen PA is assumed to be the best option. Robustness is given by the large strain capacity of the material. This is required because the fabric has to withstand peak stresses (from folding and dynamic loading) that are hard to predict. A great strain capacity can spread these stresses and provide therefore more safety. See also Table 4 for strain comparison.

	<i>elongation at break [%]</i>
Nylon / balgstuw (PA)	20
Stabilenka (HMPET)	10
Kevlar en Twaron (HMPET)	3 - 4
Dyneema (HMPE)	3 - 4
Vectran (LCP)	3

Table 4: Strain for several fibers. (Naeff 2009)(Driessen 1998)(DSM - Dyneema 2009)

When PA is combined with rubber the required thickness and weight of the material is far greater than Dyneema®. However the screen is submerged in the water and the weight is assumed not to be normative. (This depends on the final design.)

PA performs better in the endurance test than steel, however less than Dyneema® or LCP. Furthermore, in combination with rubber, the surface of the material is more rough than the other synthetic materials. As a result the connection between the screen and for instance the concrete sill is easier to construct.

Stabilenka® could be an alternative because it still has a great strain capacity, however due to the costs and lack of experience in manufacturing PA is chosen above Stabilenka®.

The screen for the “balgstuw” at Ramspol is used as a reference material. In Table 5 some loading and screen figures are presented.

LOADING:		
head	4.4	[m]
max. water level	+3.55	[m NAP]
sill height	-4.65	[m NAP]
design probability of failure	1/2000	[year]
closing frequency	1.1	[../year]
average loading	200	[kN/m]
max. Loading *)	936	[kN/m]
SCREEN:		
weight	19.2	[kg/m ²]
Thickness	1.6	[cm]
length fabric (across)	24.3	[m]
tensile strength	1300	[kN/m]
shear modulus	100	[kN/m]
bending stiffness	10	[Nm ² /m]

Table 5: Loading and screen figures “balgstuw” at Ramspol. (*) are with several safety factors.) (GSW 2002)(J.S. Reedijk, Delta Marine Consultants 2004)

After fatigue loading, ageing and relaxation from pre-stresses the strength of the fabric was still over 1300 kN/m. Several safety factors were applied amongst a dynamic factor of 3 for folding (in Dutch “plooi”) of the screen.

For more information see appendix G.3.

6.4.2 CABLES / ROPES

The connection between the screen and the cables is far better when using a synthetic material for the cable. Steel cables will cause a lot of friction and wear problems, while a synthetic cable can be stitched on and into the screen.

For the cables of the ‘open fabric’ barrier a large strain capacity is not especially required, perhaps even not desired because the different tensile stresses cause dissimilar extensions and because the possible increase of the abutments structures. Vibrations, however, are decreased when applying Dyneema® ropes in comparison to steel cables. Furthermore the cables will be relatively light, which can be a large benefit for an ‘open fabric’ barrier designs.

Dyneema® fibers look to be the best option for the barrier cables. UV resistance, wear and tear and the endurance of this fiber are better than arimid (Kevlar® and Twaron®) and LCP fibers (Vectran®). The costs of these fibers are in the same range.

The ropes could also be a good alternative for guys in a cable-stayed bridge. The endurance is good, low maintenance and ropes are very light weighted; which means less sagging. In addition the strength of Dyneema® ropes are in the same order of magnitude as that of steel cables. In Figure 20 a graph is presented which gives the strength of ropes made by Dyneema® fibers per rope diameter.

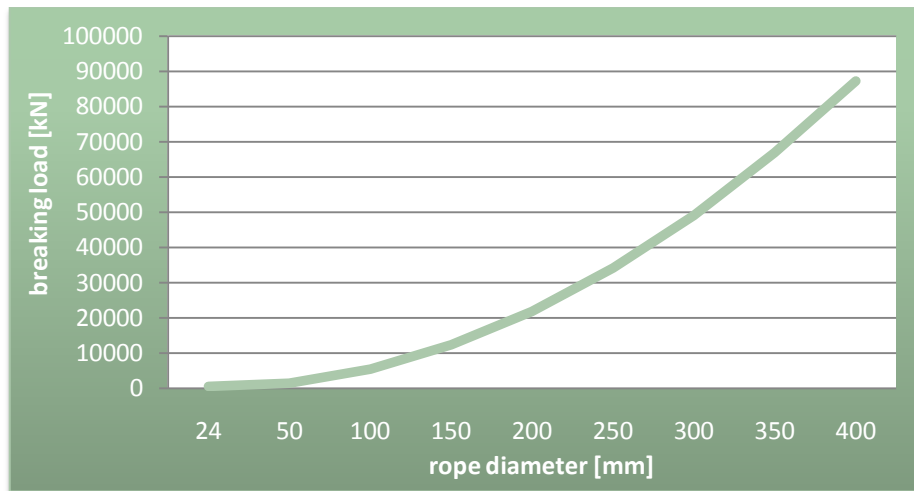


Figure 20: Breaking load Dyneema® SK75 ropes. (With a material safety factor of 1.1.)

The largest rope made with Dyneema® fibers is 183mm in diameter. Presumably this is in range with the required diameters for the water barrier designs. A rule of thumb is applied for estimating the breaking strength of larger diameter ropes: the breaking strength increases with the square root of the diameter, as can be seen in the graph. (R. Bosman, DSM Dyneema)

For more information over Dyneema® fibers and ropes see appendix G.2.

6.5 POSSIBILITY FOR PREFABRICATION

Water barriers are normally constructed in cofferdams. This allows traditional construction methods, equipment and conventional quality control inspections. The costs however are high; it requires a large temporary structure. Also some risk issues are introduced like leaking, overtopping and thus potential damage of the construction, delay and extra costs.

Prefabrication has long been used for the gates of a water barrier. Many improvements in technology and engineering skills have been made concerning prefabrication. Nowadays a better final structural quality can be obtained with prefabrication. It is possible to completely construct a water barrier without cofferdams. The subgrade and foundation can be prepared 'in the wet'. Floating equipment prepares the river bed and great accuracy can be obtained for placing the construction. Shells for the substructure and/or superstructure are constructed offsite, transported over water to the site and set in place. The structure is then filled with concrete and joined with the foundation. (PIANC 2005)

This method is excellent applicable for a barrier with a simple foundation, sill structure. An 'open fabric' water barrier has the potential of a simple sill structure if the loads are diverted towards the abutments. Prefabrication is, next to the costs and risks benefits, ideal for a short construction time and therefore reduces hazards for inland navigation. One of the main functions of the waterways in the Northern delta is inland navigation. Hazards to the inland shipping industry can cause millions of economic damage. Therefore prefabrication is stated as a starting point for the design of the UOOC barriers in the next chapter.

7 DESIGN SPECIFICATIONS

In this chapter the main structural design specifications are presented for a movable water barrier. The starting points (or general design concerns), the loads and the requirements (in addition to the general requirements in chapter 4) of the movable barrier are given. (The assumptions that are made in chapters 4 and 5 are not repeated as requirements, these are boundary conditions for the design.) In addition also specific design concerns concerning an 'open fabric' barrier are discussed.

7.1 DESIGN STARTING POINTS

7.1.1 GENERAL

Safety level:

As stated in the general requirements each movable barrier has to have a minimum safety-level and therefore a maximum probability of failure. This probability is equal to or smaller than the required safety-level that gives adequate safety to meet the safety standards of the dike-areas of Rotterdam and Dordrecht. The safety standard in the Rotterdam polder is 1/10000.

To obtain this safety standard the failure probability of several barriers (that are located behind one another) have to be summated. The failure of one barrier depends on many different things and the failure of one barrier is also correlated with the failure probability of the other.

Another issue is that engineers can calculate within a reasonable margin a safety level of 1/200. Beyond that the unknowns are relatively large. By designing conservative; the safety levels of movable barriers are stated up to 1/4000.

It is assumed that the highest safety level of the polders that are connected by the UOOC barriers is the required safety level for the UOOC barriers, namely: 1/4000.

Flexibility and sustainability:

The design should be flexible in order to take not only climatic changes into account but also different social views and ecological changes.

A possibility is a modular barrier design: a water barrier that is assembled out of small individual water barriers. Not only can the smaller barriers be replaced for larger (higher) versions but also the amount of small barriers can be increased. (Assuming fabric as main closure material that have to be replaced every approx. 30 years.) This way the water barrier can grow with the climatic changes, and possibly also with the social and ecological changes. To construct a modular barrier; the costs and ease of the installation and foundation of the small barriers have to be low. In addition it must be possible to strengthen the primary water barriers that are connected to the movable water barrier in the future.

Apart from the flexibility also ecological sustainability should be addressed in the barrier design. Using environmental friendly materials and building techniques as well as diminishing leaching of chemicals and dust into the environment. In addition dismantling of the structure should be possible without harmful consequences for the surroundings and the materials that are being disengaged have to be reusable.

Construction feasibility and prefabrication:

An important concern for large hydraulic engineering structures is the building technique. Each structure is unique and the construction feasibility can be normative because of the maximum size of equipment or transport capacities and the availability of the equipment. In addition the manufacturing of a certain material can be normative.

Because the UOOC barriers have to be built in extremely busy waterways, prefabrication could be a good solution to minimize the downtime of the transport waterways. (See also paragraph 6.5.) The maximum sizes for transport and installation have to be considered and can be normative as well.

Aesthetics:

The movable barrier has to be implemented within the surrounding of the barrier location. The design can make a statement or merge together in shape and color with the surroundings. Therefore, the abutments and (guidance, securing) dolphins have to be incorporated within the design.

To obtain more social acceptance for constructing a large civil structure, with a large impact on its surroundings, it is useful to investigate the possibility to combine the civil structure with another desired (social) function. A fabric water barrier combined with a bridge function could be promising, also because of the possibility to combine load distribution and inspection access.

7.1.2 RELIABILITY

Minimize:

To meet the safety standard the reliability of the barrier is very important. Therefore the design should minimize wear and tear, movable parts (jamming and fatigue), submerged movable parts (vulnerable for corrosion, sedimentation and debris), exposure to environmental forces and prevent or cope with ship collisions, vandalism and sedimentation.

Deformation capacity / 'warn':

The structure also has to have enough deformation capacity, so the structure can 'warn' / 'give signs of failure' before actual failure.

A modular system could enhance the reliability in a great way; the small barriers that are closing off the waterway are closing independent and when failure occurs only one collapses instead of the whole barrier.

Experience:

Another part of reliability rest in the construction methods and experiences with similar structures. Using fabric as a building material is not common practice and therefore special attention is required during designing and construction such a barrier. Also within the inspection and maintenance requirements this lack of experience must be addressed.

Trial closure:

Also a trial closure have to take place every year to enhance the reliability of the barrier. Especially when a new type of barrier is chosen and were no experience is in closing such a barrier. This holds for an 'open fabric' barrier but even more for a modular barrier.

Awareness:

Awareness and knowledge about the function(s) of a structure are important for its acceptance and usages. The awareness of the surrounding society can be increased with a trial closure and benefits the reliability of the movable water barrier.

When combining the barrier with a bridge function this awareness for a flood protection structure could be diminished but also increased if the barrier function can be seen at all times.

7.1.3 STRUCTURAL

Minimize the requirements for high quality foundations:

The impact of a gate design and the corresponding load distribution often dictates the associated civil engineering works and can cause design problems for the total barrier. These works, like the foundation, sill and (concrete) abutments may become more important, complex (higher construction risks) and expensive with a certain gate design. In other words: a simple design for the upper structure can invoke a complex design for the lower structure. This concern is especially valid when dealing with fabric and a new type of water barrier.

In general, the impact of the gate design depends mainly on the load distribution:

- If the loads that are distributed towards the piers/abutments are too concentrated; heavy and expensive concrete reinforcement is required and design limits may be reached;
- If the loads are mobile; special devices and reinforcement must be considered related to wear, blockage and vibration;

When using fabric as a construction material, and therefore working with tensile stresses, grout and suction anchors could provide a cheap foundation method. Also diverting the loads to the abutments simplify the sill construction drastically and therefore causes less hazards for the navigation and discharge functions of the waterway.

Minimize Complexity of the structure:

A complex structure is more difficult to design and construct. Moreover, a complex structure has inherently higher risks of error and weaknesses that may in turn have a negative impact on maintenance and durability. A simple and robust design of all structural elements decreases the probability of mechanical failure.

One of the main issues when dealing with a fabric barrier is the storage of the fabric when the barrier is in nonuse. When the fabric lays on the sill, currents, especially vessel passing's, could shift the fabric and damage it. In this case the fabric has to be tied or sucked down.

Minimize the structure exposure to environmental loads:

Minimizing the structure exposure during non active periods can enhance durability, reliability and lower maintenance costs. When dealing with fabric some loads, such as UV-light and biomass, are more critical than with conventional construction materials.

Environmental loads are amongst others:

- UV-light;
- Waves;
- Currents;
- Biomass increment;
- Wind;
- Salt;
- Etc.

Other structural aspects of movable gates:

Response or sensitivity to dynamic water and wind loading; the stiffness and the natural frequencies of the structural elements define the response of the structure to dynamic loading. Dynamic loads and vibrations are often normative for the barrier design, they can cause higher stresses and large alternate deflections.

Vibrations can be either mechanical or water flow invoked. The lack of aeration in gate overflow is one of the major causes of vibration.

The closing and opening mechanism of the movable barrier; to move the gate not only an engine and a mechanism is required. The ease of movement is important for abrasion and fatigue. Vibrations from the movements have to be considered during the design.

The number of middle pillars depends on the gate and the load distribution of the gate. A minimum of middle pillars is preferable because of the discharge functions of the waterway and the hinder to vessel navigation.

7.1.4 OPERATION AND MAINTENANCE

Maintenance:

Easy access to the site during the construction period and during its operation and maintenance service is important to minimize the associated costs.

- The gate(s) and its main elements need to be accessible for inspection and maintenance;
- Inspecting and maintaining the elements that are submerged are of especially important. Abrasion is the result of contact with the water current, mainly in the presence of sediment transport. It is particularly important for gates that have under water hinges;
- Replacement should be possible for mechanical elements and steel elements are required to be accessible for inspection;

Operation:

The operation concerns are the ability to control water levels and currents and to handle debris and sediments.

- Wear due to friction is important in the moving parts, such as hinges and wheels. Excessive wear can create deformation, vibrations and alter the load distribution;
- Redundancy is required to maintain acceptable operability in the event that key elements fail;
- Degradation of the structure during its lifespan and during the period of operation;
- The ease of operation and the readiness of the barrier for instant operation when required should be considered. The time before closure and the time of actual closing have to be acceptable;
- It is assumed that leakage is allowed up to 700 m³/s with a storm duration of 1.3 days. This raises the water levels around Rotterdam with 15cm. (see also appendix E);
- Sedimentation on or near the sill must be avoided or taken care of, (some gates flush the sill clean during closure);

7.2 LOADS

In this paragraph a list with loads is given that have to be considered for the movable barrier design. In the previous and next paragraph more elaboration is given. The quantity of the loads are, if needed, given in the corresponding calculations, in this paragraph the different loads are only mentioned.

When designing and dimensioning the barrier a combination of loads in different time interfaces has to be taken into account. The normative head figures that are presented do not occur with the same water-management strategy, nor at the same moment. (For the derivation of the normative head parameters see appendix E.3.)

1. Hydraulic loads:

- 1.1. Hydraulic pressure (horizontal and vertical);
- 1.2. Water heads ²;
 - Spui: positive: 1.4m, negative: 3.8 m;
 - Drecht: positive: 1.4m, negative: 3.8 m;
 - Merwede: positive: 2.4m;
 - Lexmond: positive: 4.4m;
- 1.3. Currents (pressure, vibration, erosion and abrasion);
- 1.4. Waves (force and erosion);
- 1.5. Piping.

2. Other environmental loads:

- 2.1. Wind;
- 2.2. Seismic;
- 2.3. Ice;

² Positive direction is from the river (in this case Haringvliet) towards the Northern Basin around Rotterdam.

- 2.4. Corrosion;
 - 2.5. Temperature;
 - 2.6. UV-light;
 - 2.7. Sediment;
 - 2.8. Biomass increment.
3. **Other loads:**
- 3.1. Own/dead weight;
 - 3.2. Water absorption;
 - 3.3. Ground mass;
 - 3.4. Dynamic (invoked by waves, currents, wind, traffic or mechanical movements);
 - 3.5. Ship collision;
 - 3.6. Ship anchor;
 - 3.7. Debris;
 - 3.8. Industrial impact (explosion, chemicals);
 - 3.9. Transport and installation;
 - 3.10. Operation invoked;
 - 3.11. Abutment surface loading;
 - 3.12. Vandalism.

7.3 REQUIREMENTS

In this paragraph some specific requirements are stated beside the general requirements as stated in chapter 4. Requirements concerning norms and laws are not mentioned.

7.3.1 STRENGTH AND STABILITY

It is obvious that the barrier have to cope with all mentioned loads and combinations of loads. In this paragraph some specific strength and stability requirements are given.

Strength requirements:

- S.1. Hydraulic loads: The structure should be designed to withstand the hydrostatic pressure during the maximum differential head. In addition, the structure should be fully controllable at all design flow and wave conditions, including reverse differential head conditions;
- S.2. The structure should be designed to take the impact forces resulting from ship collision into account or should be protected from such an impact. This presents a loading with a low probability but potentially with high consequences;
- S.3. The structure should withstand the wind effect on loads. The loads include drag forces, wind generated waves including associated waves slamming forces and additional hydrostatic pressure;
- S.4. The structure should be designed to resist wear, UV-light and corrosion and ensure that its structural integrity will not be compromised during the lifetime of the structure;
- S.5. Steel parts that are fixed in concrete or joined to other irreplaceable parts have to be corrosion resistance;
- S.6. Steel construction parts that have to be protected against corrosion in such manner that replacement is needed should be postponed as much as possible with a guaranteed minimum of 30 years;
- S.7. Friction loads need to be considered where applicable as neglecting or underestimation of these friction forces may lead to floodgate failure;
- S.8. Transport and installation loads have to be considered for separated elements;
- S.9. Vandalism may not lead to failure of the structure;

Stability requirements:

- S.10. The foundations should be capable of resisting the forces applied by the structure and loads. The total settlement of the structure should be limited and no sliding or tilting may occur;
- S.11. Side surface loads should be possible in all times, (temporary cranes and such must be possible to come near the barrier structure);
- S.12. The design should minimize flow or wave induced vibrations and oscillations on the structure, and the dynamic response of the structure, or elements of the structure, should be limited;
- S.13. Bottom and bank erosion (and sedimentation) should be prevented;
- S.14. Piping and heave may not occur.

7.3.2 CONSTRUCTION

- C.1. Temporary closure of one of the waterways during construction is allowed for one day;
- C.2. The waterways Beneden Merwede and Dordtsche Kil may not be closed off or reduced in capacity at the same time;
- C.3. During construction one way shipping lane has to be maintained in all waterways;
- C.4. During construction water runoff from the rivers must be preserved;
- C.5. The river bottom around temporary structures and works has to be protected against erosion;
- C.6. Locations with temporary structures and works have to be brought back in the original state after the construction activities;
- C.7. During construction hazards invoked by vibration, dust, noise, building traffic, etc. have to be minimized for the surroundings;
- C.8. During construction the connections with and of the primary water barriers have to be preserved;
- C.9. The construction planning should be robust enough to minimize the (seasonal) weather, river runoff, water levels, currents and tides influences.

7.3.3 OPERATION AND MAINTENANCE

- OM.1. Life-span of elements shorter than 100 year have to be replaceable without influence on the reliability of the movable water barrier;
- OM.2. Closure under current conditions (relatively high water wave) should be possible;
- OM.3. No disturbing noises (vibration, flutter, whistle) or banging noises invoked by wind, currents or waves may occur during non operation conditions;
- OM.4. Debris accumulation along the face of the structure should be prevented; (Because it can hinder closing of the barrier.)
- OM.5. Vessel navigation should be warned before the closure of the barrier. Signs, lights and resting places should be provided;
- OM.6. Vessel navigation must be guided by lights and guiding dolphins through the barrier structure;
- OM.7. Cold weather protection should be provided for the mechanic parts;
- OM.8. An inspection post during storm conditions with sight on the vessel navigation channel towards both sides of the barrier must be available and accessible;
- OM.9. Also a storm shelter visitors side or building has to be provided;
- OM.10. Structural elements have to be easy accessible, inspect-able, maintainable and if necessary replaceable;
- OM.11. The barrier must be accessible from both river side's;
- OM.12. During normal maintenance vessel navigation should be possible;
- OM.13. Large maintenance may disturb vessel navigation for just several hours;
- OM.14. Maintenance and inspection have to be possible with common methods and

means.

7.3.4 COSTS

- Co.1. Costs optimization should be done regarding the total life-span of the structure;
- Co.2. Construction and financial risks (also possible benefits) should be included in the total costs analysis;

7.4 SPECIFIC DESIGN CONCERNS

There are, besides the general design starting points, also specific, or structural, design concerns to be mentioned regarding an 'open fabric' movable water barrier.

7.4.1 SCREEN SIZE AND SHAPE

Length:

The length of the screen determines the angles at the abutments, the load distribution in the horizontal plane and the needed space for the screen. In Figure 21 the symbol definitions are given concerning the length of the screen.

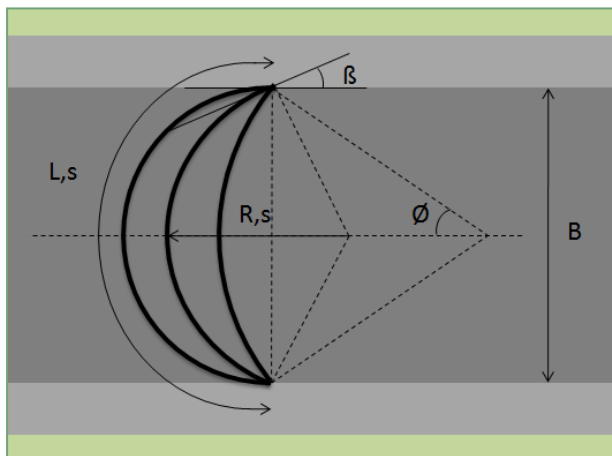


Figure 21: Definitions screen dimensions (1). (top view; L,s=screen length, R,s=radius screen, B= barrier/channel width, β=angle screen-abutment, Ø=angle waterway-abutment.)

A greater screen length (L,s) means a smaller radius (R,s) and more space needed for the screen. A greater screen length also means a smaller angle with the abutments (β) and a larger reaction force parallel to the waterway that has to be diverted towards the substrate. The first one can be considered undesirable, the second desirable because a larger reaction force directed towards (perpendicular to) the waterway is more difficult and thus more expensive to divert (towards the foundation stratum).

The relationships can be described in mathematical form as:

$$\begin{aligned}\beta &= 0.5 * \pi - \varnothing \text{ [rad]} \\ R,s &= 0.5 * B / \sin \varnothing + b \text{ [m]} \\ L,s &= 2 * \varnothing * R,s \text{ [m]}\end{aligned}$$

An 'open fabric' barrier can have a good seal with the abutments without attaching the screen to the abutments. If the screen is long enough, with some additional length, the hydrostatic pressure will press the screen against the abutment. A housing or special shaped abutment is not needed, however, friction wear of the screen can occur. (Regeling 1989)

Possibly a synthetic (low maintenance smooth material) that is placed against the concrete abutments can increase the life time of the screen.

Width:

The width of the screen determines the upper and bottom angle (α,t ; α,b), the 'connection length' (c) and the load distribution in the vertical plane. In Figure 22 the symbol definitions are given concerning the width of the screen. (Within these cross sections the screen is connected to cables at the bottom and top of the screen; called from now on resp. the lower and upper cable.)

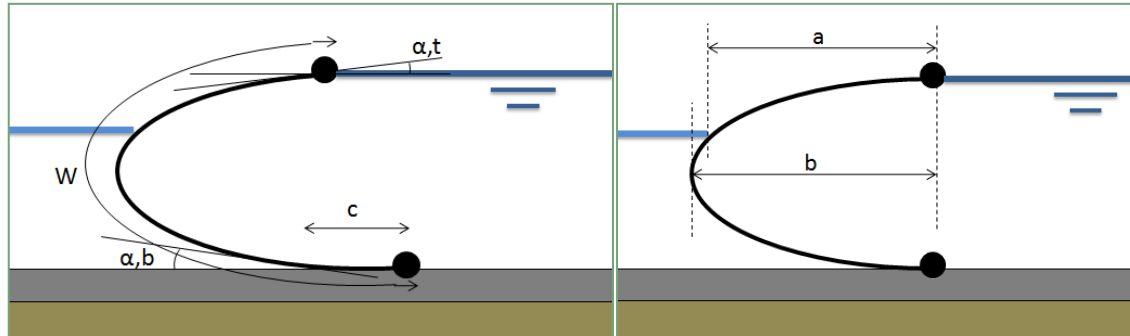


Figure 22: Definition screen dimensions (2). (cross section; W =screen width, c = screen 'creep length', α,t =top angle screen, α,b =bottom angle screen, b = 'cross screen width' = $R_s - R_c$, a = 'cable low water line' length.)

The relationships between the parameters are depending on the shape of the screen which cannot be predicted with simple model calculations. Not only the screen width of the screen (W) but also the way of dealing with the vertical loads in the design (guys (stay ropes), hydraulic jacks, several struts, etc) is important for the different parameters.

The dimension a , b and c are linear dependent on the screen width, as can be seen in Figure 23 (left). They are not linear with the water head over the barrier. (See Figure 24, left.) Especially the 'creep length' diminish with a larger water head over the barrier.

A short screen width invokes high tensile stresses in the screen. (See Figure 23, right.) Particularly the vertical stress component is (very) high with a short screen width. (The angle at the top of the screen with the horizontal plane is (very) large.) The vertical component diminish rather quickly with increasing screen width.

In Figure 22 it can be seen that the screen stresses, in particular the vertical component, increases not linear with the water head.

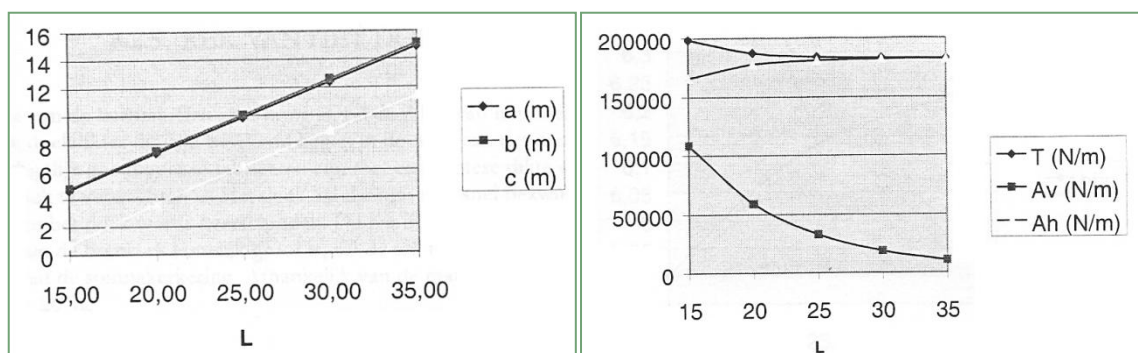


Figure 23: Screen dimensions and stresses vs. screen width. (L = screen width, T = tensile stress, Av =vertical component, Ah =horizontal component.) (Driessen 1998)

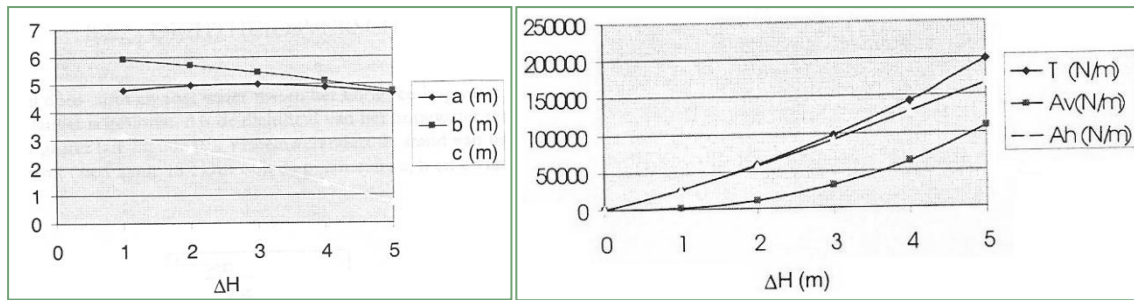


Figure 24: Screen dimensions and stresses vs. water head. (L =screen width, T = tensile stress, A_v =vertical component, A_h =horizontal component.) (Driessen 1998)

(These graphs are calculated with differential equations for a “spinnaker” barrier with a high water level of 10m, a low water level of 5m (if not variable), a screen width of 15m (if not variable) and no strain. If strain is taken into account, 20% for a PA-rubber screen, a 15m screen will be 18m with the corresponding form of a screen with a 18m screen width. See also Figure 26, left.)

The ‘creep length’ (c) has a minimum length to keep the underside of the barrier water tight. This is important because a water flow underneath the screen can cause mayor dynamic loads and leakage. Hydraulic jacks in the abutments (for instance) can help to keep the bottom cable down as well.

Perhaps there are possibilities to decrease this required length by detailing the shape of the sill in such a manner that current-attack and or even uplift is impossible. See Figure 25 for two examples.

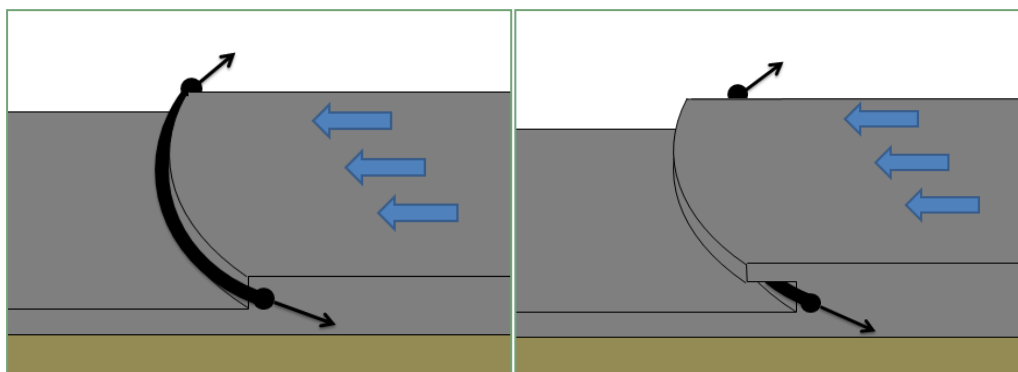


Figure 25: Reducing the ‘creep length’ by detailing sill.

However due to elongation (under tensile stress) of the screen and cables the sill structure will get more complex and expensive.

Shape:

To understand and provide more inside in the four graphs from above two additional graphs are presented in Figure 26.

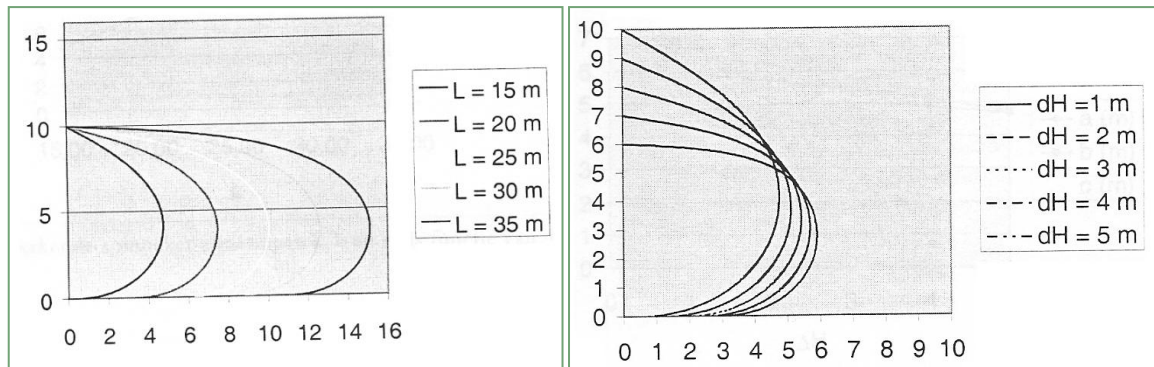


Figure 26: Different shape "spinnaker" barrier due to different screen widths (left) and water heads (right). (L=screen width, dh=water head) (Driessen 1998)

On the left several screen shapes are drawn for different screen widths (water head is 5m), and on the right for different water heads (screen width is 15m).

7.4.2 FOLDING, SHIFTING AND V-NOTCH

The overall shape and design details of the 'open fabric' barrier determines the extent of folding ("plooi" in Dutch) of the screen. Folding of the screen is a great concern because it induces peak stresses in the fabric. For the "balgstuw" at Ramspol a design safety factor of 3 was introduced just for this phenomenon. In later tests a factor of 1.7 was obtained. (GSW 2002) (J.S. Reedijk, Delta Marine Consultants 2004)

Because the screen of the "balgstuw" is connected with the sill and abutments, with the help of a clamping mechanism, folding of the screen was required to keep it run along at the ramp of the abutment. In Figure 27 the clamping mechanism is shown and at the back the sloping abutment can be seen.



Figure 27: Connection between screen and sill of the "balgstuw" at Ramspol.

The clamps itself also can cause peak stresses if they are not tightened enough. The forces have to be transferred from the screen into the sill by friction between the fabric and the concrete, and not by the steel pins that penetrate the fabric. If this occurs tearing of the fabric is possible. There are clamping mechanisms that do not penetrate the screen and make use of a steel rod where the fabric is rolled around.

The folding of the screen at Ramspol is good visible in Figure 28 left picture. Also shifting of the entire "balg" / screen is visible at the right picture.



Figure 28: Folding and shifting of the “balgstuw” at Ramspol. (High water on the left side.)

This shifting of the screen also induce secondary stresses (in the screen) due to the connection with the abutments. With an ‘open fabric’ barrier where no stiff clamp connection is made with the abutments these secondary stresses will not occur.

There will be shifting of the screen due to the loads and elongation (of the screen and cables) that can cause friction wear problems. Also some folding of the screen will occur, however less severe.

Assuming a “spinnaker” type of barrier where the hydraulic loads are distributed by horizontal cables (at the top and bottom of the screen) towards the abutments: then folding of the screen will occur near the cables (top and bottom of the screen) due to the fact that the length of the cables (L_c) and the length of the screen (L_s) are dissimilar. See Figure 29 for illustration. (The radius of the upper and lower cable can be dissimilar as well, but that is for now not assumed.)

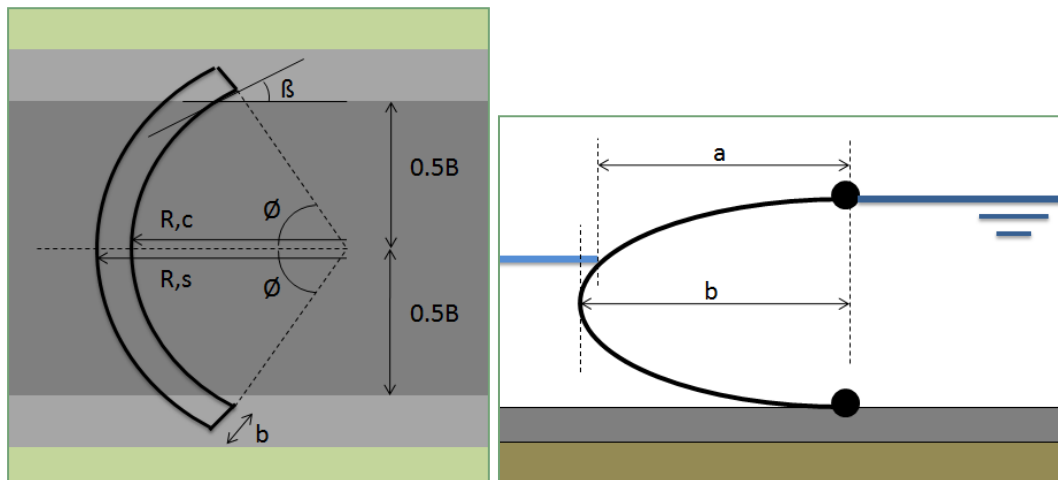


Figure 29: Definitions screen dimensions (3). (R_s =screen radius, R_c =cable radius, B =barrier/channel width, β =screen-abutment angle, ϕ =screen-waterway angle, b =‘cross screen width’= $R_s - R_c$.)

The folding will increase with a smaller radius. The relationships can be described in mathematical form as:

$$\begin{aligned}\sin \phi &= B/2R_c \\ \beta &= 0.5\pi - \phi \\ L_c &= 2\phi R_c \\ L_s &= 2\phi R_s \\ R_s &= R_c + b\end{aligned}$$

A measure for folding can be derived: $folding \cong L_s - L_c = 2\phi b$

The folding can be prevented by stitching several strips of fabric together. The costs of such an adjustment can be high. Nevertheless the “balg” at Ramspol is ‘welded’ together out of three meters wide strips.

A third issue, when dealing with a fabric water barrier, is the so-called ‘V-notch’. Such a disturbance on the shape of the “balg” can be seen in Figure 30.



Figure 30: An inflatable dam with a 'V-notch'.

This ‘V-notch’ can occur while the barrier is closing, or in other words when the bellow, “balg”, is filled. When the barrier is further filled this notch will disappear. However this phenomenon can also occur when a relatively large wave, or another initial disturbance, pulls or presses the “balg” down and a water flow over the barrier is triggered. The barrier is unable to restore its original position if the water flow is strong (large) enough. To break the stream small rubber flaps could be ‘welded’ onto the “balg”. This phenomenon (induced by an initial displacement) could also happen with an ‘open fabric’ water barrier.

7.4.3 DYNAMIC LOADS

Another concern, that is already mentioned in a previous paragraph, is the dynamic response of the structure. Stiff elements in the design and the number of connections between the screen and stiff elements can have great influence on the dynamic response of the structure.

The natural frequency of a “spinnaker” type barrier is the order of 3 to 7 seconds and is therefore relatively easy to have a resonating response. When the head over the barrier is larger, the natural frequency is lower. (Driessen 1998)

Dynamic loading occurs during closing and opening of the structure by currents and due to wave loading.

The first dynamic loading is restricted by a controlled closing mechanism and slow closure. An abrupt closure causes large dynamic effects that are highly undesired. Also translation waves can occur.

A relatively late decision for closure, with thus higher initial flow velocities gives high stresses during closure of the barrier and invokes large amount of erosion to the bottom and sides of the waterway. If the barrier is closed early, which is only possible with a good water level predictions, these loads are diminished.

An ‘open fabric’ water barrier that is closed only horizontal cause concentrated high flow velocities at the abutments and requires extensive bottom protection measurements. This way of closure is unstable and uncontrollable.

Looking at a “spinnaker” type barrier where the screen is first transported (horizontal) over the water to the other side of the waterway and after that vertical closed, the cable forces during

transport (that are relatively high) can be reduced by keeping the upper and lower cable together.

The vertical movement (when closing) can be controlled when lacers are applied (between the upper and lower cable). This way the induced currents underneath the barrier are well spread over the entire width of the waterway.

(Regeling 1989)

The second, wave induced dynamic loads, are less important. The top of the screen can move slightly up and down like a vibrating string. Though the barrier is not expected to be unstable. When the head difference over the barrier is relatively large, then the hydraulic pressure dominates the response of the barrier. Just after closure the water heads are low and resonance of the barrier has to be considered.

The wave induced dynamic loads are partly controlled by the water mass that is semi trapped in the barrier. In Figure 31 this water mass is indicated. (Driessen 1998)

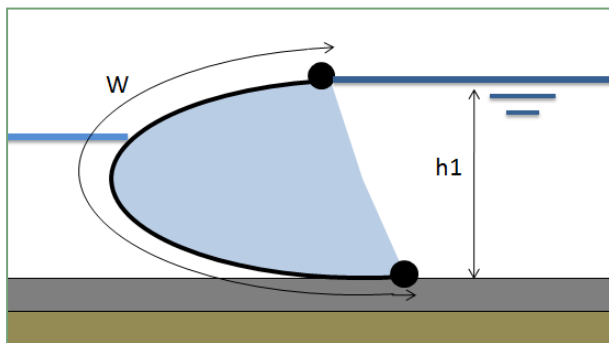


Figure 31: Damping dynamic loading due to water mass. (W =screen width, h_1 =high water level.)

The water mass acts like a 'dashpot' on the movement of the screen. The width of the screen determine the amount of water that is mobilized for damping the movement of the screen; a longer screen provides more damping.

Furthermore, the wave loads are not of great concern for the UOOC barriers because the waves that can be expected are relatively small.

Waves have little influence on stresses in the screen and cables, however they have influence of the top angle of the screen and therefore the required vertical reaction force: for instance the buoyancy of a floating body at the top of the screen. (Assuming that the floating bodies follows the water movement of the barrier.) (Driessen 1998)

The natural frequency must be relatively small or large to avoid resonance. (In the case of a "spinnaker" type of barrier it can be expected that the upper cable will vibrate and deform in the vertical direction due to different wave loading at the middle and sides of the barrier.) The ratio between cable length, screen length and the barrier width has to be small to get the natural frequency (of a "spinnaker" type barrier) lower. This gives a more expensive structure because the screen and cables are almost perpendicular to the abutments. As mentioned a load distribution that is parallel to the abutments is more desirable. This is possible for different barrier design than a "spinnaker" type of barrier. (Driessen 1998)

If no long waves are to be expected, which is in the case for the UOOC barriers, a large natural frequency could be a better option. A large length – width ratio and a long screen has to be chosen to get a large natural frequency. In addition with increasing heads, which are relatively high for the UOOC barriers, the natural frequency will further decrease. (Driessen 1998)

Because of these contradictions more detailed research is required about the wave climate and sensitivity of the UOOC barriers whit difference sized screens.

If the top of the screen of an 'open fabric' barrier is connected to a stiff element such as a bridge or the screen is clamped to the sill it can be foreseen that the dynamic behaviour of the barrier (mainly wave induced) is highly altered.

Research into the dynamic behavior of the UOOC barriers has to be done and is more essential for 'open fabric' water barriers than conventional water barriers. (Wave data at the barrier locations are required with local effects and differences in wave intensity in the middle and along the abutments of the waterway.) Within this thesis the dynamic loads and response is only discussed and taken with safety factors into account. They are not calculated because literature indicates that the dynamic issues are solvable without extreme measures.

8 'OPEN FABRIC' BARRIER SELECTION

In this chapter variants of an 'open fabric' barrier are created, discussed and analyzed. One variant will be selected for a constructive design with the help of a multiple criteria analysis.

8.1 VARIANTS

8.1.1 DESIGN-TREE

A design-tree is a helpful tool to explore new designs. In appendix H.1 a design tree is presented for an 'open fabric' movable water barrier. Four main types are characterized, where two of them are further divided, namely: 'single' and 'modular'. The deviation is further made on load distribution, horizontal and vertical, and possible closing mechanisms. Several design sketches of different 'open fabric' movable water barriers are made and presented in the same document. In Figure 32 the four main barrier types are illustrated.

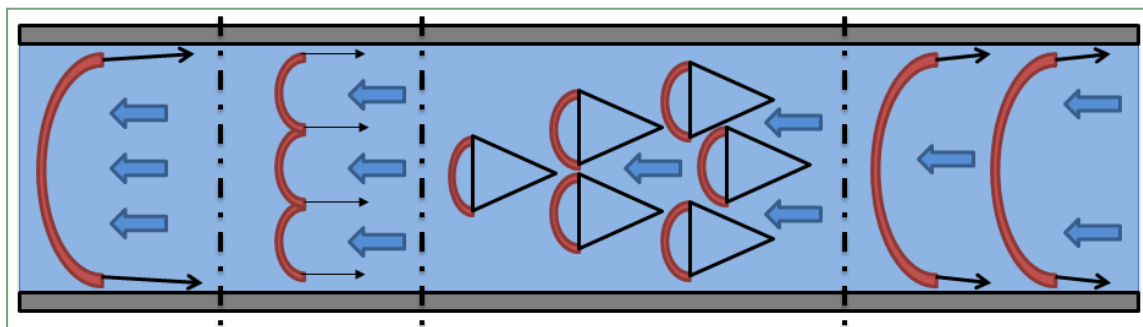


Figure 32: Main 'open fabric' barrier types: 'single', 'mattress', 'modular' and 'stepped'. (Top view.)

'Single':

A 'single open fabric' barrier is described by using only one curtain (or two acting as one) to close off the barrier width. (During the literature study it was found that all the 'open fabric' barrier types are of this type. See also appendix A.)

'Mattress':

The 'mattress' solution is prescribed as a multiple curtain solution where the load distribution is depending on all the curtains.

This type of 'open fabric' barrier is not further divided in the tree for practical reasons. However, the idea is sketched and taken into consideration.

'Modular':

The 'modular' solution holds independent curtains that invoke resistance for the water-flow. This solution is only applicable when a relatively high leakage of the barrier is allowed.

'Stepped':

The 'stepped' barrier is described by multiple curtains placed in series decreasing the water head step by step.

A barrier where only floating bodies are used for distributing the vertical hydraulic load seems to be unpractical because of the needed size of the floating bodies.

A 'stepped' barrier, where the head per barrier is diminished up to 1m, does not take this practical problem away. As calculated in appendix H.2 the floating bodies are still several meters in diameter. Different forms of floating bodies or extra structure elements for distributing the vertical loads is needed.

Because the closing material, the gate, is made out of fabric and is a relatively cheap material the stepped barrier could be an option when other elements of the barrier are simplified to a great extent. This is kept in mind for further improvement of the barrier design.

8.2 SELECTION

In appendix H several variants / design concepts are produced and some of them are further discussed. The mentioned criteria (complexity, risks sensitivity, ease of operation, maintenance, storage screen and navigation) are taken into account.

A costs analysis for each variant is not made because of practical reasons: an accurate costs prediction, that is needed to indicate a difference between the variants, is at this point not attainable. Within the criteria the costs are indirectly accounted for.

The variants have to fulfill the requirements as stated in chapter 4 and 7. The most important requirements are: closing under flow conditions (of a high river runoff) and the Spui and Drecht barrier have to be able to divert a water head in both directions.

Furthermore, some of the variants have more potential than the others when considering the following design issues:

- Complexity of the structure and closing mechanism should be minimized and submerged hinges and other steel elements increases maintenance time and costs;
- Designs with the fabric stored on or in the sill induce design problems of wear and tear of the fabric;
- Designs with only floating bodies to divert the vertical water pressure are bound to have large floating bodies or long screens and are therefore less desirable.

Five variants are presented that are probably suitable for the UOOC barriers. After that the variants are compared with one another. For elaboration on the variants and comparison see appendix H.2.

8.2.1 SPINNAKER

The “spinnaker”, see Figure 33 and Figure 34, is designed by prof.dr.ir. J.K. Vrijling in the 80ties. The barrier has a horizontal load distribution with at the top and bottom of the screen several cables made from synthetic fibers.

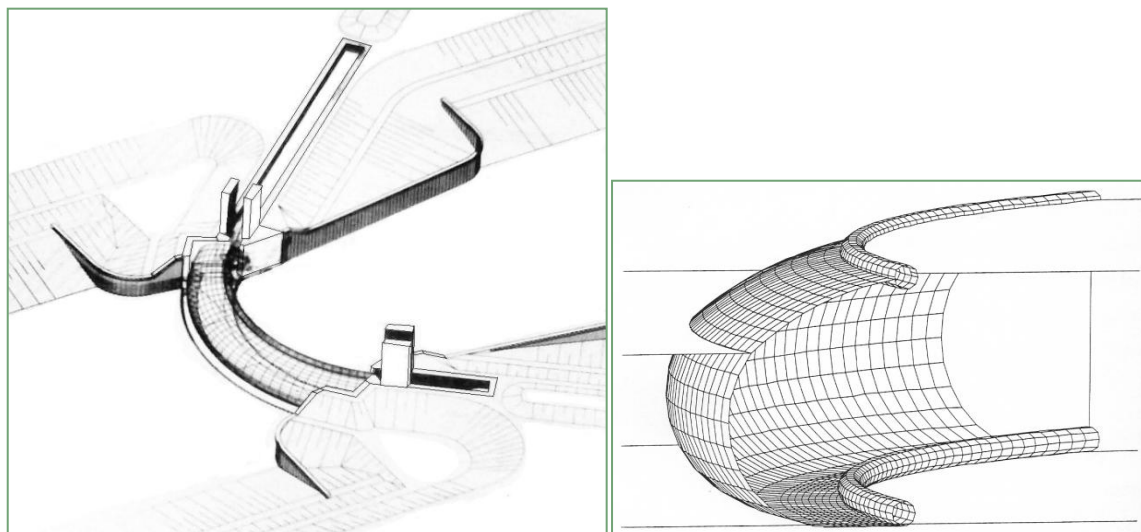


Figure 33: “Spinnaker”. (J.K. Vrijling) (Top view (Regeling 1989), 3D screen (Driessen 1998))

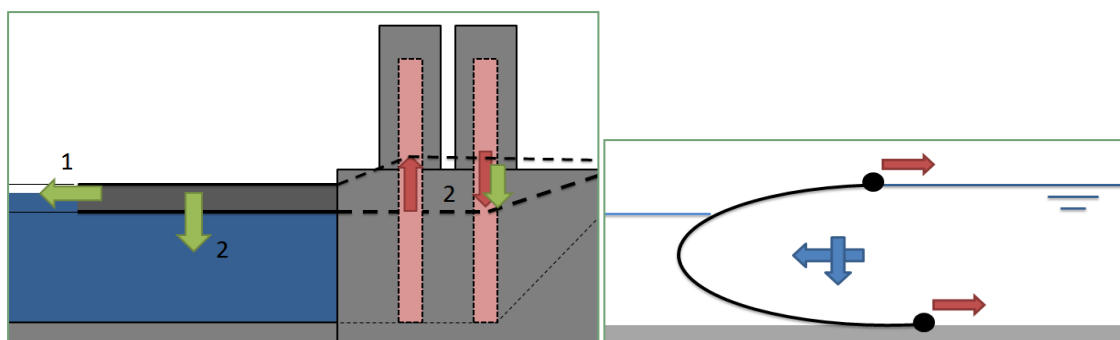


Figure 34: "Spinnaker" cross section abutment, cross section screen.

The screen is stored in one of the abutments and when needed pulled (drifting on the water-surface) towards the other side; the transport phase. After that the lower cable is lowered with two hydraulic jacks located at the abutments. The sill is washed clean from sediments due to the vertical closure from above.

With the help of hydraulic jacks at both abutments the hydraulic pressure and flow (impulse) and a small floating upper cable ensures that the screen stays open. Thus the barrier is water tight due to the water pressure that presses the screen onto the sill and the abutments. The hydraulic jacks have to withstand not only the vertical but also the horizontal forces.

Despite of several model test and researches that are confirming the "spinnaker" barrier is possible. The barrier is never designed in detail, let alone ever constructed. (Regeling 1989) (Driessen 1998) Perhaps this is due to the relatively uncontrolled movement of the screen during transport and closing phase, which induce high dynamic (and normative) loads on the cables, and the uncertainties about the probability of failure. Also the strength and required train of the materials, this cause all Dyneema® fiber based, where uncertain.

Nowadays, the strength of synthetic materials is increased, the possibility to predict the behavior of such a barrier is improved and the probability can better estimated.

The model test that was made in 1989 by Delft Hydraulics, (Regeling 1989), was a model test of a barrier with a width of 53.6m, radius 35.0m and a screen length of 76.8m. The required width for the UOOC barriers are around the 200.0m instead of 53.6m. It is questionable if the barrier will still function with these large widths. The loads induced by the screen transport will increase tremendously and the same holds for the closure of the screen. In addition the vertical reaction force that the hydraulic jacks can deliver during operation are assumable too small.

Four hydraulic jacks, a mid-sized screen length, and several large cables (due to the large width of the UOOC barriers, when using one screen) are required for this barrier.

The barrier can be suitable for a large negative head with some adjustments to the storing-location of the screen and to the foundation. The "spinnaker" is in principle suitable for all four the UOOC barriers if a greater width can be obtained, or middle pillars are used.

8.2.2 SUPPORT TOWERS

In Figure 35 the so called 'A-frame' concept is presented. The figure is only for indication because the height of the pylons cannot be estimated without calculations about the load distribution and comparison of costs between the height of the pylons and the width of the screen. Presumably the pylons can be somewhat lower, however, to divert the vertical hydraulic loads a minimum pylon height is required.

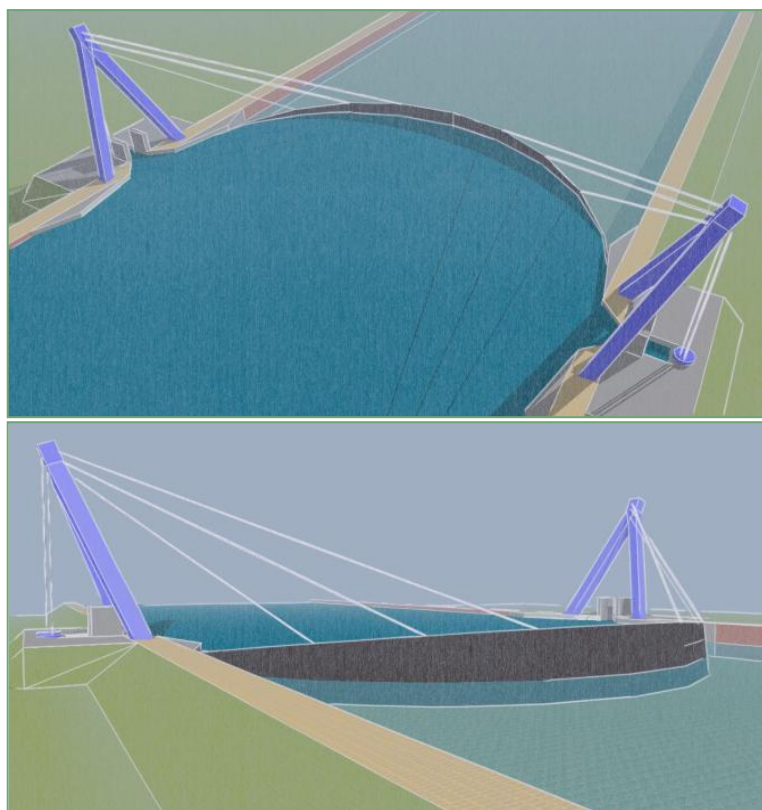


Figure 35: 'A-frame', support towers and guys, design concept.

The guys and support towers distribute the vertical and (part of) the horizontal loads. At the underside of the screen a cable (or cables) is attached and diverts only horizontal force toward the abutments. This cable is kept in place by a hydraulic jack on each side. The jacks also controls the closing and opening of the barrier. (It is assumed that the hydraulic jacks are strong enough to overcome the loads due to the undertow current.)

The screen is stored directly on the 'A-frame' pylons and the barrier is closed similar to the "spinnaker" barrier. The only difference is that the screen can be better controlled during the transport and closing phase.

A benefit of this structure is that the needed length of the screen is relatively small because large vertical force can be distributed, furthermore the diameter of the horizontal cables can be reduced. Another mayor benefit is that this barrier design concept has the potential to be suitable for great channel widths. A barrier width of 200m should be possible and therefore no constriction of the waterway or middle pillars are required. But he most important benefit is that this barrier can divert water from both sides as sketched in Figure 36. It is assumed that this is required for two of the four UOOC barriers.

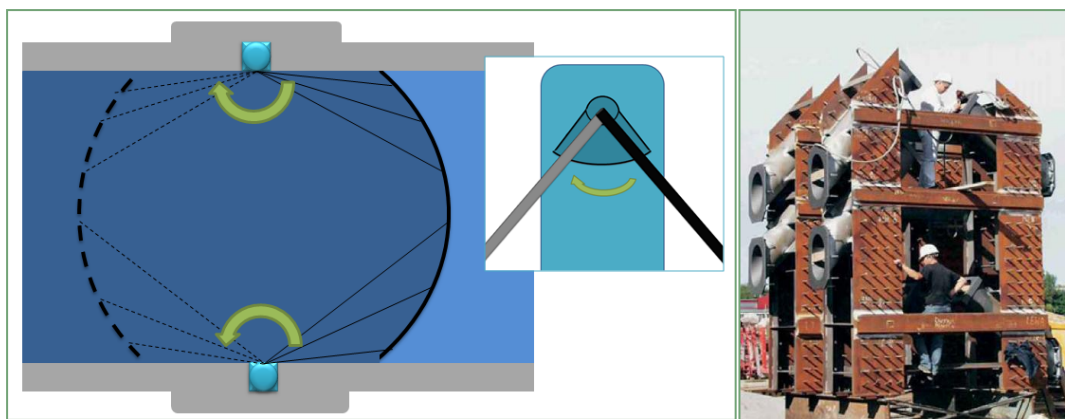


Figure 36: Left: diverting positive and negative water head. Right: Prefabricated top of the pylon, Martwa Wisla River Bridge, Gdansk, Poland.

The guys are not connected to the support towers, but are running through a steel frame (which is not new) that gives space for movement (which is new).

The closing mechanism can be similar to that of the “spinnaker” barrier.

Due to the complexity of diverting a large negative head as well, the barrier is only suitable for the Spui and Drecht barrier. Especially for the Drecht barrier because a ‘support tower’ barrier can be designed as an unique landmark.

8.2.3 BRIDGE+SCREEN

The combination of an ‘open fabric’ movable water barrier and a bridge could be promising because the load distribution of the two structures can be combined. Furthermore the possibilities to store and close the barrier are increased and the behavior of the barrier when closing is more controlled and predictable. In addition the screen length can be relatively short due to the possibility of a large vertical load distribution.

The width of the waterways that have to be closed off in the UOOC concept are in the order of 200m. This is ideal for a suspended guyed/stay roped bridge.

In Figure 37 a rough sketch is given of a ‘bridge water barrier’.

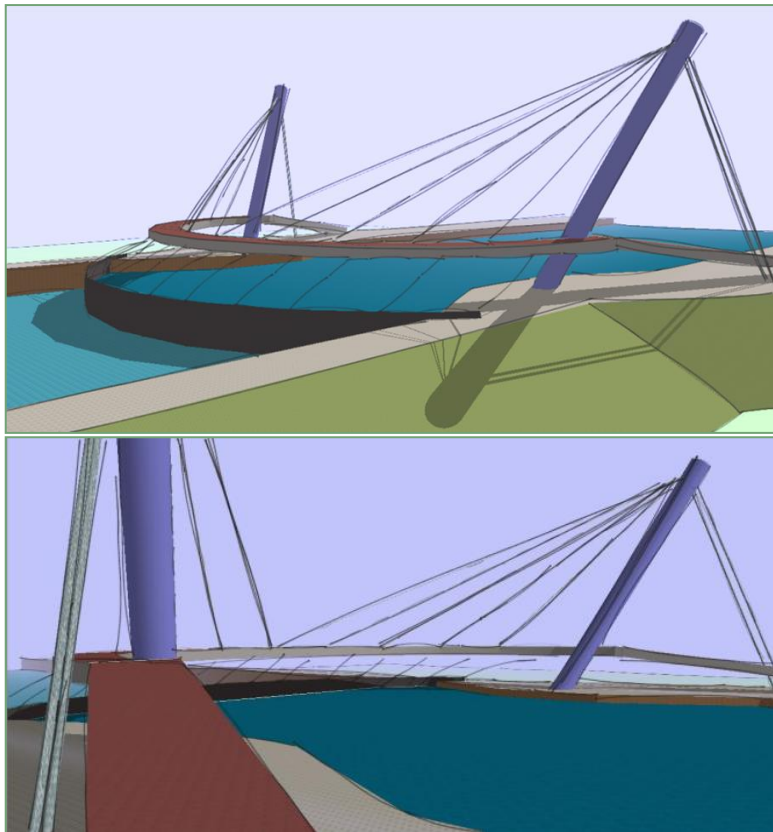


Figure 37: Fabric water barrier combined with a bridge.

Several closing mechanisms and screen storage possibilities are discussed in appendix H.2. One of the options is to store the screen in a building next to the barrier itself. When needed the screen is attached to the bridge and lowered into the water. However due to the fact that heavy machines have to be available at all times and that the closing of such a barrier is highly depended on humans and their possible mistakes, this concept is not further considered. The closing concept, as illustrated in Figure 38, is the assumed to be the best option. In potential this storage and closing system has more benefits, or lesser disadvantages, than the other concepts that are discussed in appendix H.2.

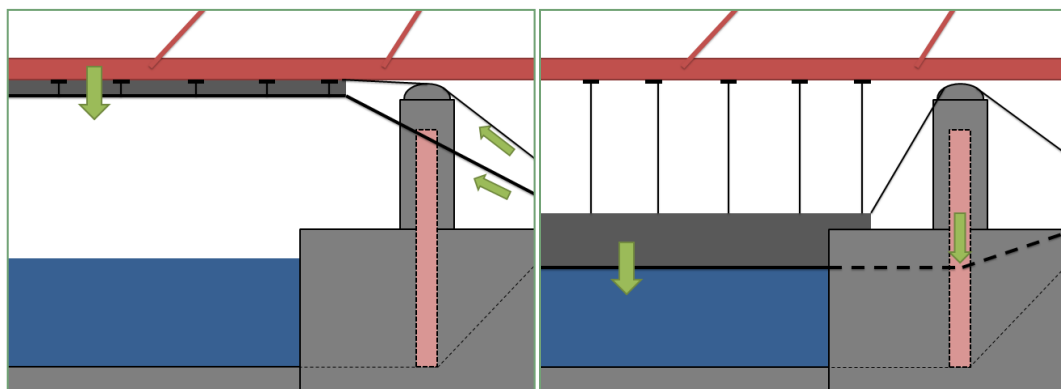


Figure 38: Operation bridge barrier concept 6; 'vertical-vertical'.

The screen is stored under the bridge and thus raised out of the water, wherefore loads such as wave induced wear during storage and biomass growth do not have to be considered. The storage and release system of the screen have to be designed in such manner that it insures a sheltered storage against wind loads, UV-light and vandalism, and also insures a robust (simple)

releasing mechanism. Whether this is possible considering the dimensions of the screen and the bridge has to be investigated.

The screen is lowered (with help of the upper cable) until it reach the water surface. After that two hydraulic jacks (one at each abutment) will pull the screen further down with the help of the lower cable. (It is assumed that the hydraulic jacks are strong enough to overcome the loads due to the undertow current.)

The bridge ensures that there is more control, in contrast to the “spinnaker” barrier that has a similar closing mechanism, of the movement and the (lower) dynamic forces during transport and closure of the water barrier.

Also the dynamic response to wave loading is altered and resonance is assumable less likely to occur. Instead of a creating a relatively low natural frequency with a relatively large screen width, it is now possible to design the screen width (very) short. This gives a relatively high natural frequency (in comparison to the wave loading).

This barrier could be an option for the Merwede barrier where recreation can be enhanced by construction a pedestrian bridge that connects the villages at the North of the Beneden Merwede with the “Biesbosch” at the South.

8.2.4 VISOR+FABRIC

The Visor gate (see Figure 39) is designed in the 50ties and three similar visor gates where constructed in the Netherlands along the river Lek at Amerongen, Driel and Hagestein.



Figure 39: Vizor gate (wier) Amerongen.

The First design idea was to bent the gate in the vertical and horizontal plane to get only tensile stresses in the gate and thereby minimizing the amount of steel that was required. However, the manufacturing of such a gate was too complex for that time and the gates where designed to only bent in the horizontal plane. (De waterstaat 1952)

When the gates were constructed bending in both planes the steel gate would be similar to a fabric screen. In Figure 40 the steel gate is replaced by a screen with at the bottom a stiff element (from steel or a hard synthetic material that is bended in the horizontal plane) and at the top a cable.

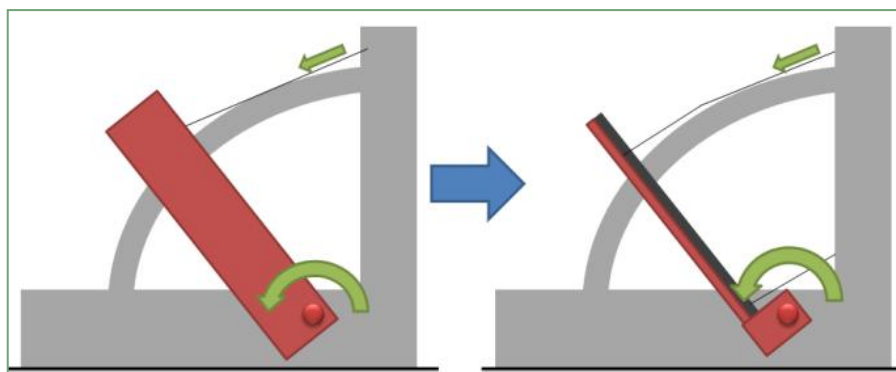


Figure 40: Steel gate replaced by fabric screen.

There are now two closure steps, first the entire gate is lowered and second the cable(s) that are connected to the (cable at the) top of the screen has to be kept under tension and keep the screen elevated.

The stiff element ensure a water tight connection with the concrete sill and at the side the gate is (similar to the original design) encased in the abutments which insures (almost) a water tight barrier.

The still element has to be designed able to divert the tensile stresses when the barrier is closed, the pressure stresses when the barrier is open and the bending loads during closure.

The water barrier is not suited for diverting a negative head. The barrier is probably suited for closure during flow conditions, and for opening under a head difference.

The width of the barrier can be larger than the present Visor weirs because of the light gate, which also decrease the number of required middle pillars. In addition the light gate also makes the closing and opening of the gate more easily.

The maintenance costs of the barrier are discussible; more research concerning maintenance of the gate, moving parts and replacement screen is required.

This new generation Visor barrier could be an alternative for the Lexmond barrier because the existing Visor weirs are located along the Lek. However the mentioned desire to have a low visibility barrier with a low impact on the surroundings is, of course, in contradiction with the high design.

8.2.5 SIDE WING

This movable water barrier concept distributes the hydraulic loads in the horizontal plane towards the abutments. From both sides, where the screen is stored, the barrier closes by means of several cables. The screen is retained in vertical position with the help of vertical floating bodies. The cables are attached on these bodies. See Figure 41 for an illustration of two 'mattress' water barriers. At first sight the barrier seems to be straightforward, however the complexity increases when looking into more detail.

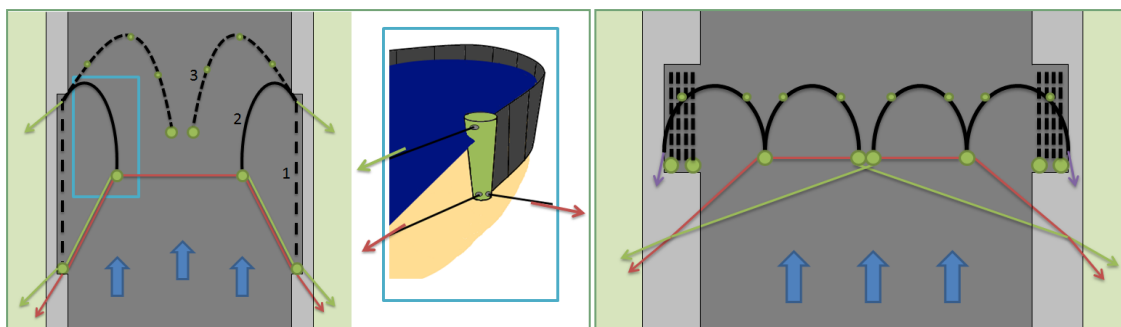


Figure 41: 'Side wing' design concept 1 and 2.

The floating bodies can be made from a synthetic material and together with the screen the buoyancy is similar to the weight of the elements. (No vertical hydraulic loads are present.) These bodies stiffen the screen in the vertical plane and prevent the so called 'V-notch'.

More research is required about the wear and tear, leakage and the dynamic response during closure and operation of the barrier. The stability of the 'side wing' barrier cannot be guaranteed without extensive model testing. (See appendix H.2 for elaboration.)

Also the dimensions of the barrier, especially the floating bodies in comparison with the (large) cables, have to be designed in more detail before anything can be said about the feasibility of the barrier.

The 'side wing' could be an option to look into for the Lexmond barrier. However this concept has challenging structural design issues.

8.3 COMPARISON

8.3.1 MULTI-CRITERIA ANALYZES

In a small multi-criteria analyzes the five barrier types are compared with each other and to a lesser extent with conventional movable water barriers.

The following criteria (from chapter 7) are considered:

<i>Width:</i>	large width is desired without middle pillars
<i>Negative head:</i>	the possibility of diverting a large negative water head
<i>Surface screen:</i>	small surface is desired (considering costs, installation, movement)
<i>Dynamic behaviour:</i>	barrier/screen response to dynamic loading
<i>Complexity sill:</i>	a simple sill design is desired (considering costs and construction time)
<i>Complexity abutments:</i>	the more complex the more expensive
<i>Control during closing:</i>	control of movement to a large extent is required to diminish sudden (dynamic) loads
<i>Maintenance:</i>	frequency and the amount of maintenance that is required
<i>Inspection:</i>	the possibility and ease of inspection (of the screen and movable parts)
<i>Flexibility:</i>	the possibility to alter or modify the barrier at later state
<i>Probability of failure:</i>	low failure probability is required; the complexity of the closing mechanism is one of the main concerns.
<i>Needed space:</i>	the total amount of space that is required for the barrier
<i>Peak stresses:</i>	folding / buckling of the screen

In Table 6 the comparison is made with simple indication from not at all suitable (--) to very suitable (++)

	Spinnaker	Support tower	Bridge + screen *)	Visor + fabric	Side wing
<i>closing mechanism</i>	4 hydraulic jacks	2 hydraulic jacks + 2 pylons	2 hydraulic jacks + bridge	hinged + support towers	cables
<i>load distribution</i>	horizontal (cables)	horizontal (cables) + vertical (guys)	horizontal (cables) + vertical (guys)	horizontal (cable + stiff element)	horizontal (cables)
<i>barrier width</i>	0	++	++	0	+
<i>negative head</i>	++	+	--	--	-
<i>surface screen</i>	+	++	++	+	--
<i>dynamic behaviour</i>	-	0	++	++	--
<i>complexity sill</i>	++	++	++	+	++
<i>complexity abutments</i>	-	--	-	--	0
<i>control during closing</i>	-	0	+	++	--
<i>maintenance</i>	++	+	+	0	+
<i>inspection</i>	++	+	+	0	+
<i>flexibility</i>	++	0	-	-	++
<i>probability of failure</i>	-	-	+	++	0
<i>needed space</i>	+	+	++	--	+
<i>peak stresses</i>	-	+	++	0	+

Table 6: Variant comparison. (+ is good – is bad; *) considering the barrier, not the entire bridge.)

With no priority for the criteria one can conclude that the 'bridge + screen' variant is the best option for further design. When no bridge is desired the "spinnaker" or the 'support tower' barrier are better options than the 'visor+fabric' or the 'side wing' variant.

8.3.2 VERTICAL LOAD DISTRIBUTION

Another comparison can be made when looking at just the vertical load distribution. A strong relationship exists between the structural element that has to divert the vertical loads and the width of the screen.

In Figure 42 three different 'open fabric' barriers are sketched and the required dimensions for the screen are indicated. In dark green (and bold figures) an estimation is made for the Beneden Merwede UOOC barrier.

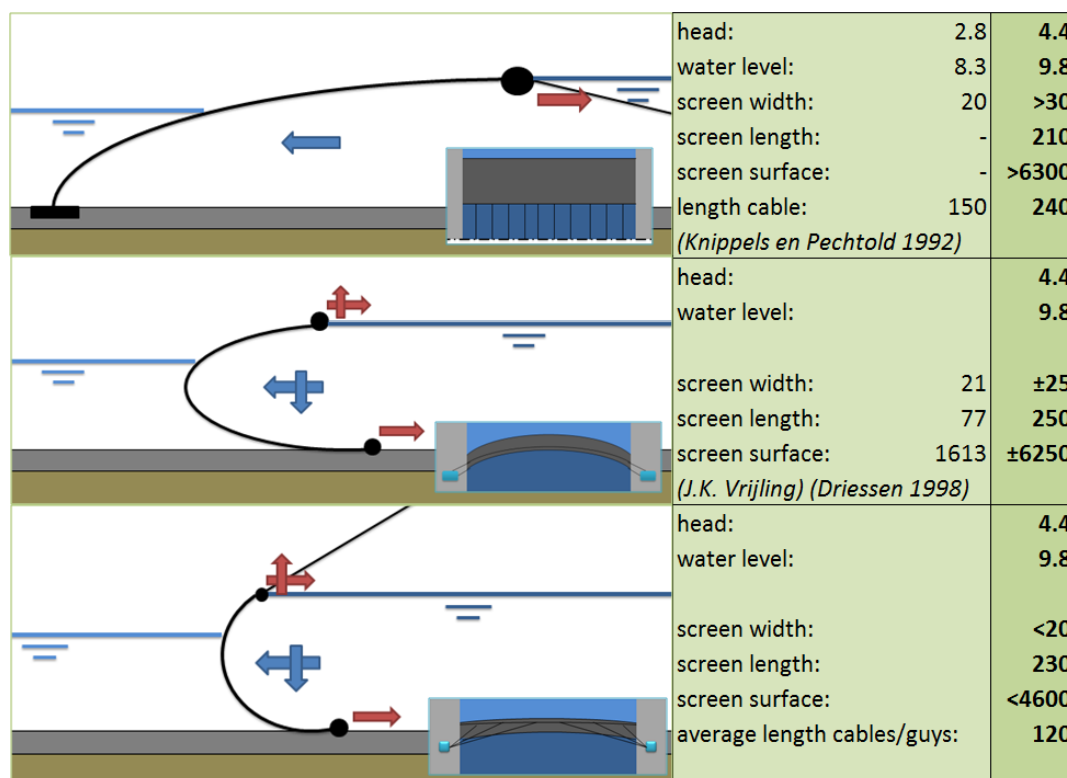


Figure 42: Comparison/indication screen length for different 'open fabric' designs. (Cross section and small top view.) [m]

The first has floating bodies to overcome the vertical loads. (These are in this case not directly induced from the water pressure, but from the weight of the screen and cables and the forces in the cables.) To keep the floating bodies within the 2m diameter the width of the screen has to be large. The length of the screen is equal to the width of the channel.

The second barrier is a "spinnaker" type of barrier. The hydraulic pressure/water flow, small floating upper cable and hydraulic jacks at the abutments keep the screen open. The screen length lays somewhere between 1.2 and 1.4 times the barrier/channel width. This is due to the small radius that is required to divert the loads for the greater part parallel to the waterway.

The third barrier is an 'open fabric' barrier combined with support towers or a bridge; 'guy supported' water barrier. Because of the possible large vertical component the screen is more lifted and the width is relatively small. The length of the screen is between 1.0 and 1.3 times the barrier/channel width. This is depending to which extent the pylons diverting the horizontal water pressure as well.

It is clear that the total horizontal load that has to be diverted (by the cables) to the abutments is larger with a larger screen length.

For the "spinnaker" and the 'guy supported' barrier a limitation, in the minimum screen-waterway angle ($\varnothing$) and thus in the minimum screen length, is given by the perpendicular (in respect to the waterway) reaction force in the abutments. As mentioned a large perpendicular force is not (at all) desired. The threshold between the distribution between perpendicular and parallel is (of course) 45 degrees.

In the final design a comparison have to be made between foundation costs of perpendicular reaction force and the screen length. These costs are depending on the substrate, water head, channel depth and channel width.

A shorter screen width induce higher stresses in the screen especially due to the increasing vertical load component.

The vertical load is a function of the creep length (c), upper and lower screen width (resp. a,u and a,l). (See Figure 43 and Figure 44.)

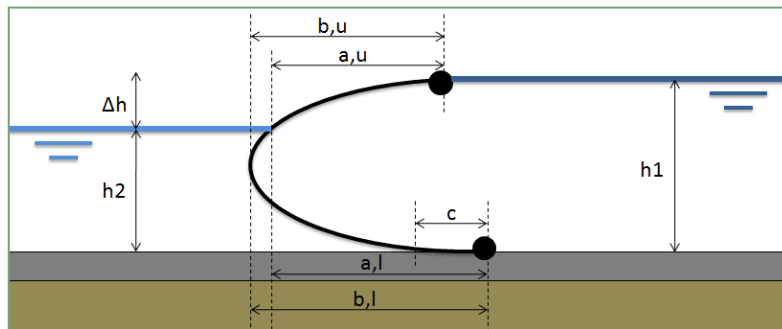


Figure 43: Definitions screen dimensions (4). (b,u/b,l=upper and lower 'cross screen width', a,u/a,l=upper and lower 'cable low water line' length, c= screen 'creep length', h1=high water level, h2=low water level, Δh= water head,.)

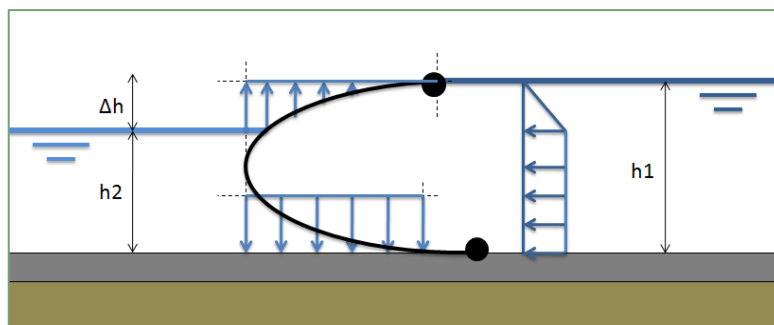


Figure 44: Residual hydraulic loads.

The vertical (downwards) load is roughly (per meter barrier width):

$$V/m = \rho g \Delta h ((a, l - c) - 0.4 a, u)$$

(The 0.4 value is depending of the shape of the barrier, for "spinnaker" barrier type 0.4 is an estimation.)

With the help of Figure 43 it can be seen that due to the shape of the screen the vertical stress increases with a shorter screen width. (The 'a,l-c' is relatively longer than a,u for shorter screen width due to 'sagging' of the screen.) For a guy supported 'open fabric' barrier the uplift component over a,u is further reduced.

The differences in screen width between a "spinnaker" and 'guy supported' barrier is small, however over a barrier/channel width of over 200 meters it is worth considering to reducing the costs. Presumably, the relative difference will increase with larger water heads which makes the 'guy supported' barrier more useful.

Moreover the screen length, and therefore the total costs, can be reduced when using a 'guy supported' water barrier. Especially when considering that approx. 40% to 50% of the total life-time costs for a 'fabric barrier' is only for the screen. (See also appendix I.5.)

The screen costs are depended on the required strength of the screen and thus on the size and shape of the screen, however, when using €5000/m² screen as a first estimation:

Screen "spinnaker" barrier of (25*250=) 6250m² costs: 31.25M euro.

Screen 'guy supported' barrier of (15*230=) 3450m² costs: 17.25M euro.

Difference: 14.0M euro costs reduction per screen; in net present value (every 30 years replacement, barrier life-span of a 100 year) this is approx. 28.3M euro.³

³ The calculation is made with an inflation rate of 2.5% and a reference rate ("discontovoet") of 4.5%.

The costs reduction that is made with the reduction of the screen surface is counteracted by the costs for the support towers and guys. Moreover the costs of the abutments, operation mechanism and maintenance are different. More detailed costs estimations have to be made.

8.4 CHOICE

Within this master thesis a 'guy supported' movable water barrier will be discussed in more detail. The 'A-frame' design concept will be briefly further discussed (in the appendix), because two of the four UOOC barriers have to be able to divert a large negative head.

For the 'bridge+screen' concept a preliminary design will be made for the Merwede barrier. This barrier, Merwede and 'bridge+screen' concept, not only fulfills the stated requirements and desires but also give compliance to the stated objectives of this Master thesis. A design that is optimized with the newest materials, integrated in UOOC research and combined with architecture and multiple land use. In Figure 45 the choice is illustrated.

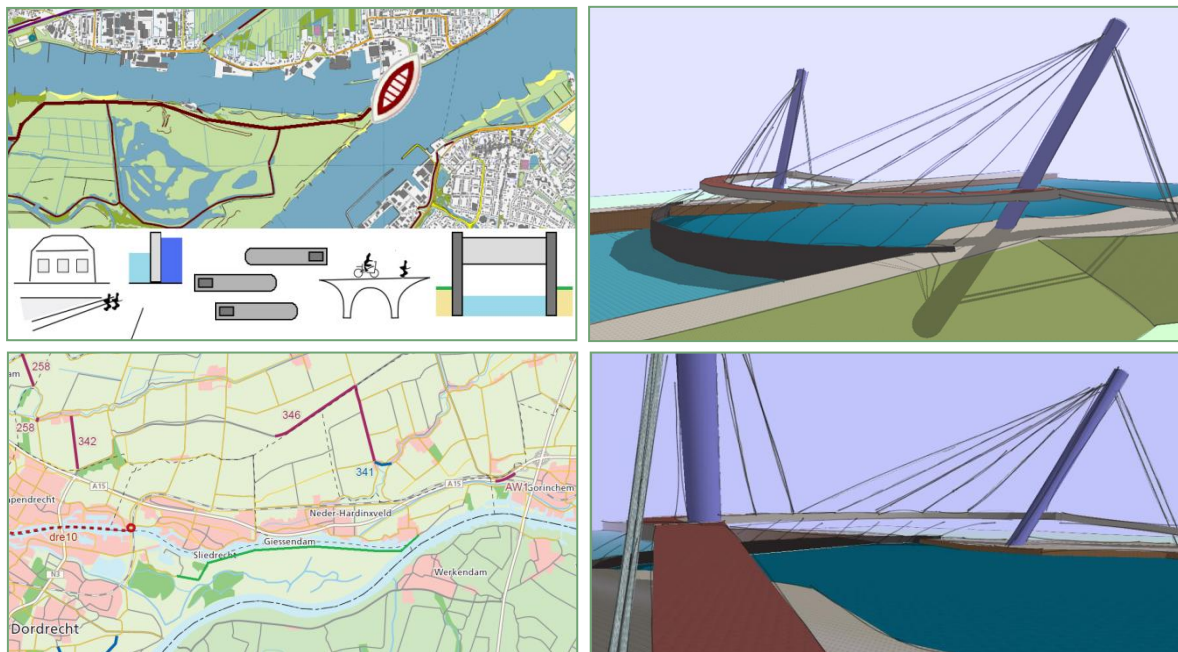


Figure 45: UOOC Merwede barrier and a combined design of an 'open fabric' movable water barrier with a pedestrian bridge that enhance the cycling network of the region.

9 STRUCTURAL DESIGN, 21ST CENTURY MOVABLE WATER BARRIER

In this chapter the movable 'open fabric' water barrier in combination with a cable-stayed bridge for the Merwede UOOC barrier is further discussed.

The main objective is to investigate the feasibility of such a barrier. Therefore the main dimensions of the bridge are determined, the load distribution is determined and some strength calculation are made. Furthermore the screen storage, life-time costs, and the construction method are discussed.

Dynamic behavior of the entire bridge is not further considered, however, it has to be stated that the dynamic response is very important when designing a pedestrian bridge.

9.1 MAIN BRIDGE DIMENSIONS

The main dimensions of the cable stayed bridge are determined with some rules of thumb. (Because the bridge is loaded by hydraulic loads that are far greater than the deck loads under normal conditions, it is not sure if these rules of thumb provides a more or less optimized design.)

In Figure 46 the proposed bridge is sketched. The bridge deck follows a horizontal curvature that is chosen to be the same curvature as the lower cable of the screen. Furthermore a symmetric system is chosen where the two pylons are placed (almost) evenly over the width of the waterway.

A fan / radial system is chosen because this system is most effective, has relatively small pressure forces in the deck and moderated bending moments in the pylons, and should be possible due to the, presumably, few guys (per pylon) that are required.

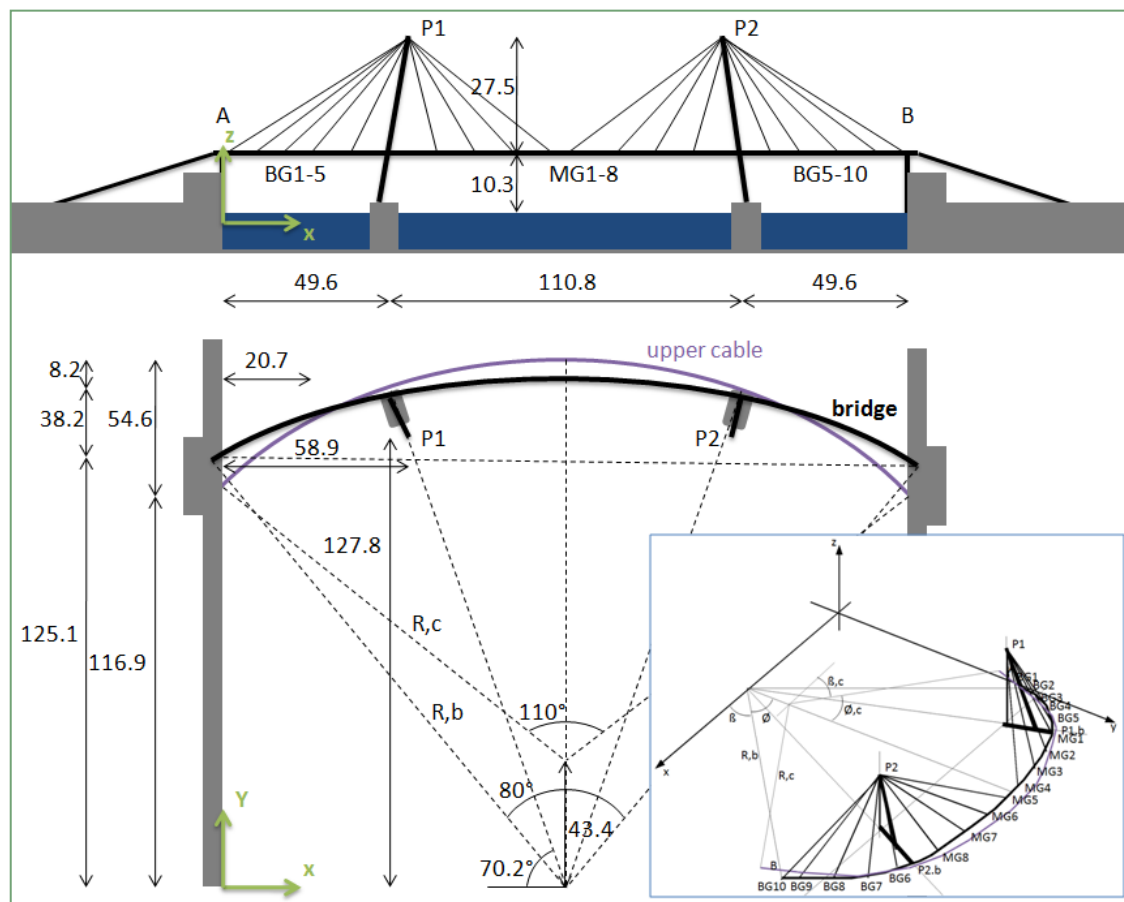


Figure 46: Sketch overview cable stayed bridge. [m]

The channels beneath the bridge are wide enough for the inland vessel navigation, however they are slightly different orientated than at the other existing bridges over the Beneden Merwede. The height of the deck is well above the existing deck heights. A movable bridge is (for now) not considered, however, the existing bridges do have a movable part.

The design is optimized towards a minimum pylon height with two criteria, namely; a minimum guy angle of 25° and a logical standard c.t.c. guy distance for the back and main (mid) span. The height of the pylons (above deck level) are in a first estimation set on 0.2 times the length of the main span. However to fulfill on the first criteria the pylon height is raised up to 27.5m. The number of guys at the back and main span are varied to get a minimum pylon height and (no extreme) tensile stresses in the back stayed cables BG1 and BG10. A choice has been made for five back guys and four main guys with resp. 11 and 12m c.t.c. distance. The deck is connected with the abutments and the two middle pillars which should divert the torsion forces in the deck.

Pedestrian bridges have small widths and are therefore sensitive to aerodynamic instability and discomfort because of the large transverse displacement. This problem will not be extensively discussed, however, the upper cable, which is attached to the deck (see Figure 47), can decrease transversal displacements and dynamic vibration. The cable follows a smaller curvature than the deck; this way most part of the tensile stresses in the cable can be diverted to the abutments parallel to the waterway. The upper cable decreases the tensile stresses in the deck and can divert the bending moments (not only induced by the hydraulic loads) of the deck in the transversal way more efficient. To which extent this upper cable is required is questionable and further investigated. Both cables, upper and lower, divert their loads directly to the abutments.

In Figure 47 a simplistic cross section is presented of the pylon and deck. A single row of guys is proposed that are connected in the middle of the bridge.

In the local system of coordinates, with the x axes in line with a radial line of the bridge curvature, the pylon is placed under a 70° angle. In a later design stage an optimum has to be found for the pylon angle. For now it is assumed that a back guy is required at the middle pillar because the required pylon angle without a back guy would be too small. (Too small because the increasing costs and construction feasibility.)

The top of the pylons are supported by the guys, at the bottom (on deck height) the pylons have a hinged bearing.

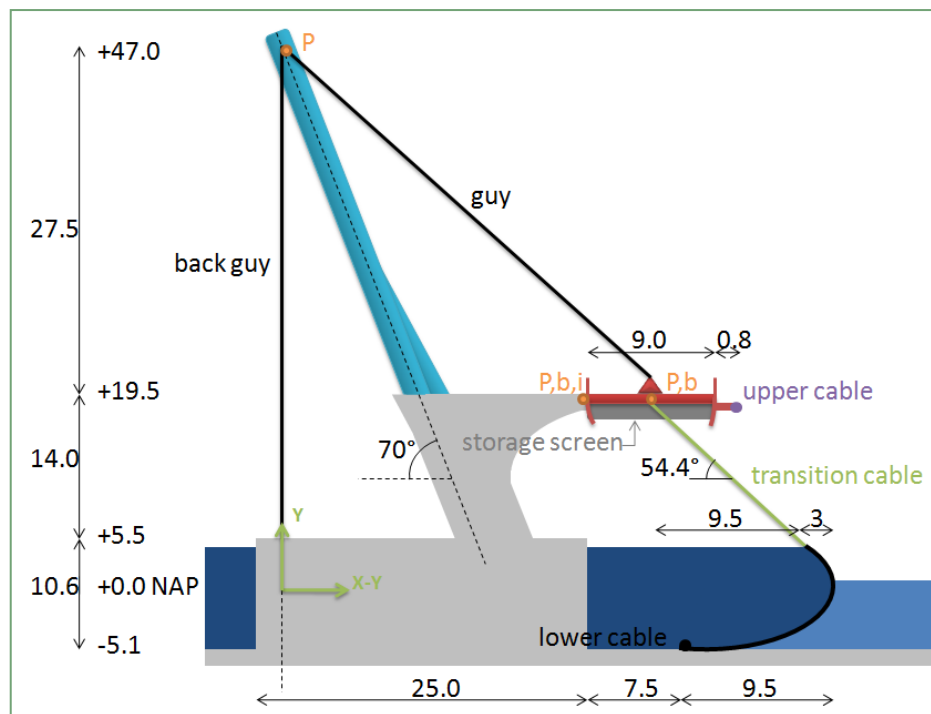


Figure 47: Simplified pylon cross section. [m]

The lower cable diverts the hydraulic loads towards the abutments where they are connected to the hydraulic jacks. These jacks can push the screen down during closure.

The screen is stored under the bridge, more investigation is need about the feasibility of such a storing and closure system.

For this feasibility study the middle pillars will be designed out of concrete, the deck out of concrete and steel, the guys from Dyneema® ropes and the pylon out of steel, however, for the pylon other materials like concrete or E-glass are also possible and are more in line with the barrier design.

At the middle pillars the upper cable is 5.8m extended from the deck mid. This is done by steel profiles to divert the pressure force to the cable.

The transition cables are connected directly under the guy connections (and at the two middle pillars) in the middle of the deck. A screen width is estimated, in relation to the hydraulic pressure, which invokes an upper angle (of the screen and the transition cable) of approx. 54°. This angle is in range with or even larger than the angles of the guys and therefore the need for the upper cable is questionable. This is because the vertical loads are diverted (assumed 100%) by the guys and pylons, this induces a horizontal component which is (due to the different angles) similar to or greater than the horizontal hydraulic load. The hydraulic loads are, therefore, mainly diverted by the bridge system.

In the next paragraph the load distribution of the cable stayed bridge and the 'open fabric' water barrier will be discussed in more detail.

9.2 LOAD DISTRIBUTION

It is assumed that the vertical hydraulic load is fully diverted by the guys; no bending stiffness in the deck. See also Figure 48 for an illustration of the main load distribution.

Furthermore, it is assumed that the lower cable and the transition cable are diverting each half of the horizontal hydraulic load. This later assumption is a rough simplification, however; this fifty-fifty load distribution can be obtained when the screen width and the position of the lower cable are chosen correctly. It is possible that the assumed screen width of 15m (18m with 20% elongation) is incorrect, however, the feasibility of the structures can still be addressed. This is

because a worst case loading is chosen, a relatively short screen of 15m induces high vertical loads, and a conservative calculation method is used.

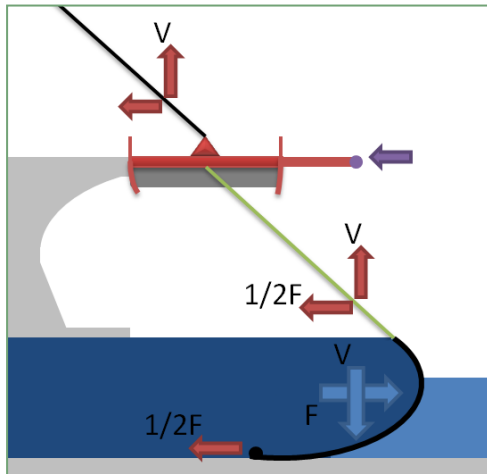


Figure 48: Diverting loads in screen and deck.

If the horizontal hydraulic forces are not fully diverted by the guys, then the water pressure invokes bending moments in the deck in the transversal direction. These forces have to be diverted by the deck and upper cable towards the abutments and middle pillars, as sketched in Figure 49.

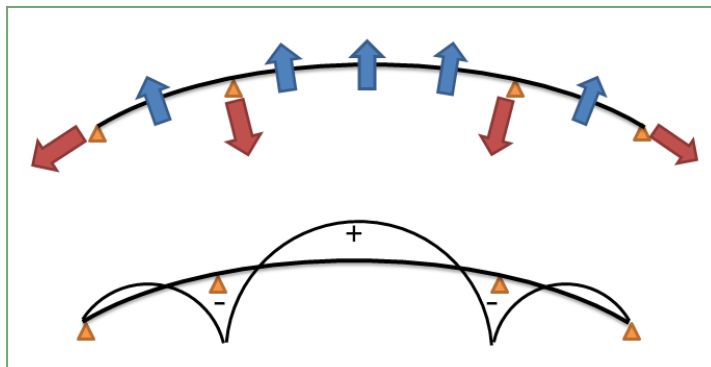


Figure 49: Hydraulic load on deck.

A continuous main girder is proposed because this invokes the smallest bending moments, with at the main span tensile stress in the outer bend due to the bending moments and at the abutments the support moments.

This stress pattern is similar when a wind load is considered. A wind load from the other side will be partly diverted by the deck in the form of a compression stress due to the curvature of the deck.

The choice has been made to design the bridge as a bi-stayed system instead of a self anchored or a back stayed system. The bi-stayed system (a combination of the other two) provides a better structural behavior (global stiffness, 2^o order effects, lower normal deck forces and lower bending moments in the pylons), however, a reaction force is required in the abutment as indicated in Figure 50. This is a drawback because the present soil conditions in the West of the Netherlands are not well suitable for shear stresses, furthermore, high reaction forces are already present due to the water barrier. However, the force in the back stayed cable are designed to be relatively small.

The behavior of the proposed bi-stayed system will be closure to a self-anchored system than to a back stayed system when.

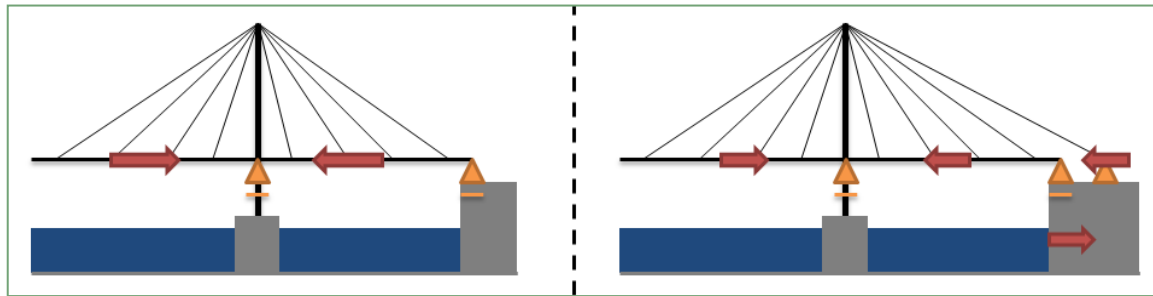


Figure 50: Self anchored vs. bi stayed system.

The guy induced forces invoke normal pressure, tensile and buckling stresses in the deck. The buckling (in Dutch: ‘spatkrachten’) are due to the curvature of the deck. These forces have to be diverted by the deck, upper cable and middle pillar. The normal forces for a fan system and a continuous main deck girder are sketched in Figure 51.

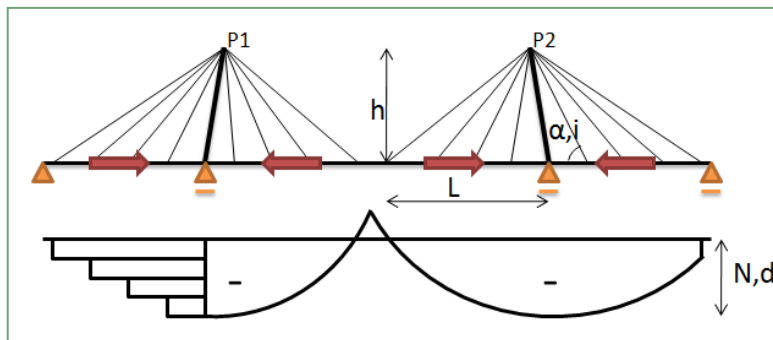


Figure 51: Expected deck pressure stress.

In formula (for (infinite) number of guys: $N, d = \int_0^L p dx * \cot \alpha, i = pL^2 / 2h$

Normal force in (straight) pylon: $N, p = 2pL$

(Where p is the bridge total load per meter.)

It is presumed that the water barrier invokes tensile stresses in the deck which counteracts the pressure forces. Calculations will be done to investigated this presumption.

9.3 HYDRAULIC PRESSURE

In the appendix I.1 the hydraulic loads are explained and calculated.

The corresponding equations are:

Residual horizontal load per running meter: $F/m = 0.5\rho g(h_1^2 - h_2^2)$

Residual vertical load per running meter: $V/m = \rho g \Delta h((a, l - c) - 0.4a, u)$

(The 0.4 value is depending of the shape of the barrier, for “spinnaker” barrier type 0.4 is an estimation.)

Wave and current induced loads are not further detailed. There are briefly discussed in appendix I.1 and it is assumed that they are taken into account within the safety factors, as presented in Table 7.

SAFETY FACTORS		
hydraulic load	γ, l	1.2
dynamic factor screen	γ, d, s	1.3
dynamic factor cables	γ, d, c	1.6
material	γ, m	1.1
folding / peak stresses	γ, p	2.0

Table 7: Barrier safety factors.

The design parameters for the “balgstuw” at Ramspol are taken as a reference project to determine the safety factors. See appendix I.1.3 for more elaboration on the choice of the height of the safety factors.

A distinction in a dynamic factor is made between the screen, the cables (and or guys), wind load (for the deck) and the folding factor is only applicable on the stresses in the screen.

In Table 8 the horizontal hydraulic load is calculated for each UOOC barrier. The vertical hydraulic load is not presented in this table because this load depends on the shape of the screen. At the Spui and Drecht barrier a negative water head is normative, therefore, h1 and h2 are switched in high and low water level.

It can be seen that at the Merwede barrier the largest hydraulic loads can be expected.

UOOC barriers	max. sill depth	barrier/ water channel level	water level in front	water level back	hor. max. hydr. hor. screen					
	.. m	B	h1 *)	h2 *)	h1	h2	Δh	F/m	F/m, γ, s^{**}	
	NAP	m	m NAP	m NAP	m	m	m	kN/m	kN/m	
Spui	-5.1	100	-0.5	3.3	4.6	8.4	3.8	242	756	
Drecht	-5.1	240	-0.5	3.3	4.6	8.4	3.8	242	756	
Merwede	-5.1	210	4.7	0.3	9.8	5.4	4.4	328	1024	
Lexmond	-4.8	120	4.9	0.5	9.7	5.3	4.4	324	1010	

Table 8: Hydraulic loads (only the horizontal) for all four UOOC barriers. (*)wind and current setup and setdown are taken into account; **)with safety factors)

9.4 FEASIBILITY PA SCREEN AND DYNEEMA® ROPES

In appendix I.2 it is investigated if these loads can be diverted by the chosen materials; PA for the screen and Dyneema® ropes for the cables. A “spinnaker” barrier is taken as a reference for this calculation. It can be concluded that the strength of the materials is sufficient for diverting the hydraulic loads that can be expected at the Merwede barrier. The largest existing Dyneema® ropes are sufficient, and if required there is no reason why large diameter ropes are not possible. (Lankhorst Ropes 2009)(R. Bosman, DSM Dyneema)

The screen is special made and, therefore, a larger tensile strength can be obtained than was required at the “balgstuw” of Ramspol.

It has to be stated that a different kind of barrier design can invoke higher stresses in the screen and cables, however, it is thus assumed that these stresses are still in range of the possibilities of the materials and without extreme high costs.

9.5 DETAILING

Strength calculation are made with the assumption of a quasi-static structure, where thus the guys are connected at the deck with hinges. Second order effects, elongation of the guys and

shortening of the pylon, are not taken into account. Also dynamic effects as flutter are in this preliminary design not considered.

9.5.1 CABLES

In appendix I.4.1 the bridge main dimensions are described, in appendix I.4.2 the loads are determined and in appendix I.4.3 the guy and transition cable forces are calculated. In appendix I.4.6 strength calculations are made and dimensions are obtained. In Table 9, the cable/rope dimensions are presented. (The transition cables are the cables/ropes that connects the screen to the deck. The positions indicate the guy and trans. cable position along the deck.)

guys and transition cables; Dyneema® ropes				
position	trans. cables		guys	
	[kN]	[mm]	[kN]	[mm]
BG1,10	2972.6	80	5771.9	100
BG2,9	5945.2	100	13178.9	150
BG3,8	5945.2	100	11600.7	140
BG4,7	5945.2	100	10287.0	140
BG5,6	5945.2	100	9356.8	130
P1,2,b	8917.7	130	-	-
MG1,8	6485.6	110	10278.6	140
MG2,7	6485.6	110	11455.8	140
MG3,6	6485.6	110	13101.0	150
MG4,5	6485.6	110	15054.4	160
BGP1,2	-	-	78494.7	370
	or		4 times	200

Table 9: Rope diameters.

All guys and cables are designed with Dyneema® SK75 fiber ropes as described in appendix G.2. Also the dimensions of the lower cable(s) is determined, four 250mm ropes. These ropes are (partly) stitched into the screen.

9.5.2 PYLON

The calculations that are made for the pylon provides a first estimation of the required dimensions of the pylon.

The pylon top is supported by the guys and the bottom is placed on a hinged bearing. The back guys, BG and BGP, keep the top of the pylon in place. A balance of moments calculation is made around the bottom of the pylon to determine the back guy forces and the pylon normal stress. This is illustrated in Figure 52.

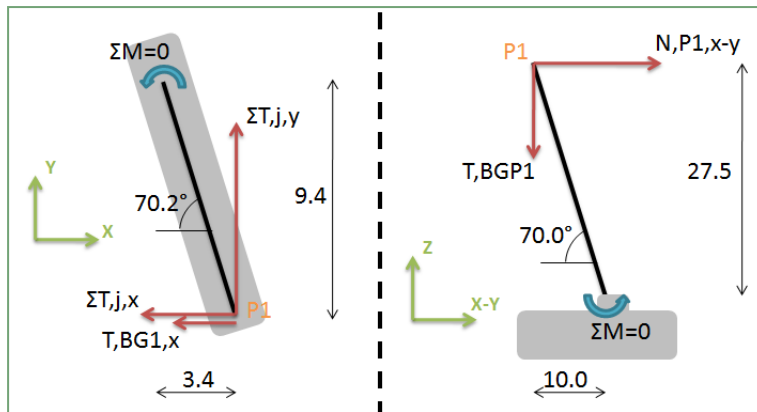


Figure 52: Pylon, BG1 and BGP1 calculations, left: top view, right: front view.

With the calculated normal stress of 140,000 kN the dimensions of the steel pylon and concrete foot are estimated. Buckling of the pylon is taken into account and it is concluded that the dimensions are in reasonable order of magnitude.

9.5.3 DECK

Decks tresses:

In appendix I.4.1 the guys positions and angles are presented and the corresponding forces for the two distinct situations, namely; the barrier in operation and a stored screen, are calculated. From these guy forces the x- and parallel- (to the deck) component are calculated. The first indicates the normal deck stresses when (more or less) a straight bridge would be considered. (It is more or less because the guy positions would be altered with a straight bridge.) The second estimate the deck stresses for a curved bridge deck. The parallel force are obtained from the x- and y-component of the guy forces.

The forces are accumulated towards the middle pillar (P) and towards the middle of the bridge (M). Towards P is done for a strength calculation at the middle pillar if a rigid moment stiff connection with the deck is constructed. Towards M is the situation when the deck is placed on roller bearings and the residual normal force in the deck at the first pylon will counteract the normal force of the second pylon. This force (normal stress at the left side of the pylon minus the that at the right side of the pylon) is not zero because of the back stayed cable and the curvature of the deck.

The estimated deck normal stresses for the situation that the barrier is in operation (and for the first half of the bridge around pylon 1) is presented in Figure 53. A negative force means a pressure in negative x direction (towards the left), a positive force means a pressure force in the x-direction (towards the right). Except for the cumulative force towards M where positive means pressure and negative tensile.

(For the calculation of the deck forces during barrier operation the residual forces are used. These are the summations of the guy and the transition cable forces.)

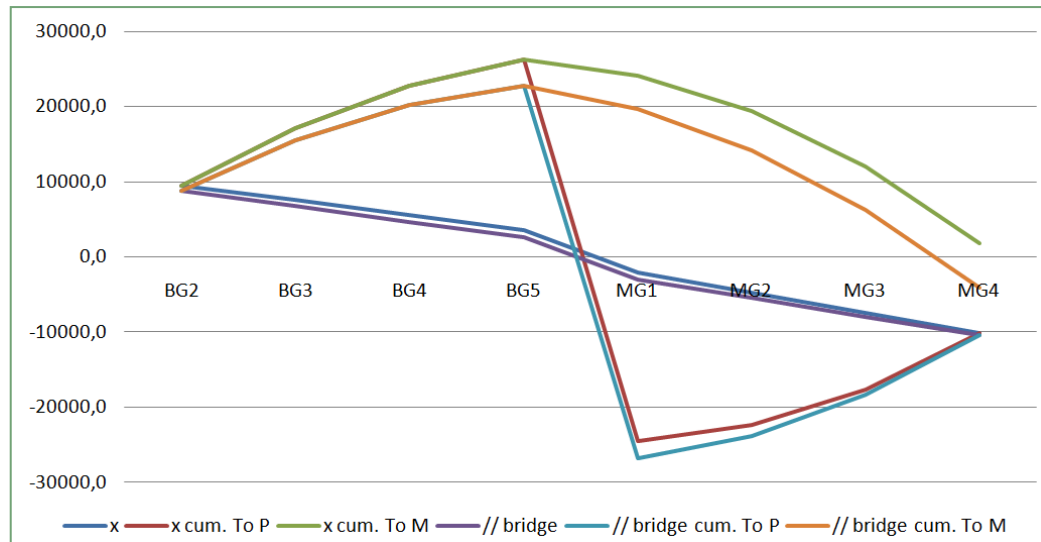


Figure 53: Deck normal loading around P1 for a straight and curved deck during barrier operation. [kN]

From this calculation it is concluded that tensile stresses at MG4 and at the middle of the span can be expected for this curved bridge with a back stayed cable BG1 and BG10 connected to the abutments. This is as expected in the previous paragraphs.

If the normal deck load is diverted into the middle pillar a residual force from the back span (in this case the left side) has to be diverted.

Furthermore an upper cable is not required because the horizontal hydraulic loads are diverted by the bridge system which causes primarily pressure forces in the deck. The presumption that the barrier will go into tensile stresses in the deck, as stated above, is for this proposed structure and screen size is not correct.

Loads that are not calculated:

- Wind loads that induce bending moments in the deck in the transversal direction and a normal pressure or tensile stress in the deck due to the curvature;
- Temperature stresses have to be accounted for in the final design, especially when stiff bearings are constructed;
- Buckling forces / “spatkrachten” due to the normal force in the curved deck have to be considered;
- Torsion stresses in the deck itself;
- Local bending moments that are induced by elongation of the guys.

Cross section:

The proposed deck structure is constructed from a steel frame with concrete. On each side of the one row guys a pedestrian or cycling lanes is situated. The screen is stored under the bridge. See also Figure 54 where a sketch of the cross section is given.

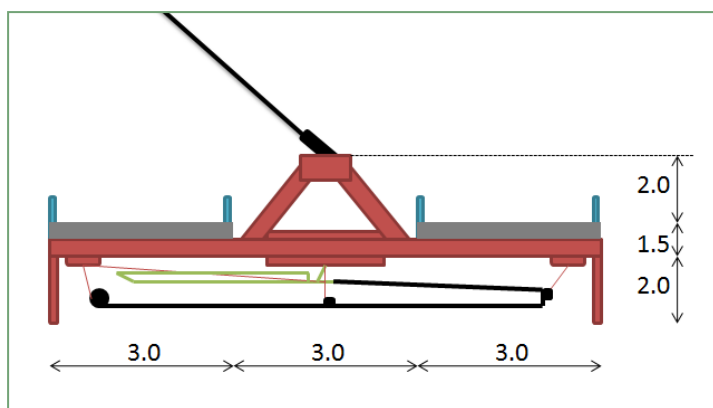


Figure 54: Main idea deck cross section.

Normally a six meter wide profile should be sufficient for a pedestrian bridge, however to create more storage room for the screen the lanes are placed away from each other and the guys are connected in the middle of the deck. The connection point is elevated so pedestrians cannot touch the cables.

A disadvantage of this design is that torsion of the deck will take place during barrier operation. This is due to the configuration of the transition cables and the guys. Already a truck/tubular profile of the bridge is required to divert the torsion moments due to the one row of guys. This truck could also divert the hydraulic induced torsion moments, however reorientation of the deck could be a better option to diminish torsion moments induced by hydraulic loads. For now, this proposed design is not altered.

No strength calculations are made for the deck girders, etc, nor further dimensioning.

9.5.4 CONNECTION DECK - MIDDLE PILLAR

A strength calculation is made for the feasibility of the concrete cross section that connects the deck in appendix I.4.5 and I.4.6.3. For this calculation it is assumed that the deck is rigid and moment stiff connected to the middle pillar. This is done because this induces the highest stresses in the connection. However, also different bearing properties are discussed in this chapter.

The connection should be able to divert:

- bending moments in the vertical plane due to torsion of the deck and a transition cable;
- shear stresses in the vertical plane due to local deck load and transition cable;
- normal stresses and shear stresses in the horizontal plane due to residual deck stresses.

Two typical situations are distinguished; namely, when the barrier is in operation and when the screen is stored.

As an example; Figure 55 illustrates deck torsion invoked by (variable) loading on the outer deck and local moment at the connection due to outer deck loading. (Torsion due to the orientation of the connection of the guys and transition cables to the deck is not taken into account.)

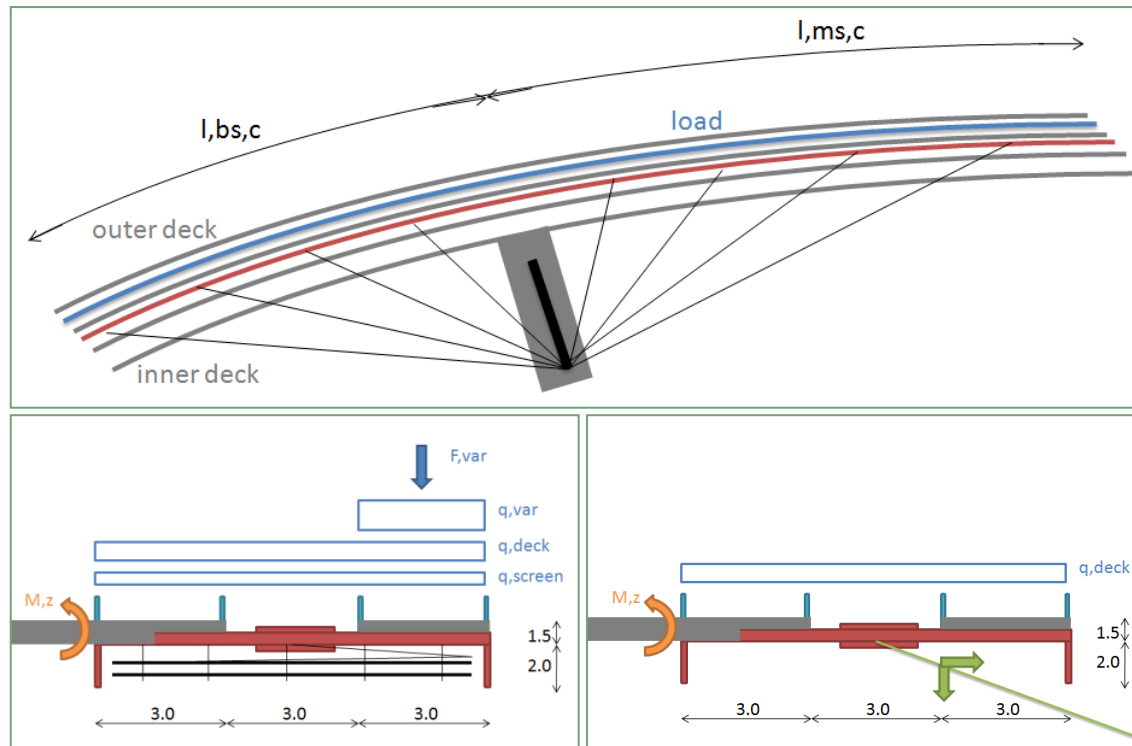


Figure 55: Top: main system top view, deck torsion due to outer deck loading, stored screen; left: local system, stored screen; right: local system, barrier in operation. [m]

It is concluded that there are no constructive concerns for the concrete cross section at the deck-middle pillar connection. For more detail see appendix I.4.6.3 .

Other bearing properties:

As already mentioned; other bearing properties at the middle pillar could have benefits for the entire bridge system. No shear forces have to be diverted at the middle pillars and lower stresses due to temperature elongation can be expected.

However, a reaction force in the (positive and negative) y-direction and a moment stiff bearing in the vertical plane are required. The first one because of the curvature and wind loading, the second due to the single row of guys. Moreover, a continuous main girder with transversal directed (y-direction) bearings at the middle pillars and abutments is desirable for diverting wind loads. (Staalkundig Genootschap 1996)

Such a deck bearing system is proposed in Figure 56. The deck rest on the concrete cantilever and (locally) the screen storage area is slightly lowered or the deck is slightly lifted.

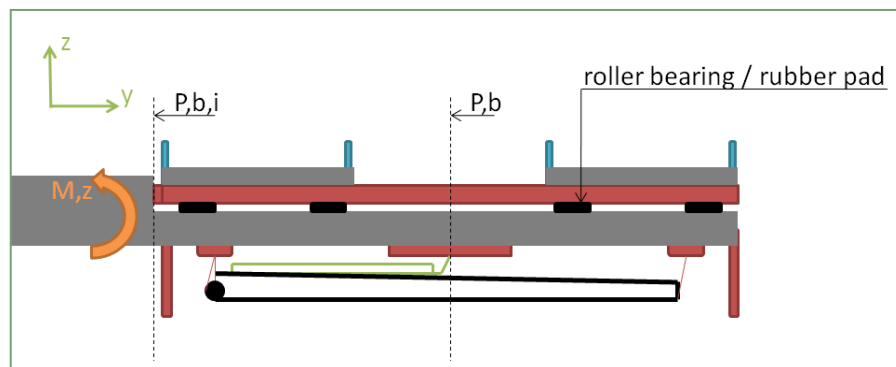


Figure 56: Deck cross section at middle pillar (P,b).

For this connection no detailed design nor a strength calculation is made. The calculation that is made is based on an old bearing proposal, however the feasibility of the concrete cross section still holds because of the similar dimensions and loads.

9.5.5 SCREEN STORAGE AND CLOSURE

The storage and lowering system of the screen can, assumable, be constructed from several ropes and winches that pulls the screen in. In Figure 57 such a system is sketched where four closure cables (support cables that do not divert any loads except closure and opening loadings) are pulled in to elevate the screen.

The first sketch is the situation when the water head is almost gone. The hydraulic jacks at the abutments raise the lower cable and the screen is starting to flood/pulled up towards the water level. After that the fourth cable is pulled in to turn the screen, the water can flush out of the screen and the screen will fold; sketch 2. The other cables are pulled to turn the screen back in position; sketch 3. After that all the closure cables are pulled in to store the screen under the bridge; sketch 4 and 5.

It is possible that a guidance cable for the transition cable is required to keep the cable from strangling.

For deploying the screen, closing the barrier, the winches of the closure cables are loosened and the screens own-weight will pull the screen down. After the screen is lowered by the closure cables and floating on the water the hydraulic jacks are connected to the lower cable. The jacks (one or two on at each abutment) pulls the cable and screen further down. During closure the sill will be flushed clean from sediments. Because of the great length of the screen (great width of the barrier) a scale model should be made to test if the screen will be lowered completely with just hydraulic jacks at the abutments. In other words: to which extent does the screen unfolds itself (due to the water flow which is similar to unfolding/opening of a parachute) and to which extent are the jacks required. Also the lowering and storage system should be tested with a scale model.

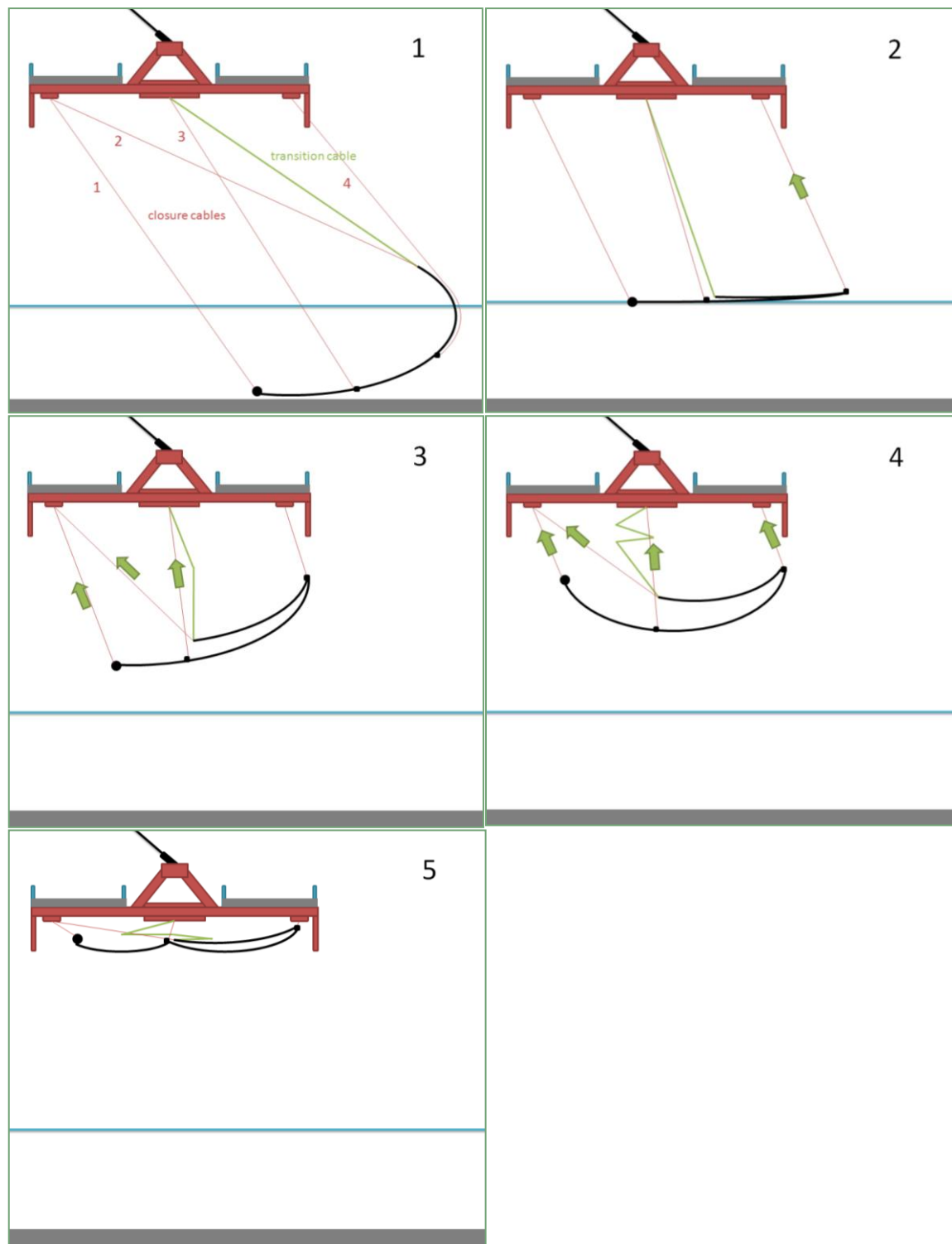


Figure 57: Barrier closure system.

The fourth and third cable are connected to the screen at the position where the fold should take place. This connection should be possible because, in many cases, on the screens of inflatable dams (weirs in this case) rubber extensions are constructed to break the laminar flow along the surface of the screen. See for illustration Figure 58. (Here the extension is made over the entire width of the barrier, also smaller multiple extensions are commonly known.) New is that nylon should be stitched into these extensions to bear the tensile stresses.



Figure 58: Rubber extension breaks laminar flow over an inflatable dam.

Tuning of the speed and length of the three cables is important to control the tensile forces in the closure and especially in the lower cable(s). In a model test of a “spinnaker” barrier, done by Delft Hydraulics in 1989, different unfolding sequences were tested. It can be concluded from the literature that the top of the screen and lower cable should be near each other when the lower cable is pulled down by the jacks.

9.6 ALTERED SCREEN SIZE AND PYLON HEIGHT

When a large screen width (cross section of the screen) is chosen with a smaller upper angle it is possible to adjust the load distribution in such way that the bridge structure has similar stresses during barrier operation and stored screen situation. An upper cable is in this case recommended because the deck will be under tensile stresses.

The positive side is that the dimensions of the guys pylons and deck girders can be reduced. In other words: no ‘over-dimensioning’ of an entire bridge structure that is fully used for just once in fifteen years (estimated closing frequency of the barrier).

However, to reduce the vertical hydraulic load in such manner the screen width and orientation has to be altered to a great extent. See Figure 59 for an illustration of the proposed screen orientation and the altered screen orientation. For the altered design the vertical load is 0.13 times the horizontal load, instead of 0.7. See for more detail appendix I.4.7.

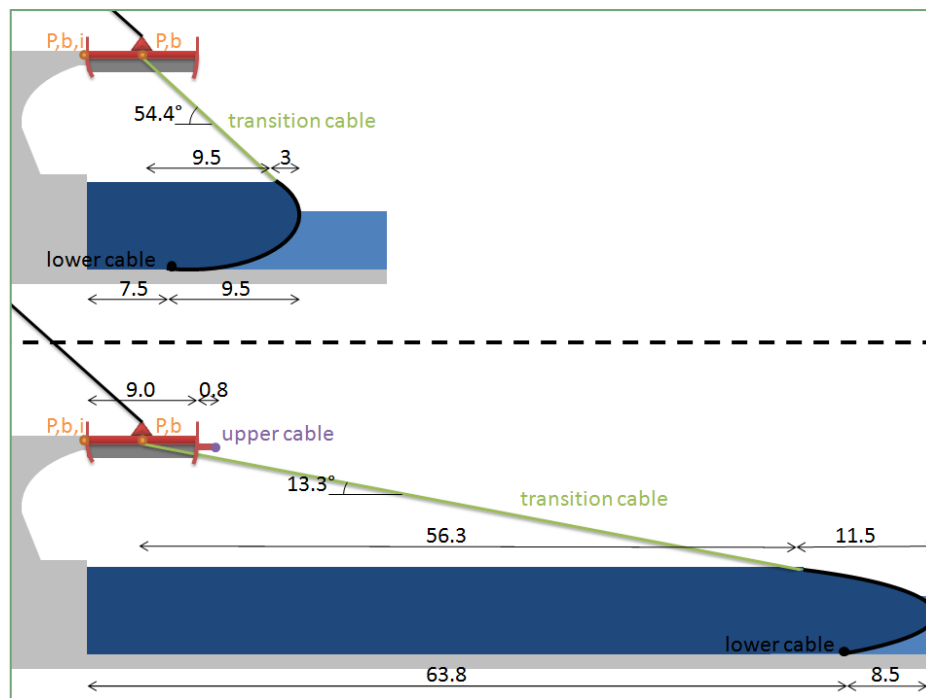


Figure 59: Two extreme screen orientations.

For a detailed design an optimization should be made for the screen orientation wherein some boundary conditions are addressed for (among others) the storage capacity, opening mechanism, dynamic response and the abutment connections of the lower and upper cable.

The screen orientation has a large influence on the hydraulic loads on the bridge structure and it is recommended to make a numeric estimation of the screen behaviour. As discussed in section 7.4.3 the dynamic response is depending of the screen length, screen width and the barrier width. The screen length is not altered because the screen radius is similar to the radius of the bridge deck which is required to be able to store the screen.

Raising the pylon decreases the overall stresses in the bridge structure, however, from appendix I.4.7 it can be concluded that this effect is far less significant than an altered screen size.

9.7 CONSTRUCTION METHOD

In chapter 6.5 a reasoning is given for prefabrication of the water barrier structure. This is still possible for the proposed 'bridge+screen' barrier. The construction can be prefabricated for the majority of the structure and placed with the help of floating barges and crane vessels. No cofferdams in the middle of the waterway nor temporary bridges will be required. This way hazards to the inland navigation are minimized and the construction risks concerning cofferdams are avoided.

The following sequences of construction could be followed:

- preparation subgrade;
- pile driving middle pillars;
- installing seepage screens (sheet piles);
- placing prefabricated shell middle pillar and filling with concrete to join with the foundation (possibly submerged concrete is required);
- placing prefab sill segments;
- placing guidance works (if they do not hinder construction);
- placing pylon and temporary support structure;

- placing or construction at side of cantilever;
- placing deck segments and connecting the guys one by one from the middle pillars out;
- installing closure mechanism for water barrier;
- installing screen;
- placing erosion protection;
- finishing works on bridge and waterways like asphalt, railing, lighting, etc;

And of course the construction of the abutments for the water barrier and bridge with ,amongst others, a closure installation for the barrier, seepage screens, traffic guidance and an operation and tourist information centre.

9.8 COSTS

In appendix I.5 a Net Present Value (NPV) calculation is made on element level for the 'bridge+screen' barrier as proposed in paragraph 9.1. The NPV's are calculated for the barrier and for the bridge separated with an inflation rate of 2.5% and a reference rate ("discontovoet") of 4.5%. For this calculation the construction and maintenance costs are estimated.

Conclusions:

- The total life-time costs to invest at this moment for the Merwede barrier, a movable 'open fabric' water barrier suspended on a guy/stay roped bridge, are estimated at: €109.2M for the barrier and €34.2M for the bridge with barrier support structure. The total investment costs are estimated at €143.4M. This is lower than the first costs estimation, made in appendix F, namely: €220M;
- The total life-cycle costs of the screen are 42.6% of the total water barrier life-time costs.
- It is estimated that a fabric gate is well over 34% less expensive than a steel vertical lifting/drop gate;
- It is stated in the main report that costs can be reduced with a smaller screen and in particular with a smaller screen width. In the NVP calculation each meter screen width costs approximately €2.81M. As a result, to decrease the stresses in the bridge structure with a larger screen width of 25m instead of 15m cost €28M. The benefits of a more slender bridge structure are not more than a few million (total costs of the bridge are €34M). Let alone if an upper cable and a large sill structure is needed. In other words, optimization towards a small screen is recommended.

10 CONCLUSIONS AND RECOMMENDATIONS

In this chapter the (most important) conclusions for the UOOC Barriers and for an 'open fabric' barrier are addressed. Furthermore, recommendations concerning an 'open fabric' barrier and in specific a 'bridge+screen' barrier are made.

10.1 UOOC BARRIERS

The UOOC water barriers are 'high water diverting barriers' that close off waterways to divert the fresh river water into another waterway. Considering the scale of the required barriers (great width) these barriers can be seen as a new type of movable water barrier.

One of the main functions of the waterways in the Northern delta is inland vessel navigation, it is one of the main concerns to reckon with. Hazards should be minimized, which means no (local) capacity decrease. The closing frequency of the barriers is low; as a result the hazards for inland navigation (can be) low and the need for a navigation lock is not certain. Furthermore a short construction period is desired, which is possible with a prefabricated construction.

It is recommended that for the design of the UOOC barriers the architectural quality and spatial planning plays an important role.

For the exact location choice also cultural and archaeological values should be taken into account.

The location choice for the Merwede barrier is most difficult because of the villages along the North side of the Beneden Merwede and the environmental protected area at the south of the river. Within this thesis it was found that a barrier at the tip of the Beneden Merwede and Nieuwe Merwede is the best option. See Figure 60 for a illustration of a barrier at this location. A long connection levee to the West is required.



Figure 60: Barrier at the tip of the Beneden and Nieuwe Merwede.

Several management strategies are discussed for the UOOC concept: 'Lowering water levels beforehand', 'Diverting river water beforehand', 'Increasing discharge capacities' and a combination of the strategies. The strategy determines the main requirements for the UOOC barriers. However, the best strategy depends on many conditions, influences and political choices, therefore a best guess is made and worst case requirements are taken for the UOOC barriers.

When the water levels at the Haringvliet and Hollands Diep are lowered beforehand the Spui and Drecht barriers have to divert also a large negative head.

A good prediction of the water levels is not only required for a good water-management-system and for closing the barriers in time, but also required for the opening sequence. The difference in the duration of high water at sea and at the river(s) can cause design problems for the UOOC

barriers. Consequences can be that the barriers have to open with still a large water head acting on the barrier or that the barriers are closed for a longer time than desired. The entire system will be complex due to the many waterways, movable barriers and scenarios. A good direct communication system and/or a warning system between the individual vessels and the barrier-operators is/are required.

From a simple storage calculation it is concluded that raising and strengthening of the levees around the Hollands Diep and the Haringvliet are most likely required to store the river water. Some leakage of the UOOC barriers can be allowed and increasing discharge capacities towards sea is perhaps required.

It seems that the feasibility of the Nieuwe Lek, which is intended to be a 'green river', is highly uncertain because of the (very) small water gradient during flood periods.

It is found that the best suitable location for the Merwede barrier is at the tip of the "Brabantsche Biesbosch", where also a possible social desire can be accommodated with the construction of a pedestrian bridge. Here for a long connection dam is required that runs through the "Brabantsche Biesbosch". To minimize impact an ecological / environmental friendly solution has to be found.

It is found that the hydraulic loads on this barrier is larger than at the other UOOC barriers.

The required investment (at present time) for the construction, maintenance and operation for the required life-time of 100 years of the UOOC barriers (life-cycle costs analysis), is around the € 850M. This depends among others on the chosen operation strategy and applying fabric or steel as a construction material.

10.2 'OPEN FABRIC' MOVABLE WATER BARRIER

10.2.1 GENERAL

From the literature study it follows that the arguments for the construction of a water barrier from fabric are not changed over the years: a fast construction that is almost maintenance free and therefore a barrier with low total costs should be possible.

In the '80s and '90s it was demonstrated that an 'open fabric' movable water barrier is technical possible, however, at that time was the ability to predict the behaviour and life-time of the barrier not adequate enough.

Another outcome of the literature study is that an elaborate research and optimization is not made for 'fabric water barriers'. Many of the researches aimed at improving calculation methods.

Overall; it can be concluded that the feasibility and restrictions of an open fabric water barrier are still unknown. In this Master thesis a follow up is presented on the possible designs instead of improving calculation methods.

Within this thesis it is stated that the design should be 'flexible' in order to take not only climatic changes into account but also different social views and ecological changes. Moreover a 21st water barrier has not only minimal impact for now but also in the future. The feasibility of this objective is not proven, however, a first start is made.

The screen can be adjusted in size every time it is replaced, so it can 'grow' with the climate changes. Furthermore certain requirements can be altered without high additional cost, for example; more or less leakage can be allowed. Where the barriers are designed for a large negative head even the strategy if the whole water system can be changed. For the screen there is no difference in diverting water from one or the other side. The only 'star' structural parts are

the bridge and the foundations. These have to be designed and constructed for one hundred years or more considering different strategies and developments.

To minimize the social impact a multiple function water barrier is proposed where the barrier function is integrated with the bridge structure.

It is pursued to design the bridge and barrier in such way that the purpose of the structure is visible at all times. This will enhance the awareness and overall safety against flooding.

It can be concluded that a fabric barrier can be suitable for the UOOC concept, because of the fast construction time, leakage is allowed, there is no wave energy (dynamic loading) and the great width in combinations with the relatively low water head that has to be diverted. Also diverting large negative heads is for a fabric barrier is more logical than for a steel gate structure. The 'A-frame' concept is one of the possible designs where the direction of the hydraulic forces plays (almost) no role in the technical design of the barrier. The literature study indicates that an 'open fabric' water barrier is presumably more suitable in rivers as a weir or high water diverting structure, than as a storm surge barrier at sea or at a lake. However, if the barrier has to open with a water difference over the barrier and control the water discharge this type of barrier is less suitable.

Steel has less or similar strength, performs less in endurance tests, is heavy and requires a lot maintenance. This makes steel as a construction material considering costs and environmental aspects less favourable for a movable water barrier.

A open fabric barrier has the option/potential for a modular movable water barrier, where individual movable barriers close off the waterway. The probability of failure could be far lower than with conventional movable barriers. The barrier can be installed in a great variety of waterways and even temporary for managing floods. Studies in modular water barriers could have promising results.

It can be concluded that there are several possible designs for an 'open fabric' movable water barrier.

10.2.2 STRUCTURAL 'OPEN FABRIC BARRIER'

Symmetry is important to design a predictable barrier, in stress and deformation, and to keep folding (in Dutch: "plooi") to a minimum. Also shifting, elongation of the materials and a possible 'V-notch' have to be addressed in a more detailed design. Connections between the screen and another element have to be as smooth as possible to diminish local peak stresses.

PA (polyamide) is supposed to be the best material for the screen. Robustness is given by the large strain capacity of the material. This is required to divert/smooth out local peak stresses. Connecting the screen and a cable is far better possible when using a synthetic material for the cable than a steel cable. Steel cables will cause a lot of friction and wear problems, while a synthetic cable can be stitched on and into the screen.

Ropes made from Dyneema® fibers are believed to be the best option for the barrier cables. The ropes could also be a good alternative for guys in a cable-stayed bridge. Better endurance, less maintenance, damping vibrations and ropes are very light weighted; which means less sagging. In addition the strength of Dyneema® ropes is in the same order of magnitude as that of steel cables.

One of the main issues when dealing with a fabric barrier is the storage of the screen when the barrier is in non-use. When the fabric lies on the sill, currents, especially vessel passing's, could shift the fabric and damage it. In this case the fabric has to be tied or sucked down.

Furthermore, the exposure to UV-light and other environmental loads have to be minimized to guarantee a 30 year life-time.

Response or sensitivity to dynamic loading can be predicted with models and different calculations methods. They are causing no impracticality when designing an 'open fabric' water barrier. However research into the dynamic behaviour of the UOOC barriers has to be done and is more crucial for an 'open fabric' water barrier than for a conventional water barrier.

Waves have little influence on stresses in the screen and cables, however they have influence of the top angle of the screen and therefore the required vertical reaction force. Resonance of the top of the screen can occur if waves at the middle of the barrier are less or more severe than at the sides.

Furthermore, the natural frequency must be relatively small or large to avoid resonance. The ratio between cable length, screen length and the barrier width has to be small or large to get the natural frequency relatively low or large.

If no long waves are to be expected, which is in the case for the UOOC barriers, a large natural frequency could be a better option. A large length – width ratio and a long screen has to be chosen to get a large natural frequency. However, with increasing heads, which are relatively high for the UOOC barriers, the natural frequency will decrease.

Because of these contradictions more detailed research is required about the wave climate and sensitivity of the UOOC barriers with difference sized screens.

In addition, if the top of the screen of an 'open fabric' barrier is connected to a stiff element such as a bridge or the screen is clamped to the sill it can be foreseen that the dynamic behaviour of the barrier is highly altered.

The conclusions about the costs of an 'open fabric' barrier are presented in section 10.2.4.

10.2.3 STRUCTURAL 'BRIDGE+SCREEN' BARRIER

Within this master thesis several 'open fabric' barrier concepts are presented, under which 'guy supported' movable water barriers. With the help of a criteria analyses the 'bridge+screen' concept is chosen and for this concept a preliminary design is made for the UOOC Merwede barrier.

For this 'bridge+screen' barrier a cable stayed bridge is proposed with a curved deck (hor. plane) that has the same curvature as the screen (which is required to be able to store the screen). Two pylons, under an angle, and several guys are keeping the bridge up under 'stored screen' situations and diverts a part of the hydraulic loads under 'barrier operation' situations. The deck is supported a single row of guys, the middle pillars and abutments, where the last two also diverting the torsion loads in the deck. See Figure 61 for an illustration of the proposed design.



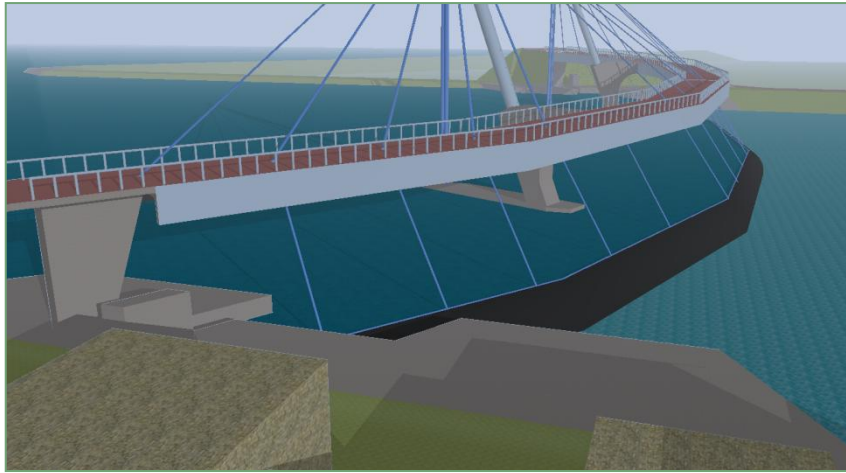


Figure 61: Sketch proposed 'bridge+screen' movable water barrier.

The advantages of this type of barrier is that the movable barrier spans a 210m width with just one 'gate'. No multiple mechanisms, operation systems, complex sill structure nor additional middle pillars are necessary and as a result there is neither a great reduction of the navigation capacity nor restriction of the water flow.

The closure and operation of the barrier can be controlled to a large extent, even tuning the shape of the screen during operation and, therefore, the hydraulic loads, is possible to get an optimal load spread at every water level and head difference.

It is expected that, because of the vertical connection to the bridge deck, the dynamic response of the barrier (read screen) is low. However, the dynamic behaviour of the bridge has to be controlled and checked for this abnormal load condition from the water barrier.

Because of the great length of the screen (great width of the barrier) a scale model should be made to test if the screen will be lowered completely with just hydraulic jacks at the abutments. In other words; to which extent does the screen unfolds itself (due to the water flow which is similar to unfolding/opening of a parachute) and to which extent are the jacks required. Also the lowering and storage system should be tested with a scale model.

A short screen width (cross section screen) is proposed to decrease the costs of the barrier. This invokes high vertical hydraulic loads and therefore vertical supports are required.

To keep the dynamic response under control a very low natural frequency has to be obtained. For the proposed 'bridge+screen' barrier this should be feasible because the bridge will also divert a part of the horizontal hydraulic load, in contrast to a "spinnaker" type of barrier where the perpendicular reaction forces in the abutments will be (too) large if a very low natural frequency has to be obtained.

In addition, a short screen width reduces buckling of the screen and makes storage under a pedestrian bridge possible. (The deck of the bridge is widened for the storage purpose.)

The screen orientation has a large influence on the hydraulic loads on the bridge structure and it is recommended to make a numeric estimation of the screen behaviour. As discussed the dynamic response is depending of the screen length, screen width and the barrier width.

Inspection and maintenance is good possible due to the available bridge and because the screen is stored above water. Wear and tear of the screen is minimized and environmental loading, for example biomass, UV-light is avoided by the storage system.

No hinges or other corrosion sensitive parts are placed under or near the water.

Because the hydraulic loads are far greater than the deck loads under normal conditions the dimensions of the bridge are determined by the hydraulic loads. In further research it can be concluded that the residual strength of the bridge under normal condition is such that the bridge is also suitable for motorized traffic. Also the storage of screen could be better suitable/feasible with at a large (car) bridge.

The required dimension of Dyneema® ropes for the lower cable, transition cables and the guys are in order of magnitude of the current possible rope diameters. Also the pylons are feasible, however, back stayed cables at the middle pillars are required. Without the guys, the pylon has to be tilted towards a 47 degree angle with the horizontal plane or the bending forces will be exceptionally large.

Moreover the moment stiff concrete connection between the deck and middle pillar is considered to be feasible.

Sagging of the guys can be normative for a cable stayed bridge design, however, due to the chosen light-weight material, Dyneema® ropes instead of steel wires, this sagging is less severe. Though, the difference in forces during 'barrier operation' and 'stored screen' are large and sagging can be a (aesthetic and dynamic) problem during 'stored screen'. A more detailed design must be made that includes sagging of the guys.

Because of the deck curvature the normal forces (induced by the guys) are higher than can be expected for a straight deck bridge. Also wind loading is partially diverted by pressure or tensile stresses in the deck. Buckling forces (in Dutch: "Spatkrachten") and temperature induce stresses that have to be accounted for in a more detailed design.

In the proposed design the transversal deck forces are diverted towards the middle pillars (and abutments). The buckling forces are in opposite direction of the guy and induce transversal forces that have to be diverted at the middle pillars.

The reaction forces at the middle pillars and abutments are calculated and diverting towards the bearing subgrade is considered to be feasible.

The perpendicular reaction forces towards the waterway can be reduced if a smaller radius is chosen for the bridge and the screen. This reduces the construction costs of the foundation at the abutments. Because it is a pedestrian bridge this should be possible and it could be worthwhile to optimize the length vs. the curvature of the bridge and screen.

It was presumed that the water barrier invokes tensile stresses in the deck which counteracts the pressure forces. Calculations show that this is not the case for the proposed 'bridge+screen' barrier. In contrary, the pressure forces are even (much) higher. Therefore the structure does not require an upper cable to divert the hydraulic loads.

Altered screen size and orientation or an altered pylon height could redistribute and diminish the loading on the structure. Even a more or less decoupled system of the barrier and bridge structure is possible. An upper cable is recommended for the last option because this can divert the tensile stresses better than the bridge deck. (The upper cable can also decrease/divert buckling and wind induced stresses.) The tensile stresses are invoked by the larger horizontal hydraulic load (relative to the vertical load); the residual deck forces in transversal direction are reversed.

A large screen width with a smaller upper angle decrease the loads which requires less strength of the deck, guys, pylons and foundations. So constructive this could be a good solution, however, when costs are considered this is questionable because the costs for the screen are

relatively high. In section 10.2.4 it is recommended to optimize towards a screen as small as possible.

In a more detailed design an optimization should be made for the screen size and orientation wherein some boundary conditions are addressed for like (among others); the storage capacity, opening mechanism, dynamic response and the abutment connections of the lower and possible upper cable.

Raising the pylon decreases the overall stresses in the bridge structure, however, from appendix I.4.7 it can be concluded that this effect is far less significant than an altered screen size. No changes take place in the direction of the residual deck forces.

10.2.4 COSTS

It is concluded from the literature study that an inflatable dam can be 15% up to 50% less expensive.

It was expected that the costs of the gate, or in this case the screen of a movable water barrier is a substantial part of the total barrier costs.

A Net Present Value (NPV) calculation is done on element level for the proposed 'bridge+screen' barrier. A life-cycle costs of the construction and maintenance are estimated.

It can be concluded that:

- The total life-time costs to invest at this moment for the Merwede barrier, a movable 'open fabric' water barrier suspended on a guy/stay roped bridge, are estimated at: €109.2M for the barrier and €34.2M for the bridge with barrier support structure. The total investment costs are estimated at €143.4M;
- The total life-cycle costs of the screen are 42.6% of the total water barrier life-time costs;
- It is estimated that a fabric gate is well over 34% less expensive than a steel vertical lifting/drop gate;
- The life-time of the fabric and the corresponding required life-time of the barrier have a great influence on the investment costs;
- It is stated that costs can be reduced with a shorter screen width. In the NVP calculation of this chapter each meter screen width costs approximately €2.81M. As a result, to decrease the stresses in the bridge structure with a larger screen width of 25m instead of 15m cost €28M. The benefits of a more slender bridge structure are not more than a few million (total costs of the bridge are €34M). Let alone if an upper cable and a large sill structure are required. Therefore, optimization towards a small screen is recommended.

11 EVALUATION

In this chapter an evaluation is given of this Master thesis. First of all the extent in which the objectives are met is described. Second, some concerns about assumptions, unconsidered issues and knowledge gaps are addressed.

For improvement of this thesis and or further design of a 'bridge+screen' barrier some recommendations are made.

11.1 OBJECTIVES

The main objectives, as stated in chapter 2.2, are regarding the proposed movable water barrier design. An innovation design is proposed which is optimized with relatively new materials, for the constructive hydraulic field, and combining multiple functions in one structure. The design is integrated in the UOOC concept and is to a less extent combined with architecture.

The feasibility of an 'open fabric' barrier for the UOOC Rhine mouth is proven and a preliminary design for a movable water barrier for the 21st century is obtained.

The sub-objectives are, in addition, met to a great extent. The boundary and surrounding conditions for the UOOC barriers are described and recommendation are made to deal with these conditions. These are based on technical, economical, architectural and landscape issues. Design concerns regarding an 'open fabric' barrier are addressed with the help of literature and more possibilities in constructing a movable water barrier with a syntactic fabric are presented. Also the differences in using fabric or steel as construction material is described. Several possible designs for an 'open fabric' movable water barrier are discussed.

The last objective, to create a 'flexible no-regret barrier', is not entirely met. Possible directions are presented however the feasibility of such a structure, one that grows in time with the technical and social boundary conditions, is not proven.

11.2 CONCERNS FOR FURTHER RESEARCH

- The assumption was made that closing of the New Waterway with the Maeslant barrier is still undesired in the future because of the enormous economic effects. However, with the construction of the second "Maasvlakte" many port activities are placed at the sea side of the Maeslant barrier. The economic effect of closure of this barrier will decrease;
- It is assumed that there is no water head acting on the UOOC barriers during opening. However, this boundary condition is discussed for the UOOC barriers. If the assumption is not valid an 'open fabric' movable water barrier is most likely not an option (as almost every existing movable water barrier);
- There are a lot of risks for a movable water barrier that diminish the reliability of the barrier. Each type of barrier has different risks; events that are most likely to occur or has great consequences. Also for an 'open fabric' barrier and in specific the 'bridge+screen' barrier these risks have to be evaluated. Within this Master thesis these risks are not addressed;
- The calculation of the vertical hydraulic load is questionable because too little literature is available to make a simple calculation without a numeric model and because the vertical load is highly dependable on the shape of the screen. Moreover, the forces in the screen determine the rest of the structure;

Within this thesis a rough estimation, with help of the available literature, is made for the shape and size of the screen. It could be possible that the vertical hydraulic load is overestimated and that the assumed load distribution is not accurate at all.

It is recommended to invest in a screen model that can estimate the shape and forces in the screen accurately.

- The closing and opening operation mechanism should be further investigated before conclusions can be drawn about the feasibility of the mechanism.
 - The storage of the screen should be looked at in more detail;
 - The lowering and lifting of the screen with the attached operation cables should be further designed;
 - The feasibility of the hydraulic jacks and lowering of the lower cable to the sill for a barrier with a width greater than 150 (or even >200) has to be investigated;
- In addition, it is stated that the costs estimation of the screen is a rough estimation based on the costs of the “balgstuw” at Ramspol. In addition the life-time costs of the screen are 43% of the NVP of the barrier and 33% of the NPV of the total ‘bridge+screen’ barrier. It can be concluded that a better costs estimation is required;
- It is unsure if the rules of thumb, that are used to determine the main dimensions of the bridge, are applicable for a bridge that also loaded by a water barrier;
- A better design for the deck cross section is required. The induced torsion moments due to the orientation of the connections of the guys and transition cables should be taken care off;
- Only (some) strength calculation are made. These are presumably normative during the situation that the barrier is in operation, however, during stored screen situations displacement and acceleration calculations, discomfort for the pedestrians, should be made;
- Erosion protection and seepage screens are not designed. Only an erosion length is estimated;
- Temperature, buckling, torsion, wind and local bending loads on the bridge deck structure are not investigated;
- The connection between the transition cables and the screen is not mentioned in the report. Stitching into the screen or a stiff small (floating) beam at the top of screen are two possible options to investigate;
- An estimation of the costs reduction of a screen that is designed in strength and dimension for 30 years instead of 100 years is not made, however, it could give a cost reduction;
- The costs of obstructing inland navigation during construction is not considered, however, it is expected that the construction time of a fabric barrier is shorter and with less hazards than for the construction of a conventional water barrier.

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