Paper 122 – Conceptual Design of a high discharge barrier in the Closed-Open-super dike ring "Rijnmond"

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ABSTRACT: During winter months the city of Rotterdam, Netherlands, experiences storm surges from the North Sea and high discharges in the River Rhine. Due to climate change the probability of simultaneous high ocean water levels and high river water levels will increase. Therefore, Rotterdam must be protected from both the North Sea and the River Rhine. In 2008 the Delta Commission proposed the construction of the Closed-Open super dike ring "Rijnmond" to protect Rotterdam during such simultaneous events. In this paper a short overview of a barrier designed for the Beneden Merwede, part of the Rijnmond super dike ring, is given.

1 INTRODUCTION

According to the 2008 "Working with Water" Delta Commission Report: "The task in the Rijnmond and Drechtsteden region (the area around the mouth of the Rhine river and its hinterland) can be simply summarized: how can the region be protected against floods in both the rivers and the sea and how can the adverse effects of salinization be avoided?" (Veerman, 2008) The purpose of the Delta Commission is to explore the possible effects of climate change and to "formulate a vision on the long-term protection of the Dutch coast and its hinterland." (Veerman, 2008).

The Maeslant Barrier was designed and constructed to accommodate a sea level rise of 50 cm. The challenge posed by climate change is that after 2050, the frequency of closures of this barrier may rise. Figure 1 shows possible increases in sea level rise by 2100. The greater the increase in temperature, the higher the ocean water level, the higher the storm surges, and the greater the discharge in the River Rhine. Since the high water level in the River Rhine occurs during the storm surge season, there may be an increased risk of closures of the Maeslant Barrier while the Rhine water level is simultaneously high. Because the range in the potential increase in temperature is large, planning must begin now to accommodate climate change.

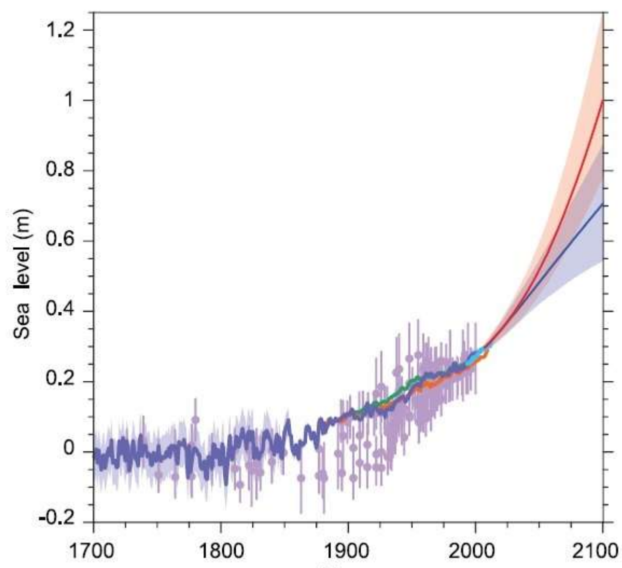

Figure 1: Projected 2100 Global Sea Level Rise Scenarios (Stocker, 2013)

The delta commission favors constructing a "closeable open" dike ring that flood-proofs the area and takes into account the needs of nature. A large ring consisting of dikes and barriers would be constructed surrounding the Rotterdam area and used in conjunction with the Maeslant barrier. This system would allow tidal flow during average water levels and prevent flooding during high water levels by redirecting the water southward to reservoirs in the Zeeland province (Veerman, 2008).

This paper explores the feasibility, alternative designs, general lifecycle and preliminary design of a barrier to be constructed in the Beneden Merwede. This barrier would be part of the larger "closable-open" Rijnmond super dike ring. This ring can be seen in **Error! Reference source not found.**.

Figure 2: Rijnmond Super Dike Ring (Veerman, 2008)

2 FUNCTIONAL REQUIREMENTS

According to the Delta Commission, the idea behind this super dike is to allow natural tidal movement while protecting the Rotterdam area from flooding. The Commission proposes that the Haringvliet remain open except during storm surge events. However, the Spui must remain as a freshwater inlet. And, salinization will become a problem in the Nieuwe Waterweg due to the flow of fresh water through the previously closed Haringvliet. In addition, due to the importance of shipping in this area, river traffic must not be hindered by a storm surge barrier. Because of these reasons, the barrier to be constructed must have null interference in the river when not in use. This would allow for normal shipping operations and for unimpeded water flow.

Error! Reference source not found. lists the boundary conditions along the Beneden Merwede. These conditions give a physical description of the environment that the barrier will operate in at this location.

Table 1 - River Boundary Conditions (van der Ziel, 2009)

River Boundary Conditions Merwede Barrier	
Width (m)	300
River Waal Max Discharge year 2100 (m^3/s)	11375
Sill Depth (m) NAP	-5.10
Max. Water Level (m) NAP	4.70
Min. Bridge Height movable (m)	11.62
Min. Bridge Height fixed (m)	13.06
Gate Width (m)	210
Gate Height (m)	10.30
Max. Head (m)	4.40

The possible planned functions of the barrier are listed in **Error! Reference source not found.**. These functions are typically gathered from the stakeholders and must be addressed. For example, the shipping industry requires that navigation on the river not be interfered with. And, the people living in the Rotterdam area require that they do not flood during a high water event. Also, the people living adjacent to where the barrier would be located require that the design be aesthetically pleasing.

Table 2 – Barrier Functions

Permeable Storm Surge Barrier Functions	
1	Defend the hinterland, differentiate low and high value lands
2	Maintain current water salinity levels
3	Regulate peak discharge of fresh river water during a North Sea storm surge event
4	Make IWT possible (study possible breakdowns during construction)
5	Improve car traffic if possible
6	Make inspection and maintenance activities possible
7	Give a viewpoint to visitors
8	Landmark

Error! Reference source not found. and **Error! Reference source not found.** list additional boundary conditions that could affect the structure during construction and/or operation and should be investigated further.

Table 3 – Hydraulic Boundary Conditions

Hydraulic Boundary Conditions	
1	bathymetry of the dry and wet part of potential boundary location (by GIS)
2	flow discharge and current velocities, directions and frequencies
3	water density (variable in space and time)
4	wind velocities, frequencies and directions
5	fog density and frequencies
6	river run-off in amount and frequencies of exceeding
7	morphology of the river, estuaries or sea
8	ice occurrence, thickness, period and frequencies

Table 4 – Land Boundary Conditions

Land or Under Water Side Boundary Conditions	
1	origin, nature and building up of the (sub)soil
2	soil properties (type, origin, density, bearing capacity, compressibility, permeability)
3	Earthquakes due to gas and oil exploration

Next, the height of the barrier and the maximum water level difference between each side of it must be determined. It is proposed that the height of the barrier be a function of the height of the existing adjacent dikes, the length of time of closure, the amount of discharge expected from the Rhine River, and the size of the potential reservoirs that will temporarily store the flood water.

The average height of the dikes in the Rijnmond-Drechtsteden area is assumed to be 4 m +NAP. This is estimated from the mean high water (MHW) at Dordrecht which is 2.9 m + NAP (Slootjes, 2011). Therefore, the height of the proposed barrier will also be at least 4 m +NAP. With the height of the dikes and the barrier fixed, the main variable will then be the amount of water stored in the reservoirs.

Since the average closure time of the Maeslant barrier due to storm surge is ~24 hours, this barrier will be designed with an average closure time of ~24 hours. Although, actual closure time may be longer if the barrier is to open and close when there is no head difference. This will be due to the amount of time required to release the water from the reservoirs in order to lower the water level outside of the barrier. This should also be taken into account.

3 LOCATION

The location where the barrier will be built is shown in Figure 3. This location was chosen via a multi-criteria analysis and a cost-benefit analysis contrasting this location with another in the area. The barrier is proposed to be located near a bridge that is downstream of the beginning of Beneden Merwede (See red line in Figure 3). On the north bank, the dike is very close to the river. On the south bank, there is much more room to store the gate of a barrier, if it is not located within the river area itself (such as an inflatable barrier, parachute barrier, lifting or visor gates, et cetera). Therefore, given the design requirements, most of the barrier structure and/or auxiliary constructions if needed will likely be located on the south bank.

The grey line shows a new dike that will need to be constructed. It will connect with a small barrier that will reach across the Wantij (bottom of Figure 3). This barrier will connect with the Wantijdijk on the south bank of the Wantij. The length of the new dike will be about 1.45 kilometers. The length of the small barrier will be about 75 meters. However, the design of this new dike and small barrier is not a part of this study. In addition, the lowlands east of the proposed dike in Figure 3 can be flooded during high water events adding storage capacity to the overall system. However this must be further discussed with local stake holders.

Figure 3: Location Description (Earth, 2013)

4 FLOODED AREAS

4.1 *Description*

The Rotterdam area is heavily influenced by the North Sea and the Rhine River. To obtain the reservoir boundary, it is necessary to decide on the maximum flooded area. The potential areas that could be used as a reservoir during a storm surge event are indicated in Figure 4, including rivers and some wetlands. The estimated total flooded area is approximately 678,500 km^2. A storm surge event has an average duration of ~24 hours. For a maximum discharge of 14,000 m³/s, the maximum water level resulting from a flood wave would be around 1.80m if all of the areas were opened. Considering that the average discharge of the Rhine is approximately 2,300 m³/s and that the height of the dikes are 4 m + NAP, there should be more than enough storage space for future high water events.

Figure 4: Reservoir Areas (Earth, 2013)

4.2 *How the System Would Work*

As previously mentioned, the height of the surrounding dikes is assumed to be 4 m +NAP. Because of this, we assume a maximum water level of 3 m +NAP outside the barrier. In order to maintain a water level below 3 m +NAP, we will use the areas shown in Figure 4 in a sequence thereby ensuring the water level does not rise above 3 m +NAP anywhere in the system.

When the water level outside the barrier is projected to be above 3 m +NAP, additional areas will be opened for flooding. For example, if a potential flood wave is projected to cause the water level in the Haringvliet to be above 3 m +NAP, the Volkerak and the Grevelingen would be opened to flooding in order to decrease the water level in the Haringvliet to below 3 m +NAP. Before a flood wave arrives, water level projections will be taken into account and a timing sequence formed.

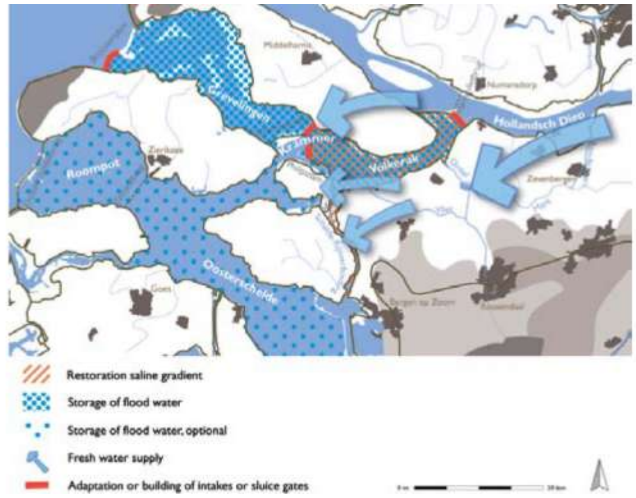

Figure 5: Flooding Sequence (Veerman, 2008)

5 ANALYSIS OF ALTERNATIVE GATE TYPES

5.1 *Approach*

The PIANC report published by Working Group 26 of the Inland Navigation Commission, "Design of Movable Weirs and Storm Surge Barriers," (PIANC, 2006a) presents an inventory of barrier gates located around the world. It includes visor gates; flap gates; inflatable weirs; miter gates; innovative, double, and single radial gates; and sector, swing, and vertical gates. This PIANC report is the basis of an investigation performed to explore the possible gate types for the Beneden Merwede.

Following this investigation, a multi criteria analysis (MCA) was performed in order to select the optimal gate type. The MCA was based on the descriptions of the barrier types in the PIANC report and how these descriptions addressed the functions listed in Table 2.

5.2 *Conceptual Design Selection*

From the MCA, it was determined the sliding gate is the best option. Some of the practical reasons are as follows:

- The gate will be located in a dry chamber allowing for easy inspection and maintenance.
- There will be only one movement allowing for a lower failure risk (in case of gravity stabilized barrier).

- The barrier is also balanced hydrostatically per stretch meter of the barrier and not at one point allowing for a lower failure risk.

- This is not "new" technology so design and construction experience is available.

- This design is more robust and cannot be as easily destroyed as a bellow barrier for example. This aspect decreases the risk of destruction due to terrorism.

However, some disadvantages (with solutions following) are:

- Damage to the rail could hinder gate movement, and therefore, the closing of the barrier.

  (Solution: The rail will be inspected once yearly for potential damage. And, there will be a cleaning mechanism in front of the gate as it travels along the track.)

- Due to its size and the materials used, this solution is one of the most expensive of the available solutions.

  (Solution: Advanced computational optimization will be used.)

- During construction, there is great potential for interference with shipping. This would occur when the track is being constructed in the river bed.

  (Solution: Several options will be explored such as temporarily redirecting shipping traffic to different routes and placing the track in sections to avoid major shipping interruptions.)

5.3 *Principle Solution*

Initially, the sliding barrier proved to be difficult to scale to existing, realized projects. Some possible reference projects include: the Antwep lock, the third set of Panama locks that are currently under construction, and the Maeslant Barrier. None of these projects present a design that could be scaled up or scaled down exactly. Therefore, there is not really a true existing "look-a-like reference project". However, the cost of the Maeslant Barrier could give an initial idea of the cost of a sliding barrier. Similar materials will be used, the length and head of both barriers would be similar. However, the height of the sliding barrier would be half that of the Maeslant Barrier; therefore, it would be approximately half the cost. The 2012 cost of the Maeslant Barrier is approximately 1.025B Euros. (1991 cost: $450{,}000{,}000*(1.04)^{21}$ = ~1,025BЄ with 4% annual inflation rate (van der Toorn, 2010)). This very rough calculation and comparison shows that the cost of the sliding gate should be around 500M Euros.

There was an alternative design to the Maeslant barrier before it was built. Although actual dimensions for it could not be found, it is scaled in Figure 6 assuming a 15 m base. This was a good estimated base width because the height from top to bottom according to this scaled drawing is approximately 10 m - the same has the proposed dimensions.

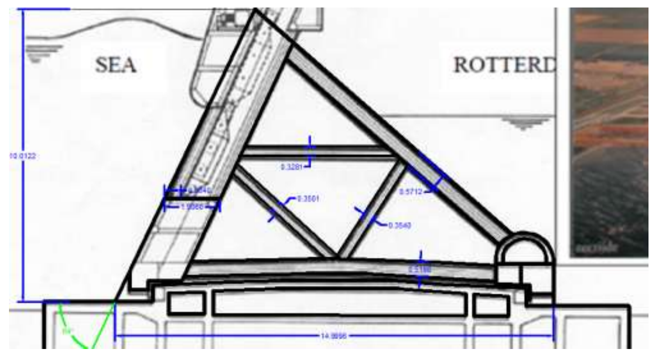

Figure 6: Scaled Dimensions with Overlay (m) (Rigo, 2006b)

5.4 *Cost Benefit Analysis*

According to the lecture notes of the course Hydraulic Structures II at TU Delft "When people feel safe behind the primary dike rings and people or goods are easy to transship and to transport, then the value of buildings is increasing and there is a positive attitude to (more) investments." (Van der Toorn, 2013). This is the living and working environment that should be strived for in the Rotterdam area. The super dike ring should have the ability to effectively protect the Rotterdam area from major flooding and, equally important, give the public confidence that their physical investments will be safe. This will encourage future investment and thereby justify the cost of constructing the dike ring.

Table 10 shows the initial projected costs of the project to be constructed in the Beneden Merwede. This total including the Beneden Merwede barrier, new dike and additional small barrier is approximately 561M Euros. It should be noted this is a very rough estimate and the final costs can vary significantly from this initial estimate. Overall, the monetary goal for the entire project is for it to cost less than the anticipated benefits created by the Rotterdam area.

Table 10: Initial Projected Costs

Aspect	Factor	Unit	Height (m)	Head (m)	Length	Unit	Total (M€)
Dike	6,305,000	€/m/km	4	–	1.45	km	36.5
Barrier 1	31,500	€/m3	10.3	4.7	300	m	457.8
Barrier 2	31,500	€/m3	6	4.7	75	m	66.7
Total							561.0

6 Design

6.1 *Operational Design*

The barrier will be located on the Beneden Merwede southeast of Rotterdam (See Figure 7). The barrier will consist of just one gate located in a dry chamber on the south bank of the Beneden Merwede. When activated, this gate will travel north along tracks previously installed on a sill located on the bottom of the river. Once full travel is achieved, the gate will connect with the dike that is under the Baanhoek road. The gate will likely not completely stop the flow of water.

The width of the river at this crossing is about 300 meters. This will also be the approximate length of the gate. The dry chamber (large gate recess) will extend slightly into the river to allow for safe operation of the gate. And, there will be a receiving structure on the northern bank (small gate recess) that will extend slightly south into the river also for safety reasons.

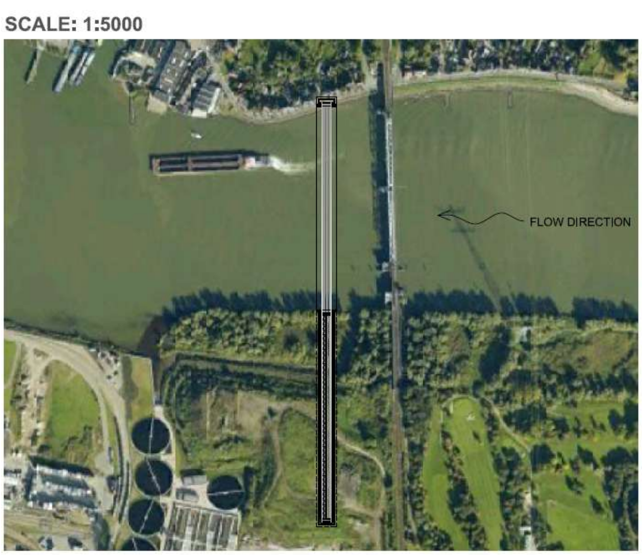

Figure 7: Site Layout (Earth, 2013)

The front end of the gate will be box shaped and will feature a guard similar to that of a cattle guard of an old train. The guard will clear away any large debris that may have fallen on the rails.

The gate will slide north along the frictionless material rails/guides such as ultra-high molecular weight polyethylene (UHMPE). It will stop traveling just before reaching the small recess. This will increase the velocity of the water in this small area and clean out the recess and the debris guard. Next, the guard and boxed end of the gate will travel into the recess to block the flow of water around the front of the barrier.

Also, the back end of the gate will be boxed shaped. This will prevent water from flowing around the back of the gate through the chamber once the gate has reached full travel.

And, a small UHMPE lifting gate will act as a door for the barrier's large recess. This will allow for the recess to be sealed and pumped dry when the gate is not in operation. However, in order to do this, the section of the rail (in case of rolling barrier)/contact surface (sliding barrier) where the sliding door is to go should either be removable or there should be a permanent gap in the rails, the second option is decided. Also, the door will have valves and a breaker plate to fill the recess before the sliding door is opened. Pumps will be required to pump the recess dry after the gate returns to the recess.

6.2 *Operational Sequence*

1. A flood wave with a head above 3 meters is predicted in the Rhine River.
2. The coastal barriers adjacent to the reservoirs are closed at low tide if a storm surge event is simultaneously expected.
3. The valves in the sliding door are opened and the chamber is flooded.
4. The lifting door is opened.
5. The barrier is slowly pushed by a locomotive along the tracks until it reaches the north recess where it stops just before entering to allow the recess and the guard to be cleaned by the flow of the river.
6. Once the guard and the recess are clean, the guard and front box move into the recess until the water stops flowing around the front of the gate.
7. The gate remains in this position for the duration of the flood wave.
8. Once the storm surge subsides (~24hrs later) the barriers along the coast are opened and the excess water in the reservoirs is drained.
9. Once the water level in the river is the same on both sides of the barrier, the barrier is slowly brought back to the chamber.
10. Next, the lifting door is closed.

11 The water is pumped out of the chamber.
12 Inspection and maintenance of the barrier can now occur in the dry chamber.

6.3 *Dimensions*

Several variables were taken into account when determining the dimensions of the gate. These included boundary conditions such as the sill depth during normal river conditions, the maximum water level, and climate change as previously mentioned. Table 12 shows the basic proposed dimensions of the barrier. These dimensions are based on the boundary conditions stated in Table 1.

Table 12: Sliding Gate Geometry

Sliding Gate Geometry:			
Base Width:	B	15.00	*m*
Gate Height:	H	10.00	*m*
Gate front slope:	s_f	0.50	
Gate rear slope:	s_r	1.00	

Table 13 shows the proposed maximum water level outside the barrier of 4 m. The maximum head during this time would be 4 m resulting from the assumed water level inside the barrier being 0 m +NAP.

Table 13: Elevations

Elevations:			
Gate Base EL:	EL_b	-5.10	*m*
Gate Top EL:	EL_t	4.90	*m*
OW (Outside Water) EL:	EL_{hw}	4.00	*m*
IW (Inner Water) EL:	EL_{tw}	0.00	*m*
Foundation Top EL:	EL_s	-5.10	*m*
Foundation Thickness:	T_{fs}	3.00	*m*
Foundation Base EL:	EL_{Base}	-8.10	*m*

Table 14: Hydrostatic Calculations

Hydrostatic Pressure:			
Outside Water			
Specific Gravity of Water	γ	10.00	kN/m
Distributed Water Pressure	$\sigma_{woutside}$	91.00	kN/m^2
Horizontal Water Force	H_1	414.05	kN/m
Inclin. w.r.t vertical (angle)	α	26.00	deg.
Hor. Dist. Over Concrete Slab	x	4.44	m
Vertical Force	V_1	305.40	kN/m
Inside Water			
Distributed Water Pressure	$\sigma_{winside}$	51.00	kN/m^2
Horizontal Water Force	H2	130.05	kN/m
ΣH (H_1 - H_2)		284.00	kN/m

Figure 8 shows the inial proposed dimensions of the barrier. In the figure 0.0m +NAP =0.00m.

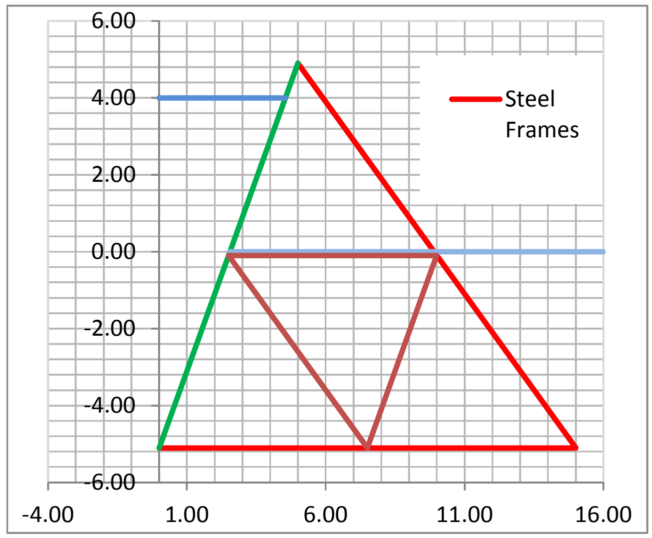

Figure 8: Initial Design Sketch (High Water on East Side of Barrier)

6.4 *Chosen Barrier Design*

This design uses steel tubing and a concrete face as its main components. The tubing is especially meant for ease of maintenance and to be assembled offsite in segments. The segments are then shipped to location and welded together in place. Once this truss is formed, steel plates will be placed on the up river side of the truss. Next, the high resistant to abrasion concrete will be placed on the steel plates. However, bending moments regarding concrete faces and normal expansion/contraction need to be taken into account. Expansion joints may be required in the concrete face or rebar reinforcement to cope with shrinkage. If so, it could be easier and more cost effective to precast these face segments offsite and later attach them to the truss on location.

One possible disadvantages of this design is:

1. Maintenance from corrosion of steel. Although it is minimized by using steel tubes, this is the lesson learned from the Eastern Scheldt Barrier.

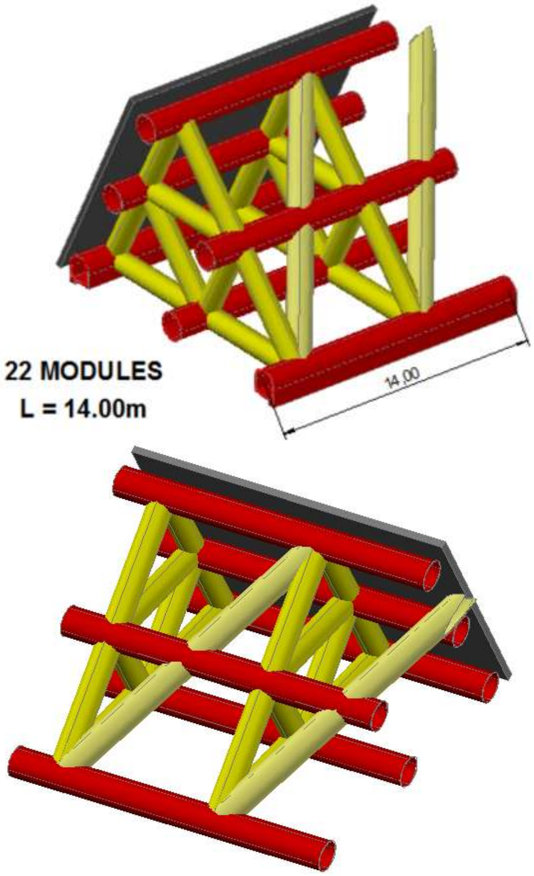

Figure 9: Main Barrier Design: Steel and Concrete

6.4.1 *Horizontal Stability*

This design should be horizontally stable due to its very heavy weight and should remain on its position due to the lateral guides, as shown in Figure 9. That, along with the designed foundation should prevent any sliding that would occur. However, further soil borings and samples should be taken to overcome any kind of foundation problems.

6.4.2 *Rotational Stability*

The dead weight of this structure ensures that the entire base of the barrier be in compression during maximum head difference. This is calculated by the hydrostatic force going through the 1/6 middle of the structure corn.

6.4.3 *Vertical Stability*

Given the weight of the gate and the sill, the bearing capacity of the soil beneath the sill should be checked. Compression piles will likely be required beneath the sill to support it and the barrier's weight. The soil can also be improved through soil improvement techniques to increase its strength.

6.5 *UHMPE Barrier Design*

This design relies on composite materials or ultra-high molecular weight polyethylene (UHMPE). This material will reduce maintenance costs because it would not corrode. But, it is unproven on this scale. Due to the proposed guide sliding connection, friction and bending moments along the barrier due to differential settlement of the rails and water head should be checked. Also, the required face thickness reinforced with fiber glass profiles should be thoroughly examined. This will likely be a function of the tensile strength of this material and the distance between the supports in each segment.

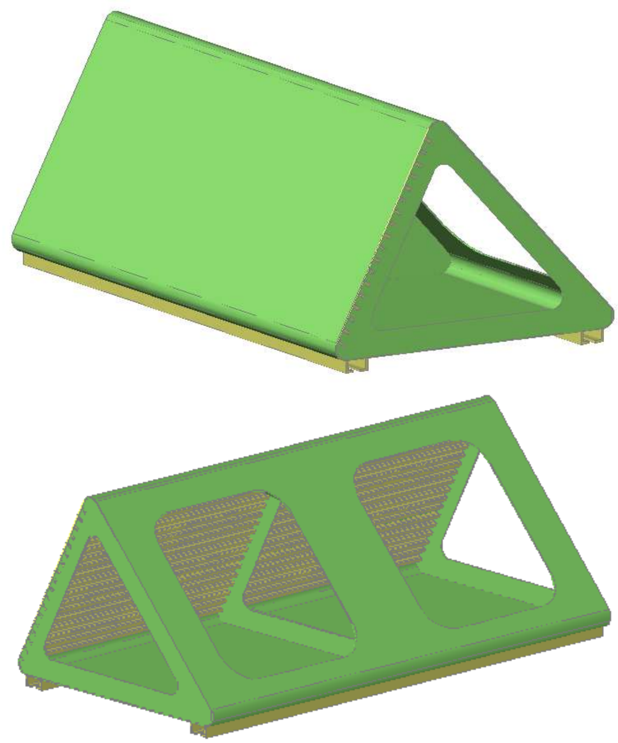

Figure 10: Alternative Composite Barrier Design

This barrier would partially float to its final position to withstand the design conditions. To avoid longitudinal bending moments along the river span, a segmented barrier with flexible connections is adopted, shown in Figure 11.

Figure 11: Alternative Composite Segmented Barrier

6.5.1 *Horizontal Stability*

Since this material is lighter, the foundation could be built in segments possibly not requiring piles. This would be a more efficient construction method because it would not disrupt shipping. But, the segments must be heavy enough to prevent sliding especially while the barrier is traveling along the sill.

Figure 12: Foundation Segments (Index, 2012)

6.5.2 *Rotational Stability*

Because of the light weight material of this structure, the up river side of the barrier will be in tension. Therefore, guides (see figure below) have been designed to keep the barrier attached to the sill. The foundation segments should also be designed to prevent rotation of the barrier. (See Figure 13**Error! Reference source not found.**). As mentioned previously, the barrier face will be reinforced by fiberglass beams (e.g. Pultex® standard structural profiles and superstructures) to withstand the design water pressures.

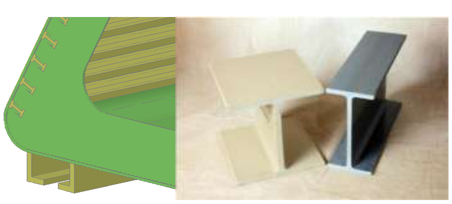

Figure 13: Guides and Fiber Glass Profiles

6.5.3 *Vertical Stability*

The soil bearing capacity should also be checked for the alternative design. The bed will likely need to be enhanced to support the weight of the segments and to prevent differential settlement among the segments.

6.6 *Flow Induced Gate Vibration*

Operation of flood barrier gates is sometimes hampered by flow-induced vibrations (FIV). In the case of the self-weight (concrete and steel) gate and as it is fixed on the rail, vibration seldom happens. The highest probability of FIV occurs when the gate is about to enter the small recess. This is due to the high flow velocity created between the front of the gate and the recess. FIV should be taken into account by ensuring that the lowest natural frequency of the barrier is greater than the dominant excitation frequency and that they are never the same.

In the case of the UHMPE gate this situation may not be critical. Nevertheless it needs to be checked.

6.7 *Foundation Design*

The foundation design is a critical aspect of this project. It must be reliable for the entire lifecycle of the project and require as little maintenance as possible. The foundation design will largely depend on the objectives of the barrier and the site conditions, e.g. soil properties beneath the river bed. During use, the barrier must be stable and not slide, rotate or subside. This implies that there has to be a horizontal, vertical and rotational stability. This can be expressed with the following well-known equations:

$$\sum H_{total} = 0; \quad \sum V_{total} = 0; \quad \sum M_{total} = 0$$

Where:

$\sum H_{total}$: total of the horizontal components of the acting and reacting forces [kN]

$\sum V_{total}$: total of the vertical components of the acting and reacting forces [kN]

$\sum M_{total}$: total of the moment caused by the acting and reacting forces [kNm]

6.7.1 *Concrete and Steel Gate Foundation Design*

As far as soil stiffness and strength are concerned, the first thing to do is to carry out borings in the river bed where the sill is to be built.

This will yield the most accurate parameters to base the stiffness and strength calculations on.

Once the profile of the soil layers is known, the stress distribution of the barrier and sill should be calculated in the soil beneath the sill. Then, the average increase in stress of the weak layers should be computed. Next, the strain, then finally the total settlement should be found. Koppejan is more accurate for weaker soils. For vertical bearing capacity or strength, the Prandtl and Brinch Hansen formula should be used for well – permeable soil, e.g. sand.

The foundation will require bottom protection and a filter bed.

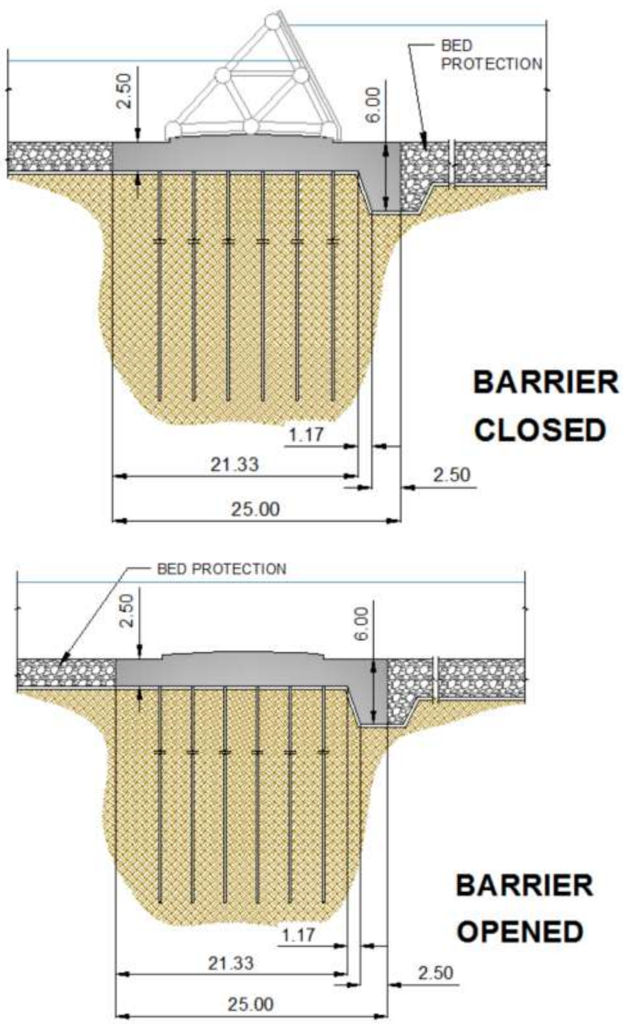

Figure 14: Preliminary Foundation Design for Steel Barrier

Below is a cross-section view of the barrier when it is dry in the chamber.

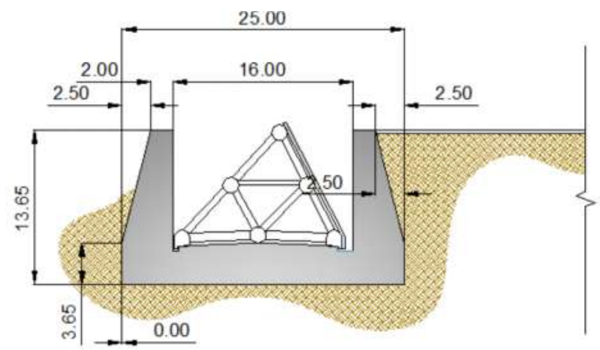

Figure 15: Chamber for Steel Barrier (Foundation piles not pictured)

6.7.2 *UHMPE Gate Foundation Design*

The design of the foundation of the UHMPE Barrier will also depend greatly on the soil parameters. However, since this barrier will weight much less than the Steel Barrier, its foundation design will be quite different.

However, calculations have not been made thus far for this foundation design because of the great uncertainty concerning the actual barrier design. As shown in Figure 12 segments could be used but this must be further investigated especially for sliding and rotational stability.

6.8 *Adapatability*

This barrier and associated water storage reservoirs are designed in such a way that the barrier height and surrounding dike heights are "fixed" and the height of the water in the reservoirs is the main variable. This is due to the ample storage area in the proposed reservoirs. Therefore, the main adaptability issues would arise from unforeseen maintenance issues and unforeseen operational challenges just after the barrier begins operation.

7 CONSTRUCTION

7.1 Construction Sequences for Steel Barrier Design

As a reference, the Maeslant Barrier took 6 years to construct. Since these two barriers share some similarities, this barrier could be expected to take a similar amount of time to construct. An overview and relative timetables for each general part of the construction sequence are given below.

Table 18: Rough Estimation of Construction Sequence and Duration

	Site (River)
1	Dredge to remove soft materials
2	Construct a cofferdam on south side
3	Drive piles
4	Place underwater concrete
5	Dewater site
6	Place slab and guide rails
7	Place erosion protection
8	Remove south side cofferman/construct north side
9	Repeat above process on north side for sill
10	Construct recess on north side
	Gate
1	Construct building pit using steps 2-6 above
2	Weld steel tubular segments offsite
3	Construct dry chamber
4	Transport framed tubular segments to the site
5	Connect framed tubular segments to form truss
6	Place concrete (in sections like a bridge span)
7	Remove cofferdam and fill behind the chamber

As stated earlier, the construction sequence for the concrete and steel gate will resemble a more traditional construction sequence that features a cofferdam and dewatering. This is due to the overall weight of the structure and the bottom slab. Drawbacks of this type of construction include: a higher cost than using precast materials, disruptions to IWT, high maintenance cost and likely longer construction times.

To begin with, dredgers will remove the top layer of soil on the river bed. Next, the soil will be compacted if needed with vibrators similar to the ones used for the Oosterschelde. After that, a cofferdam will be constructed on the south bank. It will consist mainly of sheet piles that will be driven into the riverbed. This work site will extend from the back of the chamber to halfway into the river. The sheets to be driven in the river could be driven from pontoons.

Because half of the river will be closed due to this construction site, some river traffic will be redirected to the Dordtsche Kil. This must be planned properly because of the long time required to construct the barrier and the large amount of IWT that traverses this river.

Next, the piles will be driven. This will likely be accomplished with cranes located on a barge with pile drivers attached to the cranes. Afterwards, underwater concrete will be placed.

Once the underwater concrete hardens, the worksite can be dewatered. The piles will initially act as tension piles preventing up heave. Next, the sill can be built. The picture below shows this situation. However, the actual foundation design will likely have fewer piles.

Figure 16: Piles and Underwater Concrete (Van der Horst, 2012)

Once the sill construction is completed and bed protection is placed, the worksite can be filled with water, the cofferdams removed, and the same process repeated for the north side bank of the river.

While the sill is being constructed in the river, the gate and the chamber can be built on the south bank. This construction site will also require a cofferdam, underwater concrete and dewatering. But, it will also require excavation of the soil once the cofferdam is built so that the piles could be driven and the underwater concrete placed.

Next, the site is dewatered and the chamber is constructed. Simultaneously, the tubular segments are prefabricated offsite. Once the chamber construction is completed, the segments can be transported to the site. The segments will likely arrive by boat and have to be placed in position by crane. Once in position, the segments can be welded together and the truss is formed.

Next, the concrete is placed. Once the gate is completely assembled, the door can be installed. Afterwards, the sheet walls are removed and the area behind the chamber is back filled.

7.2 Construction Sequence for Alternative Design (UHMPE Gate)

One difference between this construction sequence and the one described above for the concrete and steel gate is that blocks may be used as a foundation (pending further investigation) instead of a sill and underwater concrete. Therefore, the construction costs should be less because the cofferdam is not used and the blocks are precast offsite. In addition, IWT should not be greatly affected because the cofferdam will not be built. The blocks will be precision placed with a floating derrick and a tower crane similar to those of the Maeslant Barrier (See Figure 12).

A second difference is that the south (large) recess will not be needed for the alternative design. Due to the lightweight and flexibility of the UHMPE gate segments, they can be stored in sections on the bank, even parallel to the river, significantly reducing the costs of the overall barrier. The rails can be placed at 4.0 m +NAP following the curve of the dike and gradually sink into river.

8 CONCLUSION

This paper shows that the use of reservoirs in the Zeeland Province and the construction of a sliding barrier is the optimal preliminary design for the Beneden Merwede with the purpose of protecting Rotterdam from simultaneous high North Sea and River Rhine water levels. This is concluded from a multi-criteria analysis (MCA) and a cost-benefit analysis. A rough cost estimate shows such a barrier and connecting dike system would cost over 560M Euros.

This paper also shows that two different types of materials could be used to construct the barrier. These include the traditional concrete and steel materials and the ultra-high molecular weight polyethylene (UHMPE) materials. While there has been more experience with constructing traditional steel and concrete barriers, there could be more initial and long term cost savings by using UHMPE materials. Therefore, more research should be conducted to develop UHMPE barrier designs for the Closed-Open super dike ring "Rijnmond" to effectively protect Rotterdam from future climate conditions at a lower cost.

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