# STORM SURGE BARRIER: OVERVIEW AND DESIGN CONSIDERATIONS

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In this study an overview of existing and planned storm surge barriers in the world is provided. A systematic analysis relates functional requirements (e.g. navigation and tidal exchange) to the main barrier characteristics (e.g. gate type, dimensions). Furthermore, as the costs of barriers are an important issue in the planning, available cost information is analyzed and related to main barrier characteristics. An approach to provide a preliminary cost estimate of new barriers is presented. Finally, some critical technical challenges are discussed and related to functional requirements and boundary conditions. Overall, the results of this study can assist in the initial design and planning phase of storm surge barriers for new locations.

*Keywords: storm surge barrier, coastal structures, flood risk, coastal protection.*

## INTRODUCTION

Human population in coastal zones is exposed to a variety of natural hazards such as erosion, salt water intrusion, subsidence, tsunamis, and floods resulting from both storm surges and high river run-off (Small and Nicholls, 2003). However, due to climate change induced effects, such as sea level rise, the likelihood of natural hazards will increase, making these areas more vulnerable. Moreover, coastal zones are associated with large and growing concentrations of human population, settlements and socio-economic activities (Small and Nicholls, 2003), intensifying their vulnerability. From an economical perspective these conditions lead to a higher demand for safety and a corresponding substantial investment in improving flood protection (Van Dantzig, 1956; Brekelmans et al., 2012). Furthermore, flood protection standards are expected to increase with enlarged prosperity (Hallegate et al. 2013). It is therefore expected that in coastal regions around the world governments will continue to invest more in coastal protection.

In areas with large bays, estuaries or coastal waterways with adjacent flood defenses, constructing a barrier can be a suitable option to protect coastal zones. This type of solution is often chosen as a preferred alternative, when the required length of dike strengthening behind a barrier is significantly reduced (Jonkman et al., 2013). This measure can shorten the exposed coastline, and subsequently reduce the costs and hindrance of dike improvement in densely populated areas. In addition the construction time required to improve the dikes can be shortened considerably (Rijkswaterstaat, 1976).

Although several types of barriers (e.g. closure dams, tidal barrages and storm surge barriers) exist, storm surge barriers are mainly considered as a future intervention for more developed and prosperous regions, such as many coastal cities. In such regions preserving ecology or maintaining navigation have a large value and the high costs of storm surge barriers compared to the alternative type of barriers can be afforded. For example, storm surge barriers are currently proposed at Houston, USA (De Vries, 2014); New Orleans, Mississippi, USA (van Ledden et al, 2012), New York, USA (TU Delft, 2013; Dircke et al., 2009; Aerts et al., 2013); Manila, Philippines; Ho Chi Minh City, Vietnam and Tokyo, Japan (Ruiz Fuentes, 2014).

Currently only fifteen storm surge barriers worldwide have been designed and constructed so far. These structures show a great variety in design and appearance as many different hydraulic gate types are applied, likely due to the unique conditions and requirements they are facing. This suggests that there is not one single perfect hydraulic gate type, and often a tailor-made design is required (Dircke et al, 2009). Subsequently, while for other hydraulic structures, such as dams, dikes, locks and closure dams many design guidelines exist, no design guidelines have been published for storm surge barriers. Some publications address several design aspects of storm surge barriers. The design report by PIANC (2006) offers several options for hydraulic gate types and provides an overview of all relevant design aspects to consider. Dircke et al. (2009) give an overview of different types of barriers at a general level. Various design report and publications have been published for individual barriers; see e.g. (Rijkswaterstaat, 1986, Rijkswaterstaat Deltadienst, 1957). However, so far no systematic overview

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and analysis of storm surge barriers has been published. Subsequently, the main design aspects relevant for determining the feasibility of storm surge barriers have not been identified.

The objective of this publication is to assist in assessing the feasibility of a storm surge barrier project in the initial stages of planning. This is achieved by collecting information about the main characteristics and main design aspects of existing storm surge barriers. Next these main characteristics and design aspects are systematically analyzed and related to the functional requirements (e.g. navigation, environment). As costs of barriers are an important issue in the planning, available cost information is analyzed. The closing discussion discusses the critical design factors, trends and challenges concerning storm surge barriers more generally.

## ANALYZED STRUCTURES

### Barrier types

Several options for barriers exist and here three types are distinguished: closure dams, tidal barrages and storm surge barriers. In the next paragraphs every barrier type is described.

Closure dams close off an estuary from the sea. They prevent sea water from entering the newly formed lake, minimalizing the risk of floods here. At most closure dams the impoundment of the estuary forms a fresh water lake. This newly formed lake provides appropriate conditions for expanding agriculture by land reclamation (e.g. Afsluitdijk in the Netherlands, Saegmungeum in Korea). Therefore a closure dam is especially an interesting option when there is a demand for expansion of agriculture. Next to having closed sections most closure dams are equipped with sluices to release river run-off and regulate the water level in the newly formed lake. Furthermore most closure dams consist of a lock to allow for navigation. The size of these hydraulic structures is small compared to dam sections. For structures having larger opened sections than closed sections it is more appropriate to call them sluices or locks rather than closure dams (e.g. Haringvlietsluizen and Locks IJmuiden in the Netherlands).

Secondly, a tidal barrage is a barrier constructed to produce tidal power. A tidal barrage is equipped with turbines and sluices to allow tidal exchange between the basin and the sea. As the water in the basin is regulated, protection against extreme surges is achieved as well. Examples of these types of structures are the tidal power plants at La Rance (France) and Sihwa (Korea). These type of barriers are especially suitable for estuaries with large vertical tides (>5 m), as in these situations a barrier of this type can become economically feasible.

Finally, a storm surge barrier is a partly moveable barrier in an estuary or river branch which can be closed temporarily. Its main function during surges is to reduce or prevent the rise of inner water level and thereby sufficiently protecting the hinterlying area against inundation. Here, sufficiently regards the maximum allowable inner water level which, in turn, is influenced by river runoff and is determined by the height and safety standards of the dike ring behind the barrier. Furthermore with a storm surge barrier the water level in the estuary is not regulated during normal conditions to allow for navigation and tidal exchange. To distinguish the structure from a closure dam, the size of the movable section must be large enough to be able to allow sufficient circulation flow in the inner water in normal conditions (De Vries, 2014). A storm surge barrier only has temporary closures, meaning closures required to protect against flooding starting from the moment of closing (related to expected high water levels) until the outer water level has dropped sufficiently or closures required to make the structure available for maintenance or repair (PIANC, 2006). A storm surge barrier generally incorporates more advanced technology, and has relatively high capital and maintenance costs (UNFCCC, 1999). To reduce costs storm surge barriers often have large closed sections as well, similar to a closure dam.

### Selection

The selection of hydraulic structures mainly originates from the definition proposed in the previous paragraph. First, as the structure is open in normal conditions, there is no significant head over the structure. Subsequently there is an equal salinity at both sides of the structure. Therefore, large sluices or locks, such as the Haringvlietsluizen in the Netherlands and the Berendrechtsluis in Belgium, are not part of this study. Furthermore only structures with a temporary closure during a storm surge have been considered for this study. This rules out many hydraulic structures along the Elbe and Weser in Germany (Oste, Stor, Kruckau, Pinnau, Ilmenau, Hunte, Ochtum, Lesum), which close during both storm surges and extreme tides[3,4]. Finally the size of the movable section has to be large enough to distinguish it from a closure dam (e.g. Brouwersdam, Netherlands) or a guard lock (e.g. Keersluis Keizersveer, Netherlands). Therefore, for this study only barriers with a total length spanning over 25 meters have been selected. For locks a span of 24 meters is seen as the maximum economical span for mitre gates (Glerum et al., 2000). As generally structures with mitre gates are not considered to be storm surge barriers this is a legitimate criterion.

### Definitions of length and width

A storm surge barrier consists of three types of sections: a gated section, a dam section similar to a closure dam and in some cases a lock. The gated section consists of the hydraulic gates and the structures required to operate these gates.

The main dimensions used in this study are defined here. The length of the barrier is the distance along the axis of the barrier reaching from bank to bank. The length of the opening is the same as the span of the gates. The total of all the spans of a barrier is called the cumulative span of the gates or the total span. In this study the width of the lock is the same as the span of its gates. Although the length of the lock is not investigated in this study, it is mentioned that it is perpendicular to the axis of the barrier. All these dimensions are presented in a schematic top view of an imaginary storm surge barrier with dam sections, a lock and two hydraulic gates in figure 1.

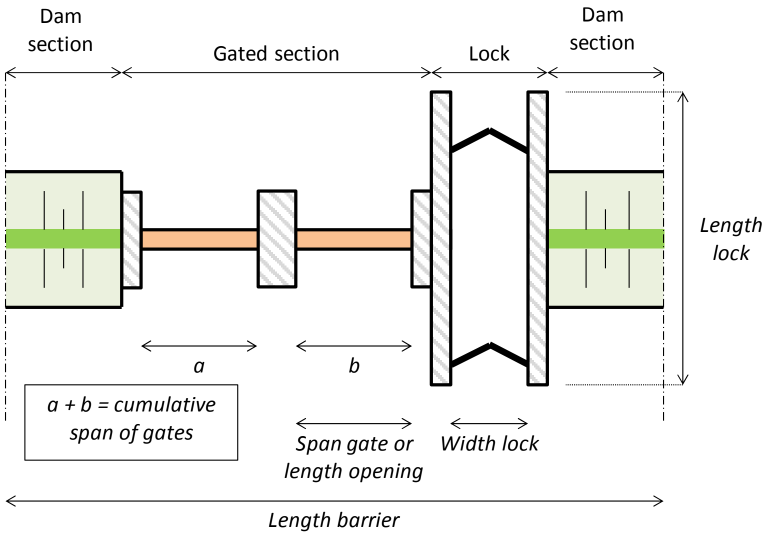
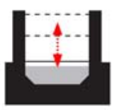


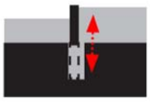

**Figure 1: Basic top view of a storm surge barrier**

### Categorization of hydraulic gate types

The hydraulic gate types are categorized by their degree of freedom, both direction of motion or rotation. At the studied storm surge barriers the following gate types are found;

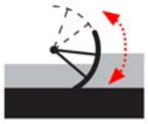
| Pictogram (Dijk et al., 2010) | Description |
|---|---|
|  Front view | Vertical lift gates are lifted vertically from the sill to open. Lifting can be done using a tower with overhead cables, sheaves and bull wheels to support the gate during its operation [0]. |

[3] http://de.wikipedia.org/wiki/Ostesperrwerk, assessed at 18/08/2014
[4] http://www.nlwkn.niedersachsen.de/hochwasser_kuestenschutz/landeseigene_anlagen/sperrwerke, assessed at 18/08/2014



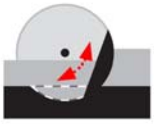
Cross-section

Vertical rising gates lie beneath the sill in open position. The gates are lifted vertically to close the barrier. Both in open and in closed position the gate lies under water (for a large part). To allow maintenance it is possible to lift the gate above water.



Cross-section

The segment gate rotates around a horizontal axis, which passes through the bearing center (Erbisti, 2004). In closed position the segment gate rests on the sill and in open position it is lifted. Other names for this gate type are radial or tainter gates.



Cross-section

Similar to a segment gate the rotary segment gate has a horizontal axis. It lies in a recess in the concrete sill in the bed of the river. The rotary segment gate contrasts the normal segment gate as it is possible to sail over the gate in this position. Operation of the gate is achieved by the rotation through approximately 900 thus raising the gate to the 'defense' position. A further 900 of rotation of the gate positions it ready for inspection or maintenance (Tappin, 1984)

Top view

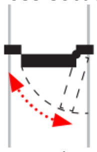
A sector gate consists of a double gate, each gate being a quarter circle transferring forces through a steel frame to the sides (Kerssens et al., 1989); It operates by rotating around two vertical axes. A floating sector is similar to a normal sector gate, but in floating position the gates can turn around spherical hinges on the riverbanks while during operation the doors will rest on a specially prepared foundation structure on the river bed; in non-operational condition the doors are stored in special docks constructed in the river banks (Kerssens et al. 1989).

Cross-section

An inflatable gate is basically a sealed tube made of a flexible material, such as synthetic fiber, rubber, or laminated plastic. It is anchored to the sill and walls by means of anchor bolts and an airtight and watertight clamping system. The gate is inflated with air, water, or a combination of the two (Sehgal, 1996).

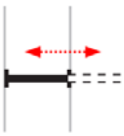
Cross-section

Flap gates consist of a straight or curved retaining surface, pivoted on a fixed axis at the sill (Erbisti, 2004). At Venice the gates are operated by filling or emptying them with air.



Top view

A barge gate is a caisson stored on one side of a waterway, pivoting around a vertical axis to close. A barge gate may be buoyant or equipped with gated openings to reduce hinge and operating forces (van Ledden et al., 2012). A barge gate can also be called a swing gate.



Top view

Rolling gates are closure panels stored adjacent to the waterway. They are rolled into position in anticipation of a flood event. Storm surge barrier designs with rolling gates {Maeslant-alternative (Rijkswaterstaat) plan for barrier at Hamburg (Sass, 1986)} are equipped with gated openings in the gate itself to limit the load during the closure.

### Existing structures and structures under construction

For this study 14 existing storm surge barriers and one under construction are investigated, they are listed in chronological order below:

- Hollandsche IJssel (Krimpen aan de IJssel, The Netherlands, 1958)
- New Bedford (New Bedford, Massachusetts, USA, 1966)
- Stamford (Stamford, Connecticut, USA, 1969)
- Eider (Tönning, Germany, 1973)
- Hull (Hull, United Kingdom, 1980)
- Thames (London, United Kingdom, 1982)
- Eastern Scheldt (Neeltje Jans, The Netherlands, 1986)

- Maeslant (Rotterdam, The Netherlands, 1997)
- Hartel (Spijkenisse, The Netherlands, 1997)
- Ramspol (Ens, The Netherlands, 2002)
- Ems (Gandersum, Germany, 2002)
- Inner Harbor Navigation Canal (IHNC) (New Orleans, LA, USA, 2011)
- Seabrook (New Orleans, LA, USA, 2011)
- St. Petersburg (St. Petersburg, Russia, 2011)
- MOSE-Project (Venice, Italy, 2014?)

## MAIN FUNCTIONS AND CHARACTERISTICS

### General

During normal conditions storm surge barriers can have several additional functions. The functions found at the investigated barriers are described below:

- Navigation; Storm surge barriers either facilitate free passage or accommodate a disturbed passage by a lock. The size of the openings depends on the type of navigation (e.g. sea going commercial traffic, inland navigation, fishery boats or recreational crafts).
- Water quality: Water quality is a measure of a condition relative to the requirements of either biotic species or human need or purpose or both (Johnson et al., 1997). Constructing a barrier will reduce the refreshment rate and thereby the condition of the water. Storm surge barriers with sufficiently large openings can preserve the typical environment of estuaries though by allowing tidal exchange.
- River run-off: Storm surge barriers can accommodate discharge of river running off to the sea.
- Road connection: To connect two shores a road can be added on top of a storm surge barrier.
- Water management: Gates can be operated in a way the land next to the estuary can easily be drained after heavy rainfall. This is done by closing the gates at low tide. It is noted that this function is only applied at the Eider barrier.

To relate the function to the characteristics, the following characteristics are collected from the studied barriers:

a. Starting and ending year of construction
b. The total length of the barrier
c. The cumulative span of the gates
d. Dimensions of the gated section for navigation
e. Dimensions of gated section for flow
f. Hydraulic gate types

All these main functions and characteristics are summarized in Table 1. The structures are sorted on the size of the cumulative span of all the gates (total span). The first column shows the name and the country of the storm surge barriers. The third column indicates the main functions other than flood protection. Moreover only the functions having a significant effect on the dimensions of the barrier are mentioned here. Finally the type of navigation has been added within brackets, to present whether it concerns sea going commercial traffic (sea), inland navigation (inland), fishery or recreation. The fourth column presents the length of the barrier and the fifth the cumulative span of the gates. The sixth and seventh column present the characteristics of the navigation and flow openings respectively. First the hydraulic gate type is mentioned, then its length. Definitions regarding the hydraulic gate type can be found in section 1. Locks and their width have been summarized in the sixth column.

**Table 1: Main characteristics of storm surge barriers**

| **Storm surge barrier** | **Period** | **Main functions** | **Length [m]** | **Total span[m]** | **Sections for navigation** | **Add. sections for flow** |
|---|---|---|---|---|---|---|
| Eastern Scheldt, Neth. [a] | 1973-1986 | Water quality, road connection | 9,000 | 2,604 | Lock, w: 16m | Vertical lift, 62 x l: 42m. |
| St. Petersburg, Russia | 1984-2011 | Navigation (sea), road connection, water quality | 25,400 [b] | 1,846 [b] | Floating sector, *l*: 200m, Vertical rising, *l*: 110m [c] | Segment, 64 x *l*:24m [b] |
| Venice (MOSE-project), Italy | 2003-2014? | Navigation (sea), water quality | 1,500 [e] | 1,460 [f] | Flap, *l*: 3x400 m [f] | Flap, *1xl*:360m [f] |
| Ems, Germany [h] | 1998-2002 | Navigation (inland), water quality | 476 | 414 | Rotary segment, *l*: 60 m, Segment, 50 m | Vertical lift, 5 x *l*:50m |
| Thames, Great Britain [i] | 1974-1982 | Navigation (sea), water quality | 530[e] | 369 | Rotary segment, 4x *l*:61m & 2 x *l*:31m | Segment gate, 4x*l*:31 m |
| Maeslant , Neth. [j] | 1989-1997 | Navigation (sea) | 610 | 360 | Floating sector, *l*: 360m | - |
| Ramspol, Neth. [k] | 1996-2002 | Navigation (inland), water quality | 450[e] | 202 | Inflatable rubber, *l*:52 m | Inflatable rubber, 2 x *l*:75 m |
| Eider, Germany [l] | 1967-1973 | Water quality, road connection | 4,900 | 200 | Lock, w: 14m | Double segment gates, 5x*l*:40m |
| Hartel, Neth. | 1993-1997 | Navigation (inland) | 250[e] | 147 [m] | Vertical lift, *l*: 98 & 49m[m], Lock, w: 24m | - |
| IHNC, USA [p] | 2008-2011 | Navigation (inland) | 2,300 | 107 | Sector, *l*: 45m<br>Barge, *l*: 45m,<br>Vertical lift, *l*: 17m | - |
| Hollandsche IJssel, Neth. [q] | 1954-1958 | Navigation (inland) | 200 | 80 | Double vertical lift, *l*: 80 m, Lock, w: 24m | |
| Seabrook, USA [r] | 2008-2011 | Navigation (inland) | 130 | 59 | Sector, *l*: 29m | Vertical lift, 2 x *l*:15m |
| New Bedford, USA [s] | 1962-1966 | Navigation (fishery) | 1,370 | 46 | Sector gate, *l*: 46m | - |
| Hull barrier, UK [t] | 1977-1980 | Navigation (recreation) | 40 [e] | 30 | Vertical lift, *l*:30m | - |
| Stamford, USA [s] | 1965-1969 | Navigation (recreation) | 870 | 27 | Flap gate, *l*: 27m | - |

[a] Ontwerpnota Oosterscheldekering (Design documents)
[b] http://www.halcrow.com/Our-projects/Project-details/St-Petersburg-Flood-Barrier-Russia
[c] http://dambaspb.ru/
[e] Estimates from satellite photos (Google Earth)
[f] http://nl.wikipedia.org/wiki/MOSE_Project
[h] W. Meinhold, Ems-Barrrier, Federal State Lower Saxony (Niedersachsen), Germany, WG26 PIANC - Project Review
[i] Vos, C.J. 2002, The Thames Barrier, Engineered Coasts, 291-308, Kluwer Academic Publishers
[j] Rijkswaterstaat, Basisdocumentatie Maeslantkering
[k] N.H. Rövekamp, Storm Surge Barrier Ramspol, Hollandsche Beton- en Waterbouw, Engineering Department, Gouda, The Netherlands
[l] Cordes, F.; Fedders, H.; Albrecht, U.; 1972, Der Wehrträger des Eidersperrwerkes, Beton- und Stahlbetonbau (10), 67. Jahrgang
[m] http://www.rijkswaterstaat.nl/water/feiten_en_cijfers/dijken_en_keringen/europoortkering/hartelkering/
[p] DeSoto-Duncan et al., 2011 , "The great wall of Louisiana", Protecting the coastline from extreme storm surge and sea level rise
[q] Rijkswaterstaat Deltadienst, Driemaandelijks Bericht Deltawerken, nr.1, Het ontwerp en de bouw van een stormvloedkering aan de mond van de Hollandsche IJssel bij Krimpen a/d IJssel
[r] USACE, 2013, Seabrook floodgate complex (brochure)
[s] Morang, A., 2007, Hurricane barriers in New England and New Jersey – History and status after four decades, USACE, Coastal and Hydraulics Laboratory, ref: ERDC/CHL TR-07-11
[t] Fleming, J.; McMillan, P.; Williams, B.; 1980, The river Hull tidal surge barrier, Proceedings of Institution of Civil Engineers, Part 1, 1980, 68, pp. 417-454

### Navigation openings

When considering the navigation openings of storm surge barriers, it can be observed that all storm surge barriers accommodate navigation. For some there is just a common lock (Eider, Eastern Scheldt). Two other storm surge barriers allow for shipping with limited clearance (Hollandsche IJssel, Hartel). Eleven of the fifteen investigated storm surge barriers have an undisturbed passage with an unlimited clearance though.

When regarding storm surge barriers with undisturbed passage, similar aspects play a role in determining the appropriate size as with common navigation channels. The dimensions of a navigation channel are mainly based on the largest vessel passing, the intensity of navigation and the maneuverability of the vessel (Rijkswaterstaat, 2012). The barriers are categorized into sea going commercial traffic, inland navigation, fishery and recreational vessels. As is expected, the barriers with sea going commercial traffic passing have the largest total span available for navigation, ranging from 300 to 400 meters. Storm surge barriers for inland vessels have gated sections lengths ranging from 50 to 150 meters. Finally the smallest gated sections are for barriers with fishery and recreational traffic.

When regarding the storm surge barriers with undisturbed passage and unlimited clearance, there is a great variety in the application of hydraulic gate types. For 11 structures, 8 different hydraulic gates types have been constructed, namely: Barge gate, Flap gate, Floating sector gate, Rotary segment gate, Rubber gate, Sector gate and Vertical rising gate. Furthermore for Hamburg [26] a storm surge barrier with a rolling gate has been planned. Especially very wide gates pose a technical challenge and an overview of the hydraulic gates for the widest gates is presented in Table 2. Therefore it does not appear that one hydraulic gate type is favored over another, when concerning these types of wide openings for navigation.

**Table 2: Hydraulic gate types for largest single spans**

| Storm surge barrier | Single span | Depth below mean sea level | Hydraulic gate | Construction year |
|---|---|---|---|---|
| Venice | 400 m | 15 m* | Flap | 2014? |
| Maeslant | 360 m | 17 m | Floating sector | 1997 |
| Hamburg (Sass, 1986) | 300-400m | 14 m | Rolling | not constructed |
| Mississippi (Van Ledden, 2012) | 274 m | 18 m | Barge | not constructed |
| St. Petersburg | 200 m | 16 m | Floating sector | 2011 |

* Depth at Malamocco

### Flow openings

The gated sections of a storm surge barrier allow flow during normal conditions. This flow can originate from tidal movement, river run-off or smaller wind-induced movements. The tidal movements are investigated here as they generally contribute most to the flow passing the barrier.

The amount of tidal flow depends on the tidal volume passing the storm surge barrier. The size of this tidal volume is influenced by the tidal basin behind the storm surge barrier and the tidal range occurring in this tidal basin. For some storm surge barriers direct information about the tidal volume is available. For others the tidal volume has been estimated based on the surface of the inner basin and the average tidal range (see Table 3). For tidal flows it is common to present the peak tidal flow during an average tide, which can be calculated with formula 1.

$$\hat{Q} = \frac{\pi \cdot V}{T} \qquad (1)$$

Here Q is the tidal flow [$m^3/s$], V is the average tidal volume [$m^3$] and T is the tidal period [s]. The factor π is required to find the peak flow.

**Table 3: Flow properties of storm surge barriers**

| **Storm surge barrier** | **Tidal properties** | | | | **Average annual river run-off [m3/s]** |
|---|---|---|---|---|---|
| | *Surface inner basin [km²]* | *Average tidal range [m]* | *Tidal volume [$10^6$ m³]* | *Peak flow [m³/s]* | |
| Eastern Scheldt | - | - | 925 | 65,000 | - |
| St. Petersburg | 329 | 0.1 | 33 | 2,300 | 2,500 |
| Venice | 500 | 0.75 | 375 | 26,000 | - |
| Ems | - | - | 52 | 3,700 | 80 |
| Thames | 11 | 5 | 55 | 3,900 | 66 |
| Maeslant | - | - | 90 (average flood and ebb) | 6,300 | 2,200 |
| Ramspol | - | - | - | - | 85 (winter) |
| Eider | - | - | 50 | 3,500 | - |
| Hartel | - | - | 15 | 1,100 | - |
| IHNC | 2 | 0.2 | 0.4 | 30 | - |
| Hollandsche IJssel | - | - | 5 | 350 | - |
| Seabrook | 2 | 0.2 | 0.4 | 30 | - |
| New Bedford | 1.5 | 1.1 | 2 | 120 | - |
| Hull barrier | 0.7 | 4 | 3 | 200 | - |
| Stamford | 0.1 | 2.2 | 0.2 | 15 | - |

To find the relation between tidal flows and the size of the gated sections, peak flows have been compared to the cross-section below mean sea level (see figure 2). The cross-section below sea level is found by multiplying the cumulative span with the average sill depth. To relate the flow requirements to the characteristics three storm surge barrier types have been defined: barriers with only navigation sections, with both flow and navigation sections and with only flow sections. As there is no tide at the Ramspol barrier, a minimal peak flow of 10 m³/s has been taken to be able to present it in this figure. Five colored surfaces are added to the figure to indicate the peak tidal velocity.

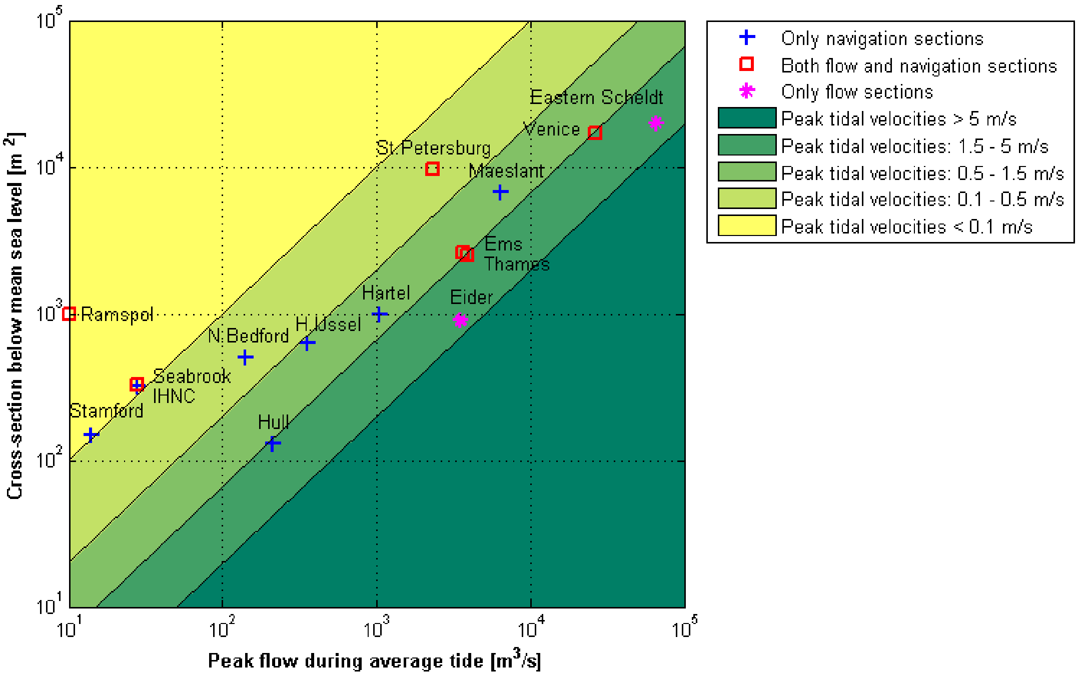



**Figure 2: Relation between cross-section and maximum flow during average tide**

When looking generally into the peak tidal velocities, two comments can be made. First, there are no storm surge barriers with peak tidal velocities higher than 5 m/s. This is actually makes sense, as these high velocities correspond with a significant head over the structure, which does not fit with the definition of a storm surge barrier. Second, there is a large spread in tidal velocities, ranging from 0 to

5 meter per second. When looking into the functional requirements there appears to be an explanation for this large spread, which is elaborated in the next paragraphs.

When considering both barriers with flow sections only, they show great similarity. These storm surge barriers have a tidal velocity that lies in the range of 1.5 to 5 meter per second. Not surprisingly with these high tidal velocities, both barriers have experienced severe damage at their bottom protections (ANP, 2013; Dietz et al., 1994). Furthermore, both storm surge barriers have an adjacent lock to allow navigation, as sailing through the barrier is not possible with these velocities. Therefore barriers with just flow sections can pass a large tidal volume with a relatively small opening size.

When looking into storm surge barriers with just navigation sections, already from appearance the navigation requirements are expected to be more stringent than the flow requirements. Still, at some barriers relatively large tidal velocities are found going up to 1.5 m/s. For some of the barriers (e.g. Hartel, H.IJssel) one can discuss whether the flow or navigation requirements are more critical.

Finally, when regarding storm surge barriers with both navigation and flow sections three barriers show a remarkable resemblance. The Venice, Thames and Ems barrier all have a peak tidal velocity of 1.5 m/s. This velocity is common in tidal areas and is considered to be just navigable. For the Seabrook barrier it is known that navigability has been the reason for adding two flow sections, similarly as for the before mentioned barriers. The tidal velocity calculated here does not represent a realistic value, as the approach presented here is too simple for this specific case. At Seabrook, the flow is driven by a tidal phase difference at either end of the canal. The two other barriers (i.e. St. Petersburg, Ramspol) have extremely low tidal velocities, which can easily be dealt with by navigation. This raises the question why additional flow sections were constructed here. As both barriers have small tides, preserving sufficient water quality has been identified as a possible cause. This is analyzed further in the next paragraphs.

For analyzing the water quality the average residence time is applied, as generally the water quality will be poorer with a longer residence time. The average residence time is found by dividing the average water volume of the basin by the average tidal flow. As both the water volume and the tidal volume are related to the surface, the residence time is not. Formula 2 can then be found to find the average residence time:

$$\tau = \frac{V}{Q} = \frac{S \cdot d}{2 \cdot S \cdot R/T} = \frac{d \cdot T}{2 \cdot R} \tag{2}$$

Where τ is the residence time in seconds, V is the average water volume [m3], Q is the average tidal flow [$m^3/s$], S is the surface [$m^2$], d is the average depth [m], R is the tidal range [m] and T is the tidal period [s]. When assuming that the tidal period is half a day, finding the residence time can be simplified even further: $\tau_d \sim d / (4 R)$. Notice that the residence time is now in days instead of seconds.

For the barriers with additional flow sections the residence time is calculated and presented in table 4. In the most right column the peak tidal velocity is added. From the table it can be concluded that the barriers with a high average residence time (>10d) all have low peak tidal velocities (<0.5 m/s). All barriers with low average residence times (<1d) have peak tidal velocities higher than 0.5 m/s. Therefore, it appears that barriers with relatively low refreshment rates require larger openings to preserve sufficient water quality.

| Table 4: Average residence time for barriers with additional flow openings | | | | |
|---|---|---|---|---|
| **Barrier** | **Average depth (m)** | **Tidal range(m)** | **Residence time (d)** | **Peak tidal velocity (m/s)** |
| Eastern Scheldt | 8 | 2,7 | 0,7 | 3.3 |
| St. Petersburg | 6 | 0,1 | 15 | 0.2 |
| Venice | 1,5 | 0,8 | 0,5 | 1.5 |
| Ems | 5* | 3,0 | 0,4 | 1.4 |
| Thames | 7* | 5,0 | 0,4 | 1.5 |
| Ramspol | 2 | 0,01** | 50 | 0.0 |
| Eider | 5* | 3,1 | 0,4 | 3.9 |
| Seabrook | 5* | 0,2 | 6*** | 0.1 |

* Estimation, based on sill level

** No tide at this location. Calculation is done with a tidal range of 0,01m and a semidiurnal period

*** As noted earlier the tidal flow is not estimated correctly by this simple method.

Another reason for the large flow sections at the St. Petersburg barrier is the large river flow. Probably both the water quality and the river flow have had an influence on the size of the openings here. Further investigation is required to clarify the most critical functional requirement here.

## COST ESTIMATION

### Introduction

Cost prediction methods are applied to estimate the costs of a project in the early stages of planning of storm surge barriers. As no detailed information of the design is available at this stage, these formulas are based on the main cost elements for a storm surge barrier. Several of these methods have been proposed (Jonkman et al., 2013; van Ledden et al., 2012; de Ridder) but the accuracy of these methods is unknown. Subsequently it is not known which of these methods is the most reliable.

The aim of this section is to find a new cost prediction method.

### Cost information

From the analyzed storm surge barriers information has been gathered about the total costs for the project (see Table 6). This information is gathered from different sources, but it is not known from these sources which costs are included and which are not. The construction costs are most likely included, but whether or not soil investigations, engineering, permitting, taxes are included is not known. Subsequently it is not known if the total costs found, represent similar total costs. For this research it is assumed that the costs found, represent the total costs for construction of the storm surge barrier, without maintenance costs, but with auxiliary costs.

As the storm surge barriers are constructed in different years, the costs are corrected for the interest rate. The equivalent costs for 2014 are found by formula 3.

$$PC = C_n \cdot \left(1 + r\right)^{2014-n} \qquad (3)$$

Here PC are the present costs [€], $C_n$ the costs in year n [€] and r the construction cost index rate[-]. For three countries (The Netherlands, Germany and the USA) a construction index has been compared with the consumer price index. For the Thames barrier the current costs and the costs during construction have been provided by the helpdesk of the Environment Agency. All construction index rates are higher than the consumer price index. Based on this analysis the consumer price index per nation is applied and raised with 0.5% to find the construction cost index rate. The calculated present costs are presented in table 5.

| **Table 5: Costs of storm surge barriers** | | | | | | |
|---|---|---|---|---|---|---|
| **Storm surge barrier** | **Source** | **Costs (Cn)** | **Year (n)** | **Rate (r)** | **Exchange rate** | **Present Costs (PC)** |
| Eastern Scheldt | A | 2360 M€ | 1986 | 2.5% | 1.00 | 4602 M€ |
| St. Petersburg | B | 4500 M£ | 2010 | 6.8% | 1.20 | 6578 M€ |
| Venice | B | 4700 M€ | 2011 | 3.0% | 1.00 | 4986 M€ |
| Ems | B | 290 M€ | 2002 | 2.7% | 1.00 | 387 M€ |
| Thames | B | 467 M£ | 1984 | 3.8% | 1.20 | 1667 M€ |
| Maeslant | A | 450 M€ | 1997 | 2.5% | 1.00 | 668 M€ |
| Ramspol | A | 100 M€ | 2002 | 2.8% | 1.00 | 136 M€ |
| Eider | B | 87 M€ | 1973 | 2.9% | 1.00 | 275 M€ |
| Hartel | A | 98 M€ | 1997 | 2.5% | 1.00 | 145 M€ |
| IHNC[5] | B | 550 M$ | 2011 | 2.5% | 0.74 | 425 M€ |
| Hollandsche IJssel | A | 40 Mf | 1956 | 4.0% | 0.45 | 173 M€ |
| Seabrook | B | 165 M$ | 2011 | 2.5% | 0.74 | 127 M€ |
| New Bedford | B | 19 M$ | 1966 | 4.8% | 0.74 | 122 M€ |
| Hull | B | 2,7 M£ | 1980 | 4.3% | 1.20 | 19 M€ |
| Stamford | B | 15 M$ | 1969 | 4.8% | 0.74 | 83 M€ |

Sources: A) Rijkswaterstaat B) see references at table 1.

### Testing cost prediction methods

The accuracy of four different cost prediction methods is tested to determine the most reliable one. These four methods are presented in table 6. The second column shows the cost prediction formula, where f represents the costs in euro. The third column explains why these parameters are tested and explains the parameters applied.

| **Table 6: Tested cost prediction methods** | | |
|---|---|---|
| **#** | **Formula** | **Remarks** |
| 1 | $f = c_1 \cdot L$ | This method is based on Jonkman et al. (2013). L [m] is the length as defined in the second section. The constant $c_1$ has a dimension of euro per meter. |
| 3 | $f = c_3 \cdot L_T$ | The method applies the length of the barrier ($L_T$ [m]), including closure dams. It is expected that analyzing this prediction formula will prove that applying the length of the spans of the gates is the appropriate parameter for cost prediction. The constant $c_3$ has a dimension of euro per meter. |
| 5 | Simple: $f = c_{51} \cdot L$<br>Complex: $f = c_{52} \cdot L$ | This method is similar to the first formula. A difference is made between barriers with simple structures and complex structures. For this analysis complex structures have larger spans (>50 m) and unlimited clearance. Subsequently, St. Petersburg, Venice, Ems, Thames, Maeslant and Ramspol have been categorized as complex. L [m] is the length as defined in paragraph in the second section. The constants $c_{51}$ and $c_{52}$ have a dimension of euro per meter. |
| 6 | Dutch/German: $f = c_{61} \cdot L$<br>Other: $f = c_{62} \cdot L$ | By looking into the results per storm surge barrier of the first formula, a difference appeared between Dutch and German barriers versus other barriers. L [m] is the length as defined earlier. The constants $c_{61}$ and $c_{62}$ have a dimension of euro per meter. |

First, all the coefficients ($c_1$, $c_3$, $c_{51}$, $c_{52}$) are found by simple linear regression with a least squares method. Both table 1 (Main characteristics of storm surge barriers) and table 5 (Costs of storm surge barriers) have been applied to provide the data for this analysis. Then, the correlation ($R^2$) of the different cost prediction methods has been assessed. Finally the standard deviation of the ratio ($\sigma_r$) of the difference between the actual costs and the calculated costs is presented to indicate the accuracy of the method.

Figure 3 shows the analysis of the correlation of the first two cost prediction methods. Figure 4 presents the correlation of the final two cost prediction methods. In these graphs the results of the first method are presented as well, to recognize the improvement in correlation. In all figures, the calculated costs are plotted on the horizontal axis and the actual costs on the vertical axis. The title of each graph presents the cost prediction formula with the calculated coefficients.

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[5] Here only the costs for the gated section is shown.

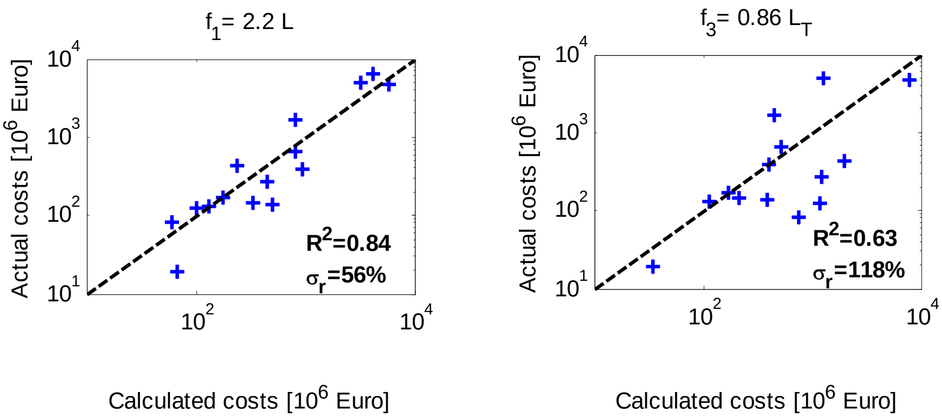


**Figure 3: Analysis of correlation of first four cost prediction methods**

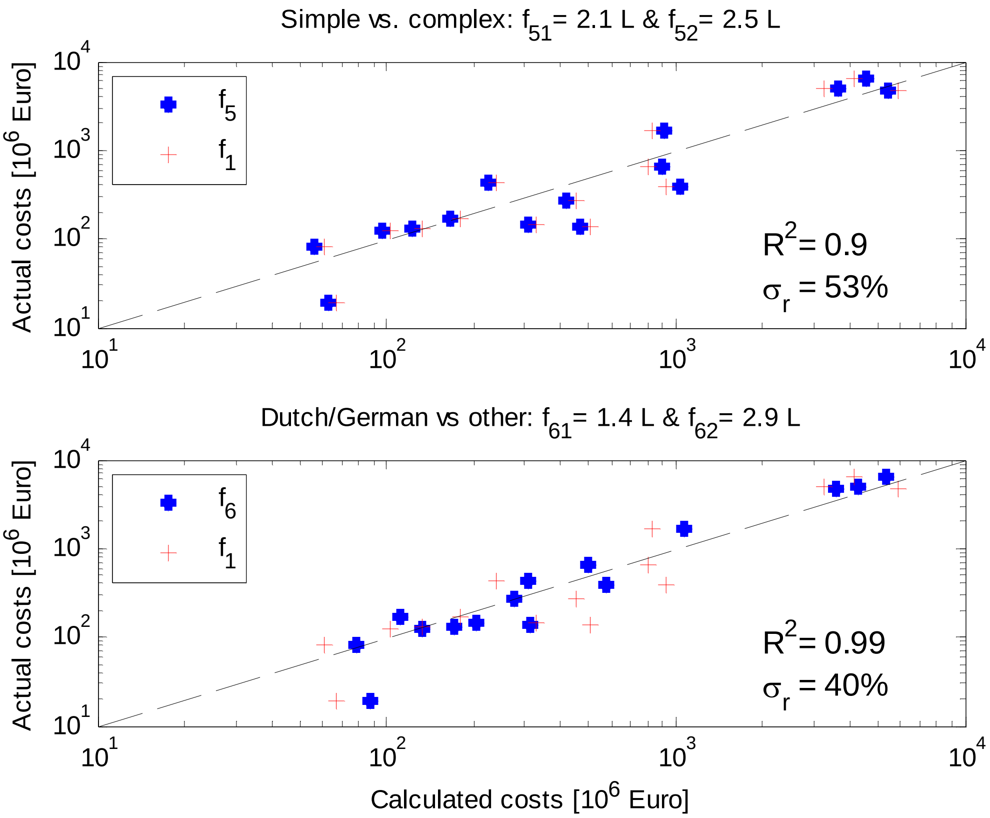


**Figure 4: Analysis of correlation of cost prediction method 5 and 6**

When considering the first two methods, the first method has the largest correlation and the lowest relative standard deviation, indicating this method is the most accurate. As has been predicted, applying the total length of the barrier including the closed dam sections for cost prediction is less reliable.

From the analysis of the third cost prediction method ($f_5$), it appears that storm surge barriers with complex structures cost about 20% more than simpler storm surge barriers on average. This leads to a slight improvement in the accuracy of the method. There are some doubts with this method though. Some of the structures categorized as complex have large components of simple structures, such as closure dams, vertical lift or segment gates (e.g. St. Petersburg). Moreover some simple structures have complex foundations (e.g. Eastern Scheldt), which are expected to lead to relatively high cost.

Finally it appears that storm surge barriers constructed in the Netherlands and Germany cost less than barriers in the UK, USA and Russia on average. This cost prediction method actually leads to the most accurate results. It is unknown what causes this difference, but some suggestions are made. First the statistical analysis is actually a subgroup analysis and as it is based on a smaller number the reliability of this method is smaller. A second possibility is that there are more German and Dutch contractors sufficiently experienced to construct these structures and therefore construct storm surge barriers for less costs. Another explanation is that the way costs are registered differ. For instance, it is also known that with these large projects political decisions can have a large effect on the costs. Finally conversion rates can influence the costs as well.

### Conclusion

The costs of storm surge barriers are generally high. For the 15 storm surge barriers here they are 2.2 million euro per meter span on average. The costs per meter vary significantly though. From a statistical analysis a standard deviation of 1.2 million (56%) was found.

Separating storm surge barriers into groups (either by country or by structural simplicity) leads to the most accurate result for hindcasting costs of storm surge barriers. However, as the physical nature of this separation could not completely be explained, it is doubted whether these methods will lead to more accurate cost prediction of future storm surge barriers. It is therefore recommend to apply the cumulative span as the key parameter for cost prediction.

## CLOSING DISCUSSION

For this study the main characteristics and the main functions of 15 storm surge barriers have been collected. The main characteristics presented in this study are the construction period, the length of the barrier and gates, the dimensions of the gated sections for navigation and for flow and the costs. Five main functions next to flood protection have been identified, namely navigation, water quality, river run-off, road connection and water management.

The aim of this exercise has been to find the most relevant design aspects in an early stage of planning storm surge barriers. It appears that the size of gated sections is the most important design aspect for determining the costs of a storm surge barrier, as the costs of the studied storm surge barriers relate best to the length of the cumulative span of the gates. Furthermore, the gated sections are the main difference between storm surge barriers and closure dams, and storm surge barriers are about 10 – 100 times as expensive as closure dams (Jonkman et al., 2013). As the size of the gated section is the most critical design aspects for costs, this should be emphasized during the initial stage of planning of a storm surge barrier project.

The studied storm surge barriers showed a great variety in the application of hydraulic gate types. Actually for eleven navigation sections eight different hydraulic gate types have been applied. Navigation sections with large single spans (>100m) and an unlimited clearance have been identified as a technical challenge for designers. At the current stage of development, the most appropriate type for these situations has not been identified. It might depend on local circumstances or on specific functional requirements, but this can be investigated further.

Moreover, for storm surge barriers where the flow is critical in the design of the openings, providing sufficient water quality is the critical issue. For barriers located in places with tides larger than about half a meter a relation between the size of the opening and the tidal flow has been established. For barriers with lower tides this proved more difficult as the water quality is more difficult to maintain. For these barriers (St. Petersburg, Ramspol) more study is required to explain their opening size.

The management and maintenance of storm surge barriers has only been limitedly addressed in this study. As the annual costs for maintenance can be related to the investment costs and are only about 0.5 to 2 percent of the investment costs (Aerts et al., 2013). Yet, for future research recent experiences with Dutch and German storm surge barriers could be investigated. Some of these topics are mentioned here.

First, scour protections of storm surge barriers can require intensive maintenance. Severe damage has occurred at the scour protections of both the Eastern Scheldt barrier and the Eider barrage several decades after their construction (ANP, 2013; Dietz et al., 1994). Both these structures experience high flow velocities during normal conditions causing erosion at the ends of the bottom protection. Other storm surge barriers have their critical flow load during the closing and opening procedure of the gates.

Second, the reliability of the closure can be an issue when there is a relatively high closure frequency and a high safety level. Furthermore, with complex gate types the reliability of closure is more difficult than with simple gate types (vertical or segment). The Maeslant barrier is an example of a barrier requiring a high reliability for a complex gate type 1/1000 per closure. Assuring sufficient reliability has been an issue here (Rijkswaterstaat, 2014).

Following both global trends for coastal protection and the rising number of storm surge barriers, it is expected that new storm surge barriers will be constructed in the future. Furthermore, several storm surge barrier studies are already being undertaken, for instance at the Mississippi, Hamburg, Houston and New York. Then there are many more coastal locations where storm surge barriers can be feasible as well, such as Rio de Janeiro, Antwerp, Lagos, Manila, Brisbane, and Tokyo. Additional research will have to indicate at which locations storm surge barriers are feasible and relevant.

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