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Overview and Design Considerations of Storm Surge Barriers

L.F. Mooyaart MSc[1,2], S.N. Jonkman PhD[3]

[1]Delft University of Technology, Faculty of Civil Engineering and Geosciences
Researcher Hydraulic Engineering
Stevinweg 1, 2826 CN Delft
The Netherlands
E: L.F.Mooyaart@tudelft.nl

[2] Royal HaskoningDHV
Consultant Hydraulic Structures and Flood Risk
George Hintzenweg 85, 3068 AX Rotterdam
The Netherlands

[3] Delft University of Technology, Faculty of Civil Engineering and Geosciences
Professor of Hydraulic Structures and Flood Risk
Stevinweg 1, 2826 CN Delft
The Netherlands
E: S.N.Jonkman@tudelft.nl

Abstract

The risk of flooding in coastal zones is expected to increase due to sea level rise and economic development. In larger bays, estuaries and coastal waterways, storm surge barriers can be constructed to temporarily close off these systems during storm surges in order to provide coastal flood protection. Worldwide, eighteen storm surge barriers have been constructed so far, but they are increasingly being considered as a future solution for other coastal locations. This study provides a systematic overview of existing storm surge barriers. It analyzes information on the main functions of each barrier, the type of gates used, and the associated costs. This study shows that functional requirements determine the design and layout of the barrier. The main design challenges are discussed. The study results may be of use in future planning and preliminary storm surge barrier design.

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

Introduction

Coastal zones are exposed to a variety of natural hazards such as erosion, salt water intrusion, subsidence, tsunamis, and floods from both storm surges and high river runoff (Small and Nicholls 2003). The likelihood of these natural hazards occurring may increase with climate change due to effects such as sea level rise. Furthermore, due to growing concentrations of human population, settlements and socio-economic activities, coastal zones are becoming more vulnerable (Small and Nicholls 2003). From an economic perspective, these conditions lead to a higher demand for safety, justifying substantial investments in flood risk reduction (Brekelmans et al. 2012; van Dantzig 1956). A typical solution to reduce flood risk is to raise the level of existing flood defenses. This solution can, however, be challenging to implement in urban areas where space is limited and social impact can be considerable. For geographical areas with long, exposed coastlines (e.g. larger bays, estuaries and coastal waterways) a coastal barrier can be an attractive and economical solution for establishing new and/or improved flood protection.

In general, three types of coastal barriers can be distinguished: closure dams, tidal barrages, and storm surge barriers.

Closure dams permanently close off an estuary from the sea. They prevent sea water from entering the newly formed lake, minimizing the risk of floods behind the dam. In most cases, impounding an estuary with a closure dam creates a fresh water lake, providing appropriate conditions for expanding agriculture by land reclamation, while having a negative impact on fisheries. Examples are the new polders that were constructed between 1930 and 1970 behind the

Afsluitdijk (Closure Dam) in the Netherlands, and the land reclamation at Saegmungeum in South Korea. Closure dams prevent tidal exchange and hinder navigation and therefore often contain sluices to discharge river runoff and locks to allow navigation.

A tidal barrage, on the other hand, allows tidal exchange to produce tidal energy. The tidal exchange, however, is constricted to create a head between the sea and the inner basin. Tidal barrages only appear to be economically feasible for tidal ranges in excess of 5 meters (Baker 1991). Examples of these types of structures are the tidal power plants at La Rance (France) and Sihwa (Korea).

A storm surge barrier is a fully or partly moveable barrier which can be closed temporarily to limit water levels in the basin behind the barrier and so prevent flooding of the area surrounding the inner basin. During normal conditions, the barrier is kept open to allow tidal exchange and navigation. As a result of these characteristics, storm surge barriers incorporate advanced technology for their operation, and involve relatively high capital and maintenance costs (UNFCCC 1999). So far, only eighteen storm surge barriers have been constructed worldwide (see section 2). The interest in storm surge barriers appears to be rising, with this type of flood protection measure being studied in a number of coastal cities. Storm surge barriers could be an alternative for the improvement of long stretches of coastal flood protection that are now located along bays or estuaries – often in densely populated areas (see Figure 1). A storm surge barrier can significantly reduce the length of the coastline that is directly exposed to flooding.

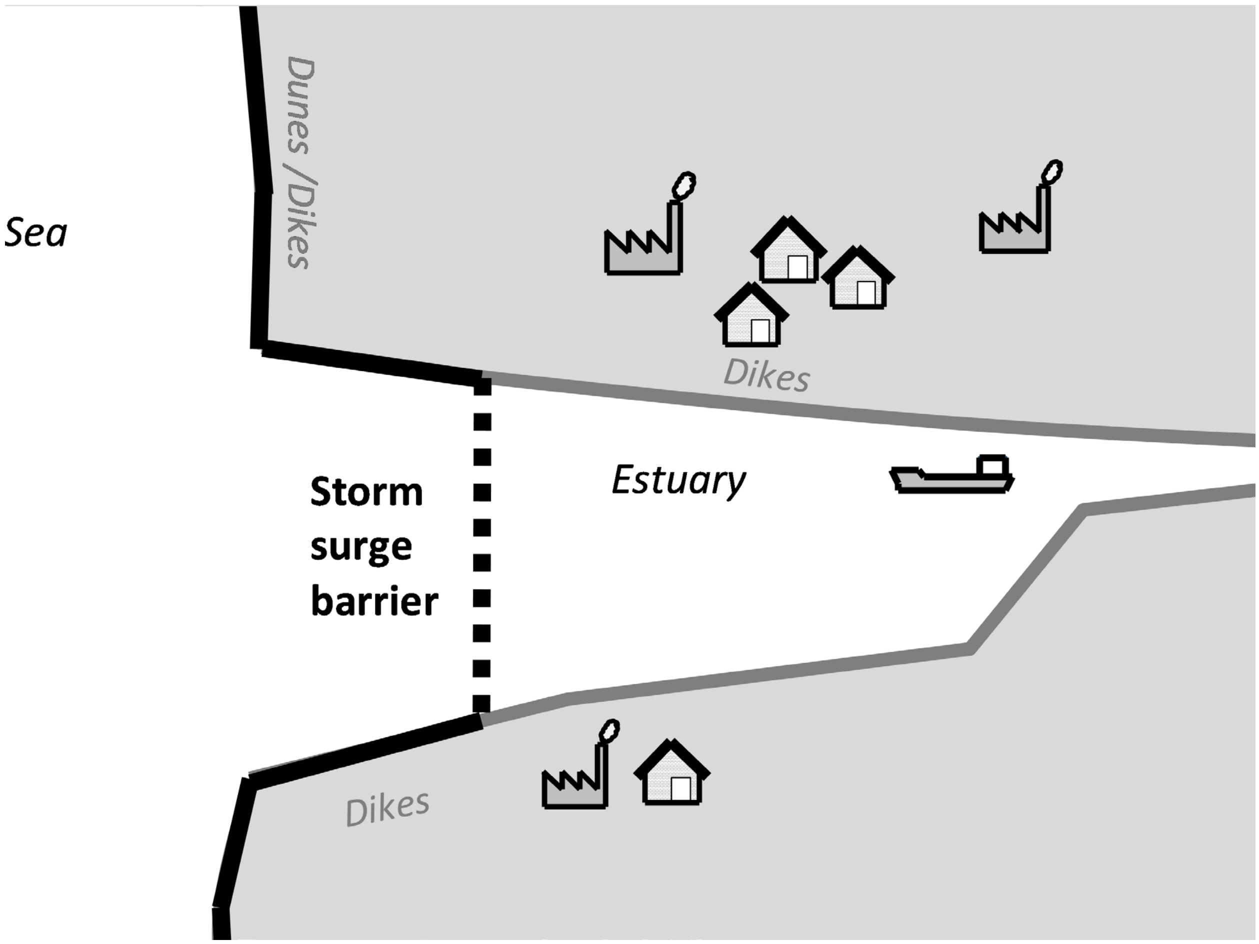


Figure 1 - Schematic plan of an estuary with a storm surge barrier as a coastal protection strategy

A systematic and complete overview of existing storm surge barriers is not yet available. Most existing overviews describe a limited number of barriers and a limited number of characteristics (Aerts et al. 2013; Dircke et al. 2012a; Jonkman et al. 2013; Mooyaart et al. 2014; PIANC 2005). Some of these overviews include other types of hydraulic structures such as sluices and weirs. A few of these overviews provide insight into various hydraulic gate types as used in storm surge barriers (Dircke et al. 2012a; b; PIANC 2005). These overviews, however, do not offer an explanation for the wide differences found between individual storm surge barriers, nor were other important design aspects regarding the main dimensions of storm surge barriers considered. In addition, various design reports and publications (Rijkswaterstaat 1959, 1986) document design choices for these individual barriers, but do not provide conclusions on the more general applicability of the designs. As the design variations of storm surge barriers are not properly understood, the main cost drivers remain unclear. To assess the feasibility of future storm surge barrier projects and improvements, more knowledge about the variations in design of existing storm surge barriers is required. In view of this, the aims of this study are 1) to provide a systematic and complete overview of existing storm surge barriers and their main characteristics; 2) to investigate the relationship between functional requirements and main characteristics of existing storm surge barriers. The results of this study may be of use in future planning and design studies.

This technical note is organized as follows. First, an overview of storm surge barriers and their main characteristics are given. Second several design aspects of storm surge barriers are analyzed. The concluding remarks look at future trends and challenges.

Overview of storm surge barriers

Selection of structures

Structures were selected based on their functional characteristics. Storm surge barriers prevent coastal flooding by using gates to temporarily close off a basin from the sea and so limit the water level within. The minimum span of movable gates was set at 24 meters to distinguish storm surge barriers from guard locks. Guard locks have a similar function, but have smaller movable gates. Guard locks generally consist of mitre gates, which are economical up to a span of 24 meters (Glerum and Vrijburcht 2000). Structures that close during astronomical high tides were excluded from the analysis. Examples are the gates along the Elbe and Weser rivers in Germany (e.g. Oste, Stör, and Krückau).

Storm surge barriers are opened during normal conditions to allow tidal exchange and facilitate navigation. Various hydraulic structures with large moveable gates (e.g. the Marina Bay barrier in Singapore and the Haringvliet barrier in the Netherlands) mainly allow river run-off. These structures differ from storm surge barriers as water only flows in one direction and there is a relatively large head across the structure. Consequently, the seaside and riverside salinities differ. The criteria resulted in a selection of seventeen existing barriers and one that is currently under construction (the storm surge barrier near Venice in Italy).

Elements of a storm surge barrier

The typical layout of a storm surge barrier contains three types of elements: a gated section, a dam section and a lock. The gated section consists of hydraulic gates and the structures required to support and operate these gates. All storm surge barriers have gated sections, while the dam section and lock are optional. A closed dam section can be used to reduce costs, and a lock can be included to allow navigation. Obviously, the main purpose of the gated section is to close a waterway during storm conditions. In practice, most of the barriers and gate types allow some leakage and sometimes overtopping and/or overflow. This measure considerably limits construction costs, while the leakage and overtopping hardly affect the water levels of larger water bodies behind the barrier . For example, the crests of the gates of the Eastern Scheldt barrier (the Netherlands) in closed position are at the design water level, allowing large wave overtopping volumes to enter the Eastern Scheldt during a storm.

Figure 2 presents the layout of an imaginary storm surge barrier with all three types of elements. It also shows the definitions of the main dimensions used in this study. The length of the barrier is defined as the distance from bank to bank along the axis of the barrier. The length of an opening is equal to the span of its gate. The total length of all the gate spans of a barrier is called the cumulative span of the openings.

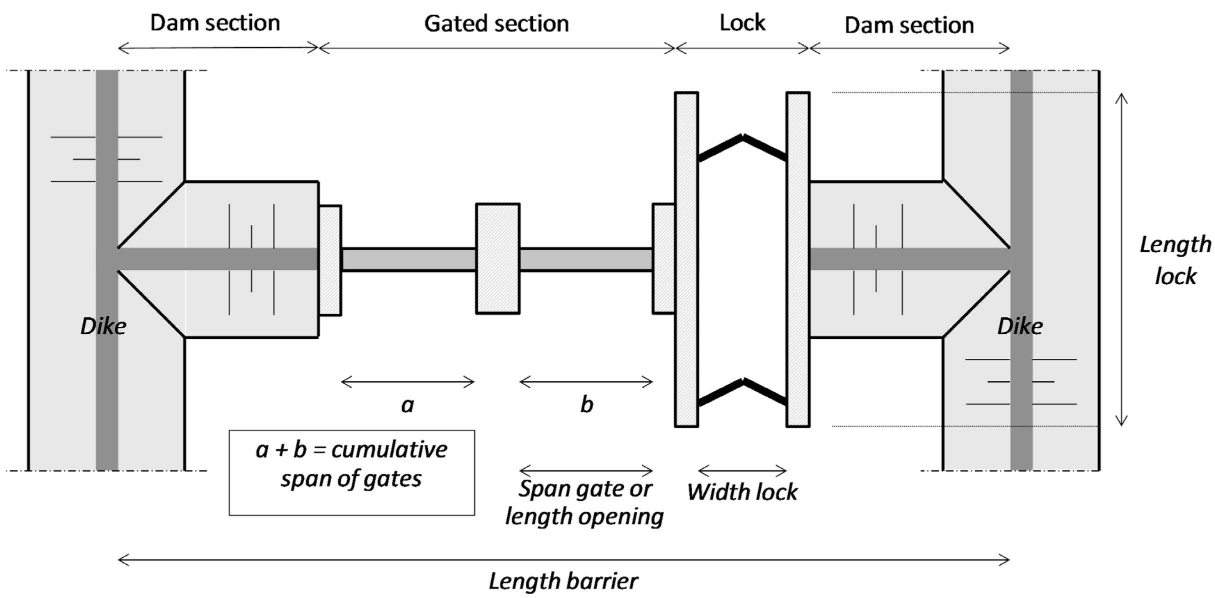
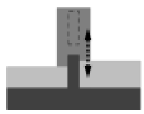
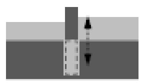
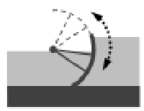
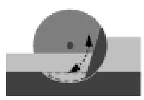
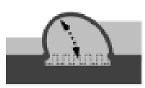
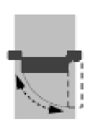
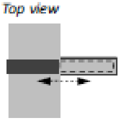


Figure 2 - Schematic plan of a storm surge barrier

Overview of main characteristics and functions

Figure 3 presents an overview of the hydraulic gate types suitable for a storm surge barrier. For this study, the hydraulic gate types are categorized by their direction of movement (e.g. vertical, rotating horizontally) and type of structure. Short descriptions of the gate concepts and applications are included in the figure. In addition to static loads, the design needs to consider dynamic loads such as waves, seiches and currents. The dynamic response of gates to these loads is not yet fully understood (Erdbrink 2014; Kolkman and Jongeling 1996) and scale model testing is often required in the design phase.

Hydraulic gate type	Pictogram [a]	Description	Application
Vertical lift gate	 *Cross-section*	Vertical lift gates are moved vertically from the sill. A tower supports the gate during its operation. Overhead cables, sheaves and bull wheels can enable lifting (USACE 1997). Alternatively, hydraulic cylinders lift the gate (e.g. Hartel barrier)	Hollandse IJssel, Hull Eastern Scheldt, Hartel, Ems, IHNC, Seabrook
Vertical rising	 *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 gates are positioned largely under water. In most applications, gates can be lifted above water to allow maintenance.	St. Petersburg
Segment	 *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. In literature, this type of gate is often referred to as a radial or tainter gate.	Eider, Thames, Ems, St. Petersburg
Rotary segment	 *Cross-section*	Similar to a segment gate the rotary segment gate has a horizontal axis. However, in recess, it lies in a concrete sill in the bed of the river. Thus, it is possible to sail over the gate in opened position. Operation of the gate is achieved by the rotation through approximately 90° thus raising the gate to the 'defense' position. A further 90° of rotation of the gate positions it ready for inspection or maintenance (Tappin et al. 1984).	Thames, Ems
Sector	 *Top view*	A sector gate consists of a double gate. Each gate has a circular shape, transferring forces through a steel frame to the hinges at each side of the opening. It operates by rotating around two vertical axes. During operation the doors will rest on the river bed. In non-operational condition, the doors are stored in special docks constructed in the river banks. A floating sector is similar to a rolling sector gate, but the gates can rotate around spherical hinges. (Kerssens et al. 1988).	New Bedford, Maeslant, St. Petersburg, IHNC, Seabrook, Harvey Canal, West Closure Complex
Inflatable	 *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 air- and watertight clamping system. The gate is inflated with air, water, or a combination of the two (Sehgal 1996).	Ramspol
Flap	 *Cross-section*	Flap gates consist of a straight or curved retaining surface, pivoted on a fixed axis (Erbisti 2004). In Venice, the gates are operated by filling or emptying them with air. At Venice and Stamford, the gates pivot around an axis at the sill, while at the Billwerder Bucht the axis lies above the water table.	Stamford, Venice, Billwerder Bucht
Barge	 *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). In literature this type of gate is often referred to as a swing gate.	IHNC
Rolling	 *Top view*	Rolling gates are sliding panels stored adjacent to the waterway. They are rolled into position in anticipation of a flood event (PIANC 2005). The new Panama locks are equipped with rolling gates. Alternative designs of rolling gates have been made for the Maeslant barrier (Rijkswaterstaat n.d.) and for a barrier near Hamburg (Sass 1986)). These designs are equipped with gated openings in the gate itself to limit the load during the closure.	

[a] adapted from (Dijk and van der Ziel 2010). The following colors are used in the pictograms: water = light grey, structure when closed = dark grey, structure at background = grey, structure when opened = dotted border, movements to open and close = black arrow. Soil / foundation in cross sections = black

Figure 3 - Overview of hydraulic gate types

Table 1 provides an overview of storm surge barriers and their main characteristics in chronological order of construction date. Appendix S1 (supplemental data) provides a more detailed description of these individual storm surge barriers. In addition to the characteristics of the structure (i.e. dam sections, gates, foundation and hydraulic loads), information about the completion years and main functions of existing storm surge barriers was collected. All information was retrieved from publicly available design reports, scientific papers and project papers.

Based on Table 1, some initial observations can be made regarding the historical development of storm surge barriers. The first storm surge barrier was constructed in the Netherlands in 1958. Since then, about two barriers have been constructed every decade. The exception is the current decade (i.e. starting 2010) in which six barriers have already been constructed: four in New Orleans following hurricane Katrina (LA, USA), one in St. Petersburg (Russia), and one near Venice (Italy).

Other developments are the significant growth in size of the cumulative span since the 1970s (i.e. the spans of the Eider and Eastern Scheldt barriers) and the increase in the single span size since the 1990s. The Maeslant, St. Petersburg and Venice barriers feature individual gate spans of 200 meters and more. Finally, it is to be noted that, with the exception of the St. Petersburg barrier, all storm surge barriers were constructed in Western countries.

Design considerations of storm surge barriers

This section discusses some of the main design considerations, including the choice of gates and openings, foundations and costs.

Navigation openings

Navigation requirements have an important influence on the layout of a barrier. Table 1 shows that all storm surge barriers facilitate navigation through the barrier. Two barriers include a lock to facilitate navigation, while all the others allow an undisturbed passage. Most of the latter also offer unlimited vertical clearance.

The size of the navigation openings appears to be related to the dimensions of the design vessel and the intensity of navigation, similar to the design of navigation channels (PIANC 1997). The type of hydraulic gate mainly depends on the required clearance. Vertical lift and radial gates are preferred where limited clearance is acceptable. When unlimited vertical clearance is required various hydraulic gate types can be applied. Six types of these gates are found in existing storm surge barriers (vertical rising, rotary segment, sector, barge, inflatable rubber and flap gates). In addition, a rolling gate was proposed for a storm surge barrier in Hamburg (Sass 1986). Overall, the realization of very wide navigation openings with unlimited clearance remains technically challenging (Erbisti 2004), and no single gate type seems to be preferred.

Flow openings

A storm surge barrier affects intertidal exchange. The related environmental impacts play a major role in the decision-making and design processes (NEDECO 2002; Rijkswaterstaat 1976, 1995). Nine of the storm surge barriers feature openings designed to allow flow through the barrier. To understand the need for these flow openings as well as their design, Figure 4 compares peak tidal flows with the opening sizes in the post construction situation. This opening size is equal to the cumulative span of the openings multiplied by the average sill depth below mean sea level. In cases for which no documentation on tidal flows was available, formula 1 was used to estimate the peak tidal flow (Battjes 2000).

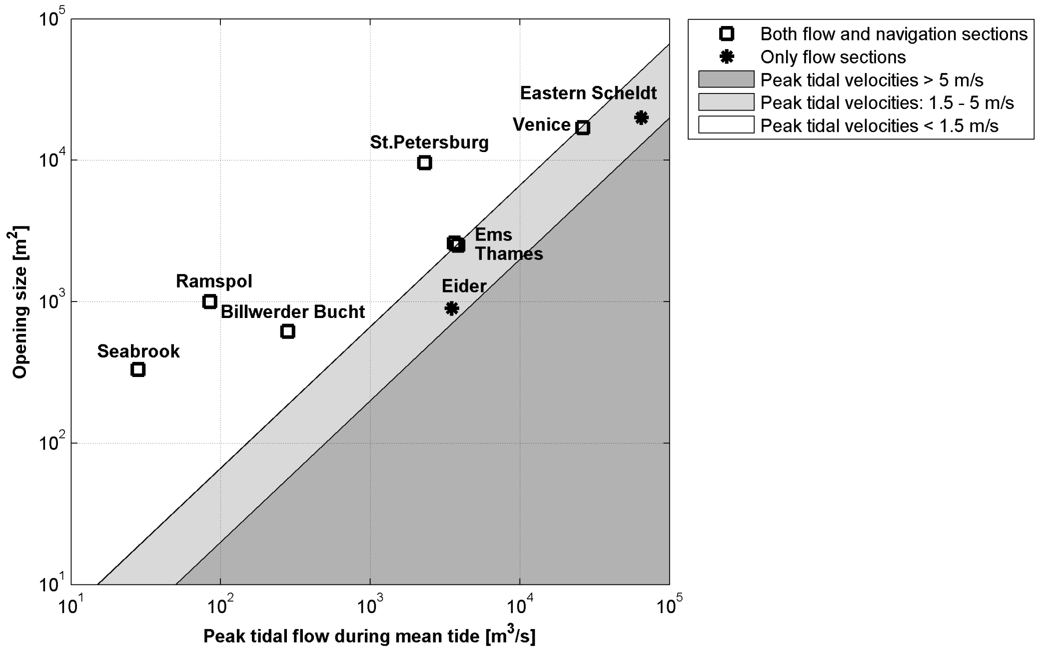


Figure 4 - Relationship between opening size and peak tidal flow during mean tide

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

In the formula, $\hat{Q}$ represents the peak tidal flow during a mean tide [m^3/s], V represents the average tidal volume running through the barrier [m^3], and T represents the tidal period [s]. Two types of storm surge barriers can be distinguished: barriers with flow openings only and barriers with both flow and navigation openings. Since there is no tidal flow at the Ramspol barrier (the Netherlands), the average river runoff during winter was used.

Figure 4 shows that the two barriers with flow openings only (i.e. the Eider and Eastern Scheldt barriers) both have a tidal velocity in the range of 1.5 to 5 meters per second. These barriers have reduced the pre-construction effective cross-sectional area, which explains these high tidal velocities. Consequently, these barriers require relatively heavy scour protection measures, requiring intensive maintenance. Both the Eastern Scheldt barrage and the Eider barrage suffered severe damage to their scour protections several decades after their construction (ANP 2013;

Dietz and Nestmann 1994). Furthermore, the flow velocities are too high to allow navigation, which explains why these barriers have locks instead of navigation openings. Another consequence of the flow constriction is the loss of valuable tidal flats resulting from the changing morphology of the basin behind the barrier (Eelkema et al. 2013).

Barriers with both navigation and flow openings have tidal velocities equal to or lower than 1.5 m/s. Three of these barriers (the Venice, Thames and Ems barriers) are all associated with a peak tidal velocity close to this value. A velocity of 1.5 m/s is common in tidal areas and is considered to be a navigable limit. At the Seabrook and Billwerder Bucht barriers, navigability was mentioned as an important criterion affecting the size of the flow openings (Gatjen 1979). At two barriers (St. Petersburg, Ramspol), tidal velocities are much lower than would be required for navigability alone. At the St. Petersburg barrier, the flow openings allow sufficient water circulation in the basin behind the barrier, the Neva Bay (NEDECO 2002). At the Ramspol barrier, the size of the flow opening is designed to preserve the pre-construction hydrodynamic behavior and inundation frequencies of valuable natural areas (Rijkswaterstaat 1995). Maintaining the pre-construction weak water circulation appears to be the common motivation for the relatively large openings at both barriers.

For all barriers with flow openings, the above considerations show that the size of the flow openings can be related to two main types of requirements, i.e. navigability requirements and water exchange requirements for preserving the inner basin ecosystem.

Foundations

Storm surge barriers are generally constructed in estuaries or deltas, i.e. areas with soft soils. In spite of this, storm surge barriers need to be able to resist large horizontal forces imposed by storm surges and waves. Storm surge barriers foundations are, therefore, relatively complex and expensive. Foundation types range from pile to caisson foundations and, in some cases, soil improvements were applied. Seven barriers have a foundation depth of more than 20 meters. Innovative techniques have been used in storm surge barrier foundations. For example, for the Eastern Scheldt barrier, special equipment was developed to compact the soil under water. For the swing arms of the Maeslant barrier, a unique ball joint was constructed to transfer the hydraulic forces to the foundation.

Safety and reliability

Storm surge barriers are part of the primary flood protection system and, therefore, strict safety requirements are often applied. The design water levels are connected to the regional standards, ranging from design water levels with a 100-year return period in New Orleans to 10,000-year protection levels in the Netherlands. A specific requirement concerns the reliability of the closing mechanism during storm conditions. As an example, the target reliability of the Maeslant barrier in the Netherlands is set at one failure every 100 closures. Advanced probabilistic techniques, such as fault trees and Monte Carlo simulation, are used to quantify the failure probability of structural, mechanical, information and communication technology, human and organizational (sub)systems (Van Manen et al. 2015; Vrancken et al. 2008; Willems and Webbers 2003). Due to the high reliability required, considerable effort is often spent on a redundant design of the main subsystems. This contributes to the costs of the barriers.

Costs of storm surge barriers

The costs of storm surge barriers are considerable. For future planning of storm surge barriers, the ability to estimate a cost range is relevant. Information was collected on the investment costs of fifteen storm surge barriers. Unless indicated otherwise the same sources as those for table 1 were used. The costs were adjusted to 2013 price levels by applying a country specific construction index rate. Further cost information is included in appendix S2 (supplemental data). The costs were compared with the cumulative span of the storm surge barriers (see Figure 5). The numbers in Figure 5 refer to the numbering of storm surge barriers in table 1. On average, the unit cost for a storm surge barrier was found to be 2.2 million euros per meter of span. Although the linear model predicts the costs reasonably well (coefficient of determination $R^2 = 0.84$), a significant variation is still found (coefficient of variation $c_v = 0.56$). Other cost estimation methods (van Ledden et al. 2012; De Ridder n.d.) apply parameters to account for the hydraulic load. However, these methods and differentiation with respect to gate type, barrier length and foundation depth do not result in a better fit. In addition to the construction costs, the management and maintenance costs of these complex structures are significant. Experience with the Dutch barriers shows that the annual costs amount to approximately 1% of the construction costs (Jonkman et al. 2013).

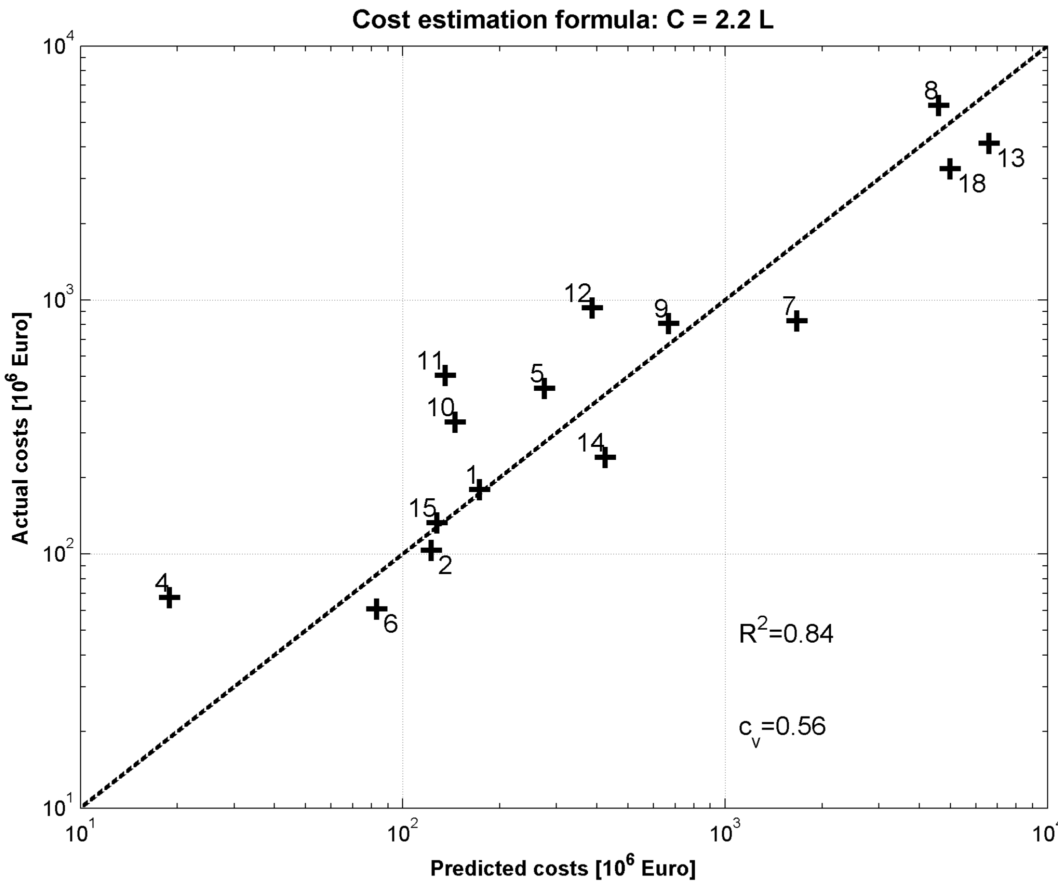


Figure 5 - Comparison of actual and predicted construction costs of storm surge barriers

Concluding remarks

This note provides an overview of existing storm surge barriers and highlights a number of main design considerations. Storm surge barriers are complex and technically challenging structures involving high costs. Main elements that determine the cost of a barrier include the gates (type and span), foundation, and scour protection. Through a systematic analysis of barriers, the relationship between functional requirements and main characteristics of the barriers was investigated. Requirements regarding navigability and water quality were related to the size and the type of gate. Storm surge barriers which significantly constrict the tidal flow were found to severely affect navigation and the ecosystem of the inner bay.

Among other factors, the rapid development of coastal cities can be explained by their easy access to the sea and the associated economic and societal benefits. For cities located on bays or estuaries, a storm surge barrier is often the only solution that can prevent or limit the need to reinforce existing flood defenses while still facilitating navigation and preserving the existing ecosystem of the inner bay. Preventing or limiting the need for reinforcement of high defenses also offers opportunities for waterfront development nearer to the average water level.

Given the potential advantages of storm surge barriers, and the recent attention for flood risk reduction and adaptation to sea level rise, it is not surprising that various coastal cities are considering storm surge barriers as an option. Examples are Nieuwpoort (Belgium), Hamburg (Germany – Sass, 1986), Götenborg (Sweden), Tokyo (Japan), New York (United States – Aerts et al. 2013; Dircke et al. 2012b) and Houston (United States – De Vries 2014).

The costs associated with the construction and maintenance of storm surge barriers are high. Consequently, mainly developed coastal cities can afford the relatively high cost of this solution. In the future, it is also expected that options for storm surge barriers will be investigated in newly advancing economies, as for example in Shanghai at the mouth of the Huangpu river in China. Given the future potential of this type of solution, more systematic documentation of (future) storm surge barriers as well as the analysis and sharing of this information is recommended. This will assist the planning of flood risk reduction and adaptation strategies in coastal areas.

Supplemental data

Appendixes S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

Acknowledgments

The authors acknowledge the support of Royal HaskoningDHV and thank Marloes van Ginkel and Mathijs van Ledden for their reviews and contributions.

Notation

The following symbols are used in this note:

$\hat{Q}$ = Peak tidal flow;

T = Tidal period; and

V = Tidal volume.

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Table 1. Main characteristics of storm surge barriers

#	Storm surge barrier	Constr. Period	Main functions [y]	Length [m]	Cum. span [m]	Navigation openings [z]	Flow openings [z]	Sill level[aa]	Foundation type, depth[bb]
1	Hollandse IJssel, The Netherlands[a]	1954-'58	Navigation (i)	200	80	Double vertical lift, 80 m, lock, 24m	-	-6.5m	Pile, 14m
2	New Bedford, USA[b]	1962-'66	Navigation (f)	1,370	46	Sector gate, 46m	-	-11.9m	Shallow (Rock)
3	Billwerder Bucht, Germany[c,d]	1964-'66	Navigation (i), tidal exchange	150	128	Flap gate, 2x34 m	Flap gate, 2x30m	-4.8 m	Tension pile, 5 m
4	Stamford, USA[b]	1965-'69	Navigation (r)	870	27	Flap gate, 27m	-	-5.5m	-, -
5	Eider, Germany[e]	1967-'73	Tidal exchange, road connection	4,900	200	lock, 14m	Double segment gates, 5x40m	-4.6m	Pile, 23m
6	Hull barrier, UK[f]	1977-'80	Navigation (r)	40[x]	30	Vertical lift, 30m	-	-4.3m	Caisson, 15m
7	Thames, Great Britain[g]	1974-'82	Navigation (s), tidal exchange	530	369	Rotary segment, 4x 61m & 2x31m	Segment gate, 4x31m	-5.8m	Impr.+ pile, 16m

8	Eastern Scheldt, The Netherlands[h]	1973-'86	Tidal exchange, road connection	9,000	2,604	lock, 16m	Vertical lift, 62x42m	-7.6m	Shallow+ impr., 22m
9	Maeslant , The Netherlands[i]	1989-'97	Navigation (s)	610	360	Floating sector, 360m	-	-17m	Impr., 5m
10	Hartel, The Netherlands[j,k]	1993-'97	Navigation (i)	250[x]	147	Vertical lift, 98 & 49m, Lock, 24m	-	-6.5m	Pile, 3m
11	Ramspol, The Netherlands[l]	1996-'02	Navigation (i), water exchange	450[x]	202	inflatable rubber, 52m	Inflatable rubber, 2x75m	-4.65m	Pile, 10m
12	Ems, Germany[m]	1998-'02	Navigation (i), tidal exchange	476	414	Rotary segment, 60m, segment 50 m	Vertical lift, 5x50m	-6.4m	Pile, 34m
13	St. Petersburg, Russia[n, o, p]	1984-'11	Navigation (s), road connection, tidal exchange, river runoff	25,400	1,846	Floating sector, 200m, vertical rising, 110m	Segment, 64x24m	-5.2m	Caisson, pile, -
14	IHNC, USA[q]	2008-'11	Navigation (i)	2,300	107	Sector, 45m, barge,	-	-5.2m	Pile, 35m

						45m, vertical lift, 17m			
15	Seabrook, USA[r]	2008-‘11	Navigation (i), tidal exchange	130	59	Sector, 29m	Vertical lift, 2x15m	-5.5m	Pile, 35m
16	Harvey Canal, USA[s]	2008-‘11	Navigation (i)	120[x]	38	Sector, 38m	-	-4.9m	Pile, 35m
17	West Closure complex, USA[t,u]	2008-‘12	Navigation (i)	525[x]	69	Sector, 69m	-	-4.9m	Pile, 35m
18	Venice, Italy[q,w]	2003-’16?	Navigation (s), tidal exchange	1,600[x]	1,560	Flap, 3x400 m	Flap, 1x360m	-10.7m	Pile, 15m

a. (Rijkswaterstaat 1959)

b. (Morang 2007)

c. (Lehmann and Jasper 2008)

d. (Gatjen 1979)

e. (Cordes et al. 1972)

f. (Fleming et al. 1980)

g. (Vos 2002)

h. (Rijkswaterstaat 1986)

i. (Rijkswaterstaat n.d.)

j. (Rijkswaterstaat 2015)

k. (Daniel 1996)

l. (Rövekamp 1998)

m. (Starke and Wolff 2000)

n. (CH2MHill 2015)

o. (Ministry of Construction and Housing of the Russian Federation 2013)

p. (NEDECO 2002)

q. (DeSoto-Duncan et al. 2011)

r. (USACE 2013a)

s. (Dircke et al. 2012)

t. (Maynord 2013)

u. (USACE 2013b)

v. (Water-technology.net 2015)

w. (Munaretto et al. 2012)

x. Estimates from satellite images (Google Earth)

y. The type of navigation {i.e. sea going commercial traffic (s), inland navigation (i), fishery or recreation (f,r)} is included within brackets.

z. First the hydraulic gate type and then its span are mentioned. For locks the width is presented.

aa. Relative to Mean Sea Level.

bb. For multiple foundations, if indicated with a plus (+) both foundation types were applied in the same section, if indicated with a comma (,) the foundation types were applied at different sections. Impr. is an abbreviation of soil improvement. The foundations depths are relative to the sill level.

APPENDIX S1: MAIN CHARACTERISTICS OF STORM SURGE BARRIERS

Tab S1. Hollandsche IJssel barrier (The Netherlands)

Parameter	**Description**
General	The Hollandsche IJssel barrier was constructed at the confluence of the Hollandsche IJssel and the New Meuse. This barrier is the first hydraulic structure of the Delta Works, which were initiated after the disastrous 1953 flood. On average, it closes 6 times a year to reduce water levels at the Hollandsche IJssel and thereby prevent flooding. It consists of one 80 meter long opening for inland navigation with two gates for sufficient reliability of closure. Furthermore, it has an adjacent lock for recreational traffic and inland navigation in case the flood gates are closed.
Length	200 m
Cumulative span	80 m
Construction period	1954-1958
Closure frequency	6 times a year
Design safety level system	10^{-4} year
Design water level (outside)	MSL + 4.5m
Design water level (inside)	MSL (estimated)
Tidal range	1.5 m
Surface inner basin	-
Tidal volume	5 10^6 m^3
Wet cross-section (below MSL)	520 m^2
Foundation	Pile foundation

Gate types	Double vertical lift
Number	1
Span	80 m
Sill level	MSL – 6,5m
Navigation	Navigation through lock (width: 24 m) and vertical lift gate

Fig S1. Hollandsche IJssel barrier (image by Jan van Galen)

Tab S2. New Bedford hurricane barrier (USA, MA)

Parameter	**Description**
General	Located in Massachusetts (USA), this barrier consists of a 2.8 km dam with a crest level of more than 6.1 m above mean sea level. The navigation opening of around 46 m wide is protected by two sector gates. The sector gates with a height of around 18.3 m are housed in side chambers in the abutments. The gates can be rolled by using steel wheels on a concrete sill. The closing time of the gate is around 12 minutes.
Length	1,370 m
Cumulative span	46 m
Construction period	1962 – 1966
Closure frequency	12- 24 times a year
Safety level barrier	1/500 y
Design water level (outside)	MSL + 4,9 m
Design water level (inside)	MSL (estimated)
Tidal range	1.5 m
Surface inner basin	1.1 km^2
Tidal volume	2 10^6 m^3
Wet cross-section (below MSL)	550 m^2
Foundation	Shallow foundation on rock ledge
Gate type	Sector
Number	1

Span	46 m
Sill level	MSL – 11,9m
Navigation	Through sector gate

Tab S3. Billwerder Bucht barrier (Germany)

Parameter	Description	
General	The Billwerder Bucht barrier was erected between 1964 and 1966 for the flood protection of the region of Billwerder Bucht and its adjacent industrial canals. Thereby, it became part of the main dike defense line of the City of Hamburg, which was drawn up after the storm surge of 1962. The barrier consisted of four flap gates with their axis above the water table. The two main openings can be used for navigation. Between 1999 and 2002 the barrier was rebuilt for the adaptation of all storm and flood protection structures to the new design water level. The reconstruction included a second line of hydraulic gates with a similar design as the first one. Therefore, it now consists of four openings with a double flap gate.	
Length	150 m	
Cumulative span	128 m	
Construction period	1964 – 1966	
Closure frequency	1 in 2 or 3 years	
Safety level barrier	-	
Design water level (outside)	MSL + 5.7 m	
Design water level (inside)	MSL + 3.5 m	
Tidal range	2.3 m	
Surface inner basin	1.7 km^2	
Tidal volume	4 10^6 m^3	
Wet cross-section (below MSL)	614 m^2	
Foundation	Tension piles ~ 5m	
Total number of gates	8	
Gate types	Double flap gate (axis above water table)	Double flap gate (axis above water table)
Number	2	2
Span	34	30
Sill level	-5.3	-4.3

Navigation	Through deep double flap gates

Fig S2. Billwerder Bucht barrier (image by GeorgHH)

Tab S4. Stamford hurricane barrier (USA, CT)

Parameter	Description
General	The East Branch Barrier at Stamford, which is constructed in 1968, is a barrier consisting of an earth-and-rock dike with the length of 866 m with the top elevation of more than 54 m and a 28 m opening channel with a single steel flap gate protection. In this flap gate, the hollow steel gates rests on the bottom of the channel and it is raised to close the opening by means of the hydraulic cylinder. The gate lifted in 20 minutes.
Length	870 m
Cumulative span	27 m
Construction period	1965 – 1969
Closure frequency	Unknown
Safety level barrier	1/500 y
Design water level (outside)	MSL + 4,5 m
Design water level (inside)	MSL (estimated)
Tidal range	2.2 m
Surface inner basin	0.1 km^2
Tidal volume	0.2 10^6 m^3
Wet cross-section (below MSL)	150 m^2
Foundation	Unknown
Gate types	Flap gate
Number	1

Span	27 m
Sill level	MSL – 5,5m
Navigation	Through flap gate

Fig S3. Stamford hurricane barrier (image by U.S. Army Corps of Engineers)

Tab S5. Eider barrier (Germany)

Parameter	Description
General	The North sea coast at Germany has experienced a serious flooding in 1962. In 1965 it was decided to construct the Eider barrier. The Eider barrier shortens the length of the coastal defense from 60 to 5 kilometer. The barrier consists of five double segment gates and an adjacent lock to allow navigation. Next to closing during a storm surge, it can operate in a way the surrounding land can be drained by keeping the level in the Eider estuary low. Furthermore, there is an operation scheme to flush accumulating sediments.
Length	4,900 m
Cumulative span	200 m
Construction period	1967 – 1973
Closure frequency	2 times per year
Safety level barrier	Unknown
Design water level (outside)	MSL + 2m
Design water level (inside)	MSL – 1.6 m
Tidal range	3.1 m
Surface inner basin	-
Tidal volume	50 10^6 m^3
Wet cross-section (below MSL)	930 m^2

Foundation	Pile foundation
Gate types	Double segment gates
Number	5
Span	40 m
Sill level	MSL – 4,65m
Navigation	Through adjacent lock

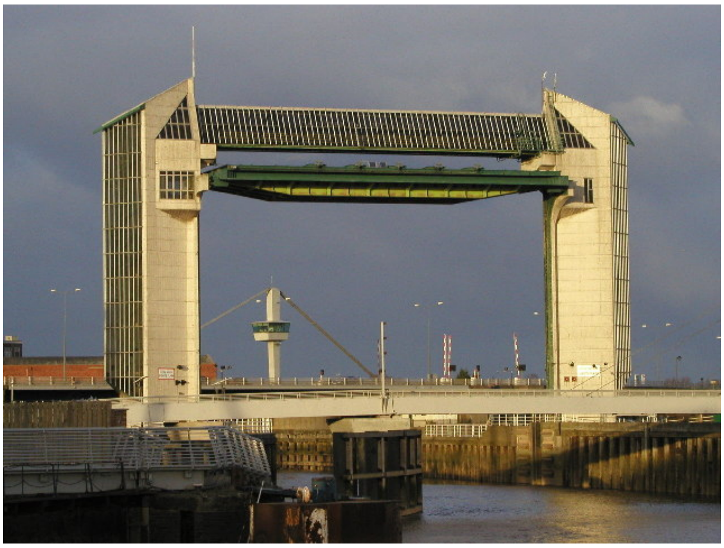
Fig S4. Eider barrier (image by Ulf Jungjohann)

Tab S6. Hull barrier (UK)

Parameter	Description
General	The River Hull Tidal Surge Barrier is located at the confluence of the rivers Hull and Humber to exclude surges and tides from the River Hull. It consists of a 30 meter long vertical lift gate that can allow tidal exchange and recreational sailing. Construction included one of the deepest single-stage cofferdams ever attempted in the UK, and an account is given of the design and practical problems encountered. The project included some unusual architectural features, ancillary flood defences and a telemetry system.
Length	40 m
Cumulative span	30 m
Construction period	1977-1980
Closure frequency	12 times per year
Safety level barrier	10^{-4} year
Design water level (outside)	MSL + 5,9 m
Design water level (inside)	MSL (estimated)
Tidal range	4 m
Surface inner basin	0.7 km^2
Tidal volume	3 10^6 m^3
Wet cross-section (below MSL)	130 m^2
Foundation	Mass concrete monoliths supporting the hoisting towers
Gate types	Vertical lift

Number	1
Span	30 m
Sill level	MSL – 4,3m
Navigation	Through vertical lift gate

Fig S5. Hull barrier (image by Andy Beecroft)



Tab S7. Thames barrier (UK)

Parameter	**Description**		
General	The Thames barrier (United Kingdom) protects the city of London against floods. It consists of ten openings with spans ranging from 30 to 61 meters. Six rotary segment gates are applied in the larger openings to allow navigation. The other four openings consist of normal segment gates.		
Length	530 m		
Cumulative span	369 m		
Construction period	1974-1982		
Closure frequency	2 times per year		
Safety level barrier	1/1000 y		
Design water level (outside	MSL + 6.9m		
Design water level (inside)	MSL - 1.5m		
Tidal range	5 m		
Surface inner basin	11 km^2		
Tidal volume	55 10^6 m^3		
Wet cross-section (below MSL)	2488 m^2		
Foundation	Soil improvement (chalk removal) and pile foundation		
Total number of gates	7		
Gate types	*Rotary segment*	*Rotary segment*	*Segment*
Number	4	2	4
Span	61 m	31,5 m	31 m
Sill level	MSL – 9,25 m	MSL – 4,65m	MSL + 0,5 m
Navigation	Navigation through rotary segment gates		

Fig S6. Thames barrier (image by Arpingstone)

Tab S8. Eastern Scheldt barrier (The Netherlands)

Parameter	Description
General	In the 1970's, originally, a closure dam was planned to protect the Eastern Scheldt estuary (The Netherlands). It was decided, however, to equip the Eastern Scheldt barrier with large openings to allow tidal exchange and thereby preserve the environment and local fishery. Due to the large tidal exchange, it has the largest cumulative span of all the storm surge barriers. It consists of 62 hydraulic gates of the vertical lift type with a span of 42 meters. Still the opening is reduced to only one fifth of the original tidal opening, due to both vertical and horizontal construction. Furthermore, the barrier consists of long bottom protections at each side of the barrier, which recently experienced severe damage. One lock, called the Roompotsluis, accommodates navigation.
Length	9000 m
Cumulative span	2604 m
Construction period	1969-1984
Closure frequency	1/2 per year
Design safety level system	1/4000 y
Design water level (outside)	MSL + 5.5m
Design water level (inside)	MSL + 0.7m
Tidal range	2.7 m
Surface inner basin	340 km^2
Tidal volume	925 10^6 m^3
Design wave height	5 to 6 meter
Pre-construction wet cross-	80,000 m^2

section below MSL							
Post construction wet cross-section below MSL	18,000 m^2						
Foundation	Soil compaction, soil improvement and shallow foundation						
Total number of gates	64						
Gate types	*Vertical lift*	*Vertical lift*	*Vertical lift*	*Vertical lift*	*Vertical lift*	*Vertical lift*	*Vertical lift*
Number	15	6	8	9	6	11	7
Span	42	42	42	42	42	42	42
Sill level	-4.9	-5.9	-6.9	-7.9	-8.9	-9.9	-10.9
Navigation	Roompotsluis, width: 16 meter (lock)						

Fig S7. Eastern Scheldt barrier (image by Rijkswaterstaat)

Tab S9. Maeslant barrier (The Netherlands)

Parameter	**Description**
General	The Maeslant barrier (The Netherlands) was constructed to prevent floods in the cities of Rotterdam, Dordrecht and the surrounding areas. It allows navigation for the port of Rotterdam. The storm surge barrier consists of a double floating sector gate spanning 360 meters. This storm surge barrier has the deepest sill level of all storm surge barriers, as it is 17 meters below mean sea level.

Length	610 m
Cumulative span	360 m
Construction period	1989-1997
Closure frequency	1/10 times per year
Design requirements safety	Structural failure: 10^{-6}/y
	Failure to close: 10^{-3}/y
	Failure to open: 10^{-4}/y
Design water level (outside)	MSL + 6.7m
Design water level (inside)	MSL + 1.2m
Tidal range	1.8 m
Surface inner basin	n/a
Tidal volume	90 10^6 m^3 (average ebb and flood)
Wet cross-section (below MSL)	6800 m^2
Foundation	Spherical hinges with a soil improvement
Gate type	*Floating sector*
Number	1
Span	360
Sill level	MSL – 17 m

Fig S8. Maeslant barrier (image by Rijkswaterstaat)

Tab S10. Hartel barrier (The Netherlands)

Parameter	**Description**
General	The Hartel Canal storm surge barrier consists of two lens-shaped vertical lifting gates with spans of 98 m and 49.3 m with a height of 9.3 m. During extreme floods, a large volume of water can flow over the gate. The sliding gates are driven by hydraulic cylinders with a long piston which are hinged to the side towers. The vertical clearance at the mean water level is about 14 m. This barrier was constructed from 1993 till 1996. An adjacent shipping lock can be used by recreational traffic and when the barrier is closed.
Length	250 m
Cumulative span	147 m
Construction period	1993 – 1997
Closure frequency	1/10 year
Safety level barrier	10^{-4} year
Design water level (outside)	MSL + 6.7 m
Design water level (inside)	MSL + 1.2 m
Tidal range	1.6 m
Surface inner basin	n/a
Tidal volume	15 10^6 m^3
Wet cross-section (below MSL)	950 m^2
Foundation	Pile foundation
Gate type	Vertical lift
Number	2
Span	98 and 47 m
Sill level	MSL – 6.5 m
Navigation	Navigation through both lock and vertical gates

Fig S9. Hartel barrier (image by Rijkswaterstaat)

Tab S11. Ramspol barrier (The Netherlands)

Parameter	**Description**
General	The Ramspol barrier, located in the Netherlands, is in operation since 2002 and can be mentioned as the only major flood protection barrier in the world of this type. It protects the Zwarte Meer (English: the black lake) in the Eastern part of the Netherlands from inundation. The barrier consists of three identical inflatable rubber gates with a length of 60 m at the bottom. The gates can be inflated to 8.2 m above the sill. In this situation both air and water is applied to fill the gate. One of the openings is applied for inland navigation. When the barrier is not in operation, the rubber sheets lie in recess at the bottom. For deflating the gates, there are 27 air vents in the abutments and additionally the water is pumped out. Finally, the sheet can be retracted into the sill by using the guiding rollers. The barrier can be closed within an hour.
Length	450
Cumulative span	225
Construction period	1996-2002
Closure frequency	2 times per year
Design safety level system	1/4000 year
Design water level (outside)	MSL + 3.55m
Design water level (inside)	MSL + 0.5 m
Tidal range	n/a
Surface inner basin	n/a
Tidal volume	n/a
Wet cross-section (below MSL)	1050 m^2
Foundation	Pile foundation
Gate type	Inflatable rubber
Number	3
Span	60 at the bottom, 80 meter at the top
Sill level	MSL - 4.65m
Navigation	Inland navigation through one section, recreational through other.

Fig S10. Ramspol barrier (image by Rijkswaterstaat)

Tab S12. Ems barrier (Germany)

Parameter	Description
General	The Ems barrier (Germany) consists of seven openings with spans ranging from 50 to 64 meters. The main navigation opening (L=60m) is equipped with a rotary segment gate and allows cruise ships to pass. The other navigation opening facilitates inland shipping and consists of a segment gate. Five other gates are flow openings with vertical lift gates.
Length	476 m
Cumulative span	414 m
Construction period	1998 – 2002
Closure frequency	2 times per year
Safety level barrier	1/1000 y
Design water level (outside)	MSL + 6.4m
Design water level (inside)	MSL + 3.5m
Tidal range	n/a
Surface inner basin	n/a
Tidal volume	52 10^6 m^3
Wet cross-section (below MSL)	2,435 m^2
Foundation	Pile foundation

Total number of gates	7				
Gate types	*Rotary segment (HSO)*	*Segment (BSO)*	*Vertical lift (NO1)*	*Vertical lift (NO2)*	*Vertical lift (NO3, 4, 5)*
Number	1	1	1	1	3
Span	60 m	50 m	50 m	63.5 m	50 m
Sill level	MSL – 8 m	MSL – 7m	MSL – 7 m	MSL – 7 m	MSL – 5m
Navigation	Navigation through HSO and BSO				

Fig S11. Ems barrier (image by Bin in Garten)

Tab S13. St. Petersburg barrier (Russia)

Parameter	**Description**			
General	The St. Petersburg barrier (Russia) is the longest storm surge barrier with a total length of 25.4 kilometers. It mainly consists of dam sections (~23 kilometer), but due to its function and the size of the openings it is still considered to be a storm surge barrier. The barrier consists of two navigation openings: one opening with a sector gate spanning 200 meters and one vertical rising gate spanning 110 meters. The other openings consist of segment gates. Next to protecting the city of St. Petersburg against flooding, the dam functions as a road connection. At the location of the floating sector gate, a tunnel was constructed to provide unlimited clearance for navigation and continuous road access.			
Length	25,400 m			
Cumulative span	1846 m			
Construction period	1984-2011			
Closure frequency	1 to 2 times per year			
Safety level barrier	1/1000 year			
Design water level (outside)	MSL + 4.55m			
Design water level (inside)	MSL + 1.6m (inundation level)			
Tidal range	0.1 m			
Surface inner basin	329 km^2			
Tidal volume	33 10^6 m^3			
Wet cross-section (below MSL)	9610 m^2			
Foundation	Caisson (S1) and pile foundation (B1-B6), S2 unknown			
Total number of gates	66			
Gate types	*Floating sector (S1)*	*Vertical rising (S2)*	*Segment (B1, B3, B6)*	*Segment (B2, B4, B5)*
Number	1	1	34	30
Span	200 m	110 m	24 m	24 m
Sill level	MSL – 16 m	MSL – 7 m	MSL – 2.5 m	MSL – 5m
Navigation	Navigation through S1 and S2			

Fig S12. St. Petersburg barrier (image by Ssr)

Tab S14. IHNC barrier (USA, LA)

Parameter	**Description**		
General	The Hurricane and Storm Damage Risk Reduction System (HSDRRS) protects the southeast Louisiana. The 1.8-mile-long Inner Harbor Navigation Canal (IHNC)-Lake Borgne Surge Barrier is located at the confluence of the Gulf Intracoastal Waterway (GIWW) and the Mississippi River Gulf Outlet (MRGO), about 12 miles east of downtown New Orleans. The surge barrier works in tandem with the Seabrook Floodgate Complex, which was constructed at the north end of the IHNC (also known locally as the Industrial Canal) near Lake Pontchartrain. The projects reduces the risk associated with a storm surge that has a one percent chance of occurring in any given year (a 100-year storm surge) for some of the areas hardest hit by Hurricane Katrina, including New Orleans East, metro New Orleans, Gentilly, the Ninth Ward and St. Bernard Parish. To allow navigation three gates have been constructed; a sector gate, a barge gate and a vertical lift gate.		
Length	2,300 m		
Cumulative span	107 m		
Construction period	2008 – 2011		
Closure frequency	1/2 years		
Design safety level system	1/100 year		
Design water level (outside)	MSL + 6.6 m		
Design water level (inside)	MSL (estimated)		
Tidal range	0.2 m		
Surface inner basin	2 km^2		
Tidal volume	0.4 10^6 m^3		
Wet cross-section (below MSL)	520 m^2		
Foundation	Pile foundation		
Gate types	Sector gate	Barge gate	Vertical lift
Number	1	1	1

Span	46 m	46 m	17 m
Sill level	MSL – 4,9m	MSL – 4,9 m	MSL – 3,7 m
Navigation	Navigation through sector gate and vertical lift, during construction and maintenance through barge gate.		

Fig S13. IHNC barrier (image by Ssr)

Tab S15. Seabrook Floodgate Complex (USA, LA)

Parameter	Description	
General	Next to the INHC barrier, the Seabrook Floodgate Complex is part of the Hurricane and Storm Damage Risk Reduction System (HSDRRS) protecting the southeast Louisiana. It is located at the north end of the Inner Harbor Navigation Canal (IHNC; also known locally as the Industrial Canal) just south of Lake Pontchartrain and the Senator Ted Hickey Bridge. The Seabrook Floodgate Complex consists of a 95-foot-wide navigable sector gate and two 50-foot-wide non-navigable vertical lift gates.	
Length	130 m	
Cumulative span	59 m	
Construction period	2008 – 2011	
Closure frequency	1/2 year	
Design safety level system	1/100 year	
Design water level (outside)	MSL + 3 m (estimation based on gate height)	
Design water level (inside)	MSL (estimated)	
Tidal range	0.2 m	
Surface inner basin	2 km^2	
Tidal volume	0.4 10^6 m^3	
Wet cross-section (below MSL)	320 m^2	
Foundation	Unknown, pile foundation	
Gate types	Sector	Vertical lift
Number	1	2
Span	29 m	15 m
Sill level	MSL – 5,5 m	MSL – 5,5m
Navigation	Through sector gate	

Tab S16. Harvey Canal floodgate (USA, LA)

Parameter	Description
General	The Harvey Canal floodgate is part of the Hurricane and Storm Damage Risk Reduction System (HSDRRS) protecting the southeast Louisiana. The floodgate is part of a second line of defence with the objective to keep the water level in the Harvey Canal low. The flood gate is a navigable 38 meter wide sector gate.
Length	120 m
Cumulative span	38 m
Construction period	2008 – 2011
Closure frequency	1/2 years
Design safety level system	1/100 year
Design water level (outside)	MSL + 2.5m
Design water level (inside)	MSL
Tidal range	0.2 m
Surface inner basin	2 km^2
Tidal volume	0.4 10^6 m^3
Wet cross-section (below MSL)	330 m^2
Foundation	Pile foundation
Gate type	Sector
Span	69 m
Sill level	MSL-4.9m

Tab S17. GIWW-West Closure Complex (USA, LA)

Parameter	**Description**
General	The GIWW-West Closure Complex is part of the Hurricane and Storm Damage Risk Reduction System (HSDRRS) protecting the southeast Louisiana. During a hurricane, both storm surge and heavy rain fall can occur simultaneously. The West Closure Complex is able to deal with both, as the complex consists of pumping station with a capacity of 540 m^3/s, a 69 meter wide navigable sector gate and 5 sluice gates. The sluice gates together with the sector gate are opened after a hurricane to drain the inner basin.
Length	525
Cumulative span	69
Construction period	2008-2012
Closure frequency	1/2 year
Design safety level system	1/100y
Design water level (outside)	n/a
Design water level (inside)	MSL
Tidal range	0.2 m
Surface inner basin	2 km^2
Tidal volume	0.4 10^6 m^3
Wet cross-section (below MSL)	330 m^2
Foundation	Pile foundation
Gate type	Sector
Span	69 m
Sill level	MSL-4.9m

Fig S14.GIWW-West Closure Complex (image by Team New Orleans)

Tab S18. Venice / MOSE-project (Italy)

Parameter	Description			
General	The objective of the MOSE-project is to protect Venice (Italy) from floods. It is still under construction, but the design indicates that the barrier consists of flap gates which are filled and emptied with air to operate the gates. All the individual gates have a length of 20 meters (perpendicular to the axis of the storm surge barrier). Combined, the gates span four openings, three openings with a span of 400 meter length and one with a span of 360 meter.			
Length	1,500 m			
Cumulative span	1,460 m			
Construction period	2003 – 2014			
Closure frequency	4 times per year			
Design safety level system	n/a			
Design water level (outside)	MSL + 3m			
Design water level (inside)	MSL + 1.1m (inundation level)			
Tidal range	0.75 m			
Surface inner basin	500 km^2			
Tidal volume	375 10^6 m^3			
Wet cross-section (below MSL)	16,760 m^2			
Foundation	Pile foundation			
Total number of gates	79			
Gate types	*Flap (Chiogga)*	*Flap (Malamocco)*	*Flap (S. Nicolo)*	*Flap (Treporti)*
Number	18	20	20	21
Span	20 m	20 m	20 m	20 m
Sill level	MSL – 11 m	MSL – 15 m	MSL – 11 m	MSL – 6m
Navigation	Navigation through Chiogga, Malamocco, Treporti			

References

“De Stormvloedkering met een geopende Algerabrug” by Jan van Galen taken on 1 juni 2006. Available under the Creative Commons Attribution-Share Alike 3.0 Netherlands license. For more information see https://creativecommons.org/licenses/by-sa/3.0/nl/deed.en <https://nl.wikipedia.org/wiki/Stormvloedkering_Hollandse_IJssel> (Nov 24, 2016)

Aerial view of Stamford Harbor and Stamford Hurricane Barrier, Stamford, Connecticut by U.S. Army Corps of Engineers, New England District. Available under the Creative Commons Attribution-NoDerivs license 2.0. For more information see https://creativecommons.org/licenses/by-nd/2.0/ < http://www.nae.usace.army.mil/Media/Images/igpage/72/> (Nov 24, 2016)

Barrage Billwerder Bucht, Hamburg-Rothenburgsort, Germany by GeorgHH taken on september 2016. < https://commons.wikimedia.org/wiki/File:Sperrwerk_Billwerder_Bucht1.jpg> (Nov 24, 2016)

Luftaufnahme des Eidersperrwerks von der Wasserseite by Ulf Jungjohann taken on 16 september 2006. Available under the Creative Commons Attribution-Share Alike 3.0 Unported license. For more information see http://creativecommons.org/licenses/by-sa/3.0/. <https://de.wikipedia.org/wiki/Datei:Eidersperrwerk_Luftaufnahme_landwaerts.jpg> (Nov 24, 2016)

Thames Barrier, pic 6 by Arpingstone (assumed) taken on 9 June 2005 <https://en.wikipedia.org/wiki/Thames_Barrier#/media/File:Thames.barrier.6.london.arp.jpg> (Nov 24, 2016)

River Hull tidal barrier. The tidal barrier is situated at the end of the River Hull where it meets the River Humber by Andy Beecroft taken on 8 February, 2004. Available under the Creative Commons Attribution Share-alike license 2.0. For more information see https://creativecommons.org/licenses/by-sa/2.0/ <https://en.wikipedia.org/wiki/River_Hull#/media/File:River_Hull_tidal_barrier_1.jpg> (Nov 24, 2016)

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Aerial view of w:Navigation Pass S-1 of Saint Petersburg Dam by Ssr taken on 21 September 2014 . Available under a Creative Commons Attribution-Share Alike 3.0 Unported license. For more information see https://creativecommons.org/licenses/by-sa/3.0/deed.ru < https://en.wikipedia.org/wiki/Navigation_Pass_S-1_of_Saint_Petersburg_Dam> (Nov 24, 2016)

"Inner Harbor Navigation Canal Surge Barrier Construction" by Team New Orleans taken on 30 September 2009, US Army Corps of Engineers - originally posted to Flickr as Inner Harbor Navigation Canal Surge Barrier Construction. Licensed under CC BY 2.0 via Wikimedia Commons. For more information, see https://creativecommons.org/licenses/by/2.0/deed.en < https://commons.wikimedia.org/wiki/File:Inner_Harbor_Navigation_Canal_Surge_Barrier_Construction.jpg> (Nov 24, 2016)

References to the data can be found in the reference section of the technical note.