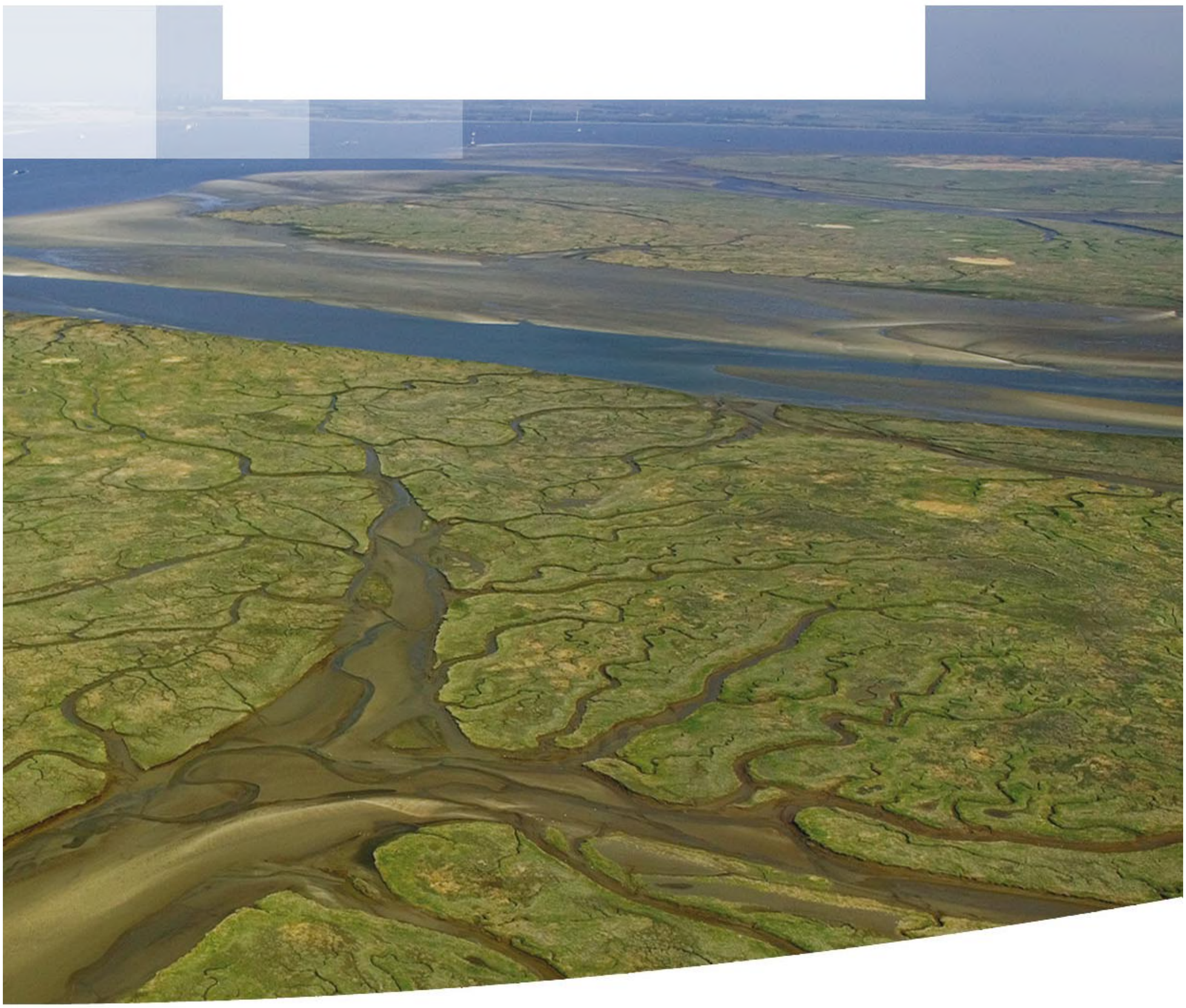
Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

Deltares
Enabling Delta Life

Overview storm surge barriers



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1 Introduction

The growth of coastal population together with the increasing utilization of coastal zones is exposing communities and infrastructure to irreversible damage caused by storm surges. In addition, the combination of storm surges with expected sea-level rise highly increases the vulnerability of coastal areas. The extensive coastline of Denmark is no exception as several large storm surges have affected coastal areas in Denmark with adverse economic impact in the past. The storm surge risk combined with obligations from the EU Floods Directive made several Danish municipalities consider flood protection measures. Storm surge barriers are being considered as possible solutions for coastal protection in large areas, especially in the fiords.

The Danish Coastal Authority (DCA) is the official coastal government agency in Denmark. One of the main tasks of the DCA is to advise the Danish Ministry of the Environment, municipalities and other public authorities on coastal protection along the Danish coastline. The knowledge and experience with storm surge barriers in Denmark is still limited. For this reason, the DCA has contacted Deltares in the Netherlands to make a first step to build up expertise in this type of flood protection method by means of this overview of storm surge barriers.

Deltares has many years of experience in integrated coastal zone management studies and flood early warning forecasting systems, ecological impact studies and scale models to test barriers and locks. In the Netherlands Deltares works closely together Rijkswaterstaat to deliver, develop and maintain the forecasting models that predict the high water levels used to make the decision to close a storm surge barrier or not. Also, some of Deltares employees are in the operational team for storm surge early warnings (WMCN), to deliver the models and knowledge on the basis of what the barriers are closed and the reliability test to meet the Dutch Law are being done (WBI). Also abroad, Deltares experience and knowledge is being recognized. For example Deltares developed the FEWS system (Flood Early Warning Systems) for the UK/Environment Agency. Deltares performed an ecological and morphological impact study for the Venice barrier and did physical model tests to optimize the placement of the foundation caissons of the Venice barrier. In St. Petersburg Deltares has been involved in setting up a forecasting model to close the barrier.

The I-STORM network brings together professionals that build, manage, operate and maintain Storm Surge Barriers in various countries all over the world. The overall objective of I-STORM is to exchange knowledge and information regarding the management and maintenance of Storm Surge Barriers, continuously improving standards of operation, management and performance in order to reduce the risk of severe flooding of people, property and places around the world, by facilitating knowledge exchange amongst members. Given the role of DCA, a direct collaboration with I-STORM partners is very valuable.

This memo aims to provide DCA with a wide and general overview of knowledge and experience on storm surge barriers, by an overview of the different types of barriers as well as some examples of the application of this flood protection method in the Netherlands, UK and Italy. The memo is a first step to assist DCA in providing adequate guidance and support to the municipalities and local associations/land-owners. The memo is followed by a workshop trip that enables DCA to gain more in depth knowledge on Dutch barriers.

The document is organized as follows. Chapter 2 introduces storm surge barriers and their function, covering the different types of barriers. Chapter 3 presents the facts and figures for 6 Dutch barriers and 2 barriers outside the Netherlands.

2 Storm surge barriers

2.1 Description

Storm surge barriers are large, fully or partly movable barriers in estuaries, waterways, rivers, bays or fiords that can be temporarily closed during a severe storm surge in order to protect vulnerable areas/cities against flooding. Usually storm surge barriers are part of a broader flood protection system composed by dikes and sea walls.

2.2 Function (why are they built)

The main function of a storm surge barrier is to prevent storm surges cause flooding in bays, fiords, estuaries, and lakes or upstream in rivers. Storm surge barriers are mostly used in combination with dikes and dams to shorten the coastline and reduce the risk and costs of raising dikes and dams behind. Water levels are kept low behind the barrier by temporarily closing off the area with a gate. During normal conditions the storm surge barriers are kept open to allow tidal exchange and, when relevant, navigation. When the water rises above a particular level, the barrier is closed, either automatically or manually, or in combination. As a consequence, the water level in the protected area remains low whereas the water level on the other side of the barrier continues to rise further. Once the water level on the high-water side has decreased to the same level as the protected side, the barrier can be opened. The main function of a storm surge barrier is to guarantee a certain level of safety against flooding.

Depending on the functions and requirements of the protected area, storm surge barriers can have other functions as well, such as integrated dams and navigation locks. Navigation locks in the Netherlands are part of the water retaining system, so at least one or two gates in the lock work as a flood protection barrier. During normal conditions storm surge barriers allow thus navigation, tidal exchange, discharge of water/ice from upstream, sediment transport and fish passage. The main function of a storm surge barrier is always to protect against flooding, protecting lives and property. Secondary functions, such as using the barrier to prevent spreading oil spills in areas where oil pollution can be a problem, are possible but may never threaten their main function.

2.3 Advantages and consequences

The construction of a storm surge barrier leads to a much lower level of defence required behind the barrier, reducing thus the risk of defence failure and costs, since there is only one protection structure to monitor and maintain. In systems with existing levees and dikes, the higher expected extreme water levels in the future can require increasing the height and reinforcing the existing structures. That solution, however, is typically associated with extremely high costs and time necessary to execute. Thus, building a storm surge barrier can be an economically advantageous solution despite the associated building and maintenance costs. Depending on the design of the barrier it can lead to open/semi-open systems. An open system (e.g. Maeslant barrier) leads to negligible/limited change in ecosystems and navigation requirements due to negligible changes in sediment transport rates, salt intrusion, fish migration, etc. Semi opened systems (e.g. Eastern Scheldt) do have impacts as they do change the water system as the tidal prism[1] is changed. When the barrier was built these impacts have not all been foreseen.

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[1] A tidal prism is the volume of water in an estuary or inlet between mean high tide and mean low tide or the volume of water leaving an estuary at ebb tide.

Storm surge barriers require the implementation of a monitoring and forecasting system so that the barriers can be closed off way before the arrival of extreme water levels. Because of this, these structures are associated with high investment and maintenance costs, specifically when lifetime (maintenance and operation) costs are calculated seriously. Regular maintenance ensures that the barriers satisfy the standards for water safety and failure rate. Regular tests to check equipment and an operational team trained to know how to respond are thus fundamental requirements.

Lessons learned worldwide show that maintenance and operation are mostly underestimated. Most barriers are “designed to build” instead of “designed to operate”. For example, to do maintenance in some barriers employees have to climb many steep stairs, making operation and maintenance not so easy tasks. The combination of complex structures, mostly one-of-a-kind and lack of experience and knowledge within the operating organisation appears often as an underestimated challenge. It is no coincidence that worldwide organisations responsible for management and operation of storm surge barriers organised themselves in the I-STORM network to learn from each other’s scarce knowledge and experience.

Depending on the location, characteristics of the site and how long the barrier needs to be closed, river flood or intense rain is also a possibility during a closing event of the barrier. If the possibility of such coinciding situation is high, then the design of the barrier should take this into account and incorporate a system to drain the excess water from the protected area. This will also have implications for the opening/closing procedure for storm surge barriers. For instance, in September 1998 the Eastern Scheldt barrier was requested to close by the water board of the region so that the nearby pumping stations could drain to the Eastern Scheldt extra water from the polders in order to avoid high water in the city of Breda due to extreme rainfall. The barrier is not allowed to close in circumstances other than preventing high water levels due to storm surges, thus this exceptional closure event lead to discussions among governmental authorities.

2.4 Types of storm surge barriers

The different types of barriers are here distinguished by the type of gate. In this memo 9 different existing types of gates are distinguished but there may be new concepts possible. For each type of gate a short description of their functioning is provided together with a gate schematization[2] and with examples of application.

2.4.1 Sector gate – vertical axis

A sector gate is a radial structure composed by two gate units that are supported laterally. The gates and arms form a sector of a circle that rotate around vertical axes. With this design, the forces are transferred through a steel frame to the hinges at each side of the opening. The gates can be moved under water pressure because the loads are directed towards the axis of rotation. When open, the gates rest on the gate chambers located in the margins of the waterway. When closed, the gates rest on a sill on the bottom of the waterway.

Top view

[2] Gate schematizations based on the technical note: Mooyart, L. F. and Jonkman, N. (2017). “Overview and design considerations of storm surge barriers”. *J. Waterway, Port, Coastal, Ocean Eng.*, 143-2

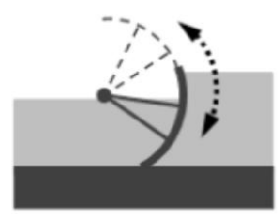
This type of gate has the advantage of requiring relatively light operating mechanisms and being able to move under water pressure. Also, the gates do not obstruct the natural waterway characteristics, allowing for instance tidal exchange, navigation and sediment transport. Disadvantages include the high costs associated, pivoting points and large construction area required for the gate chambers.

Examples of application: Maeslant barrier, New Bedford barrier, St. Petersburg barrier, Inner Harbor Navigation Canal (IHNC), Seabrook Floodgate Complex, West Closure Complex, South Korea barrier.

Figure 2.1 – Maeslant Barrier, The Netherlands.

2.4.2 Sector gate – horizontal axis

Sector gates with horizontal axis (tainter or radial gate) rotate around a horizontal axis that coincides with the center of the circle. To open, the gate turns downwards into a slot in the bottom or into a stilling chamber. It can also turn upwards, resulting in limited clearance for navigation. Advantages are light operating mechanisms and shallow gate chambers. Disadvantages include considerable forces on the pivoting points, the sensitivity to waste and silt and the considerable depth of the underwater chamber. This type of gate is widely used in dams for flow regulation. Typically used for underflows, but can also accommodate overflows.



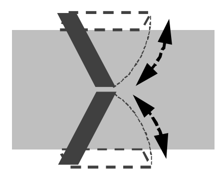
Cross-section

Examples of application: St. Petersburg barrier, Thames barrier, Eider barrier, Ems barrier.

Figure 2.2 – Eider barrier, Germany.

2.4.3 Mitre gate

A mitre gate is a flat gate composed by two gate units. When closed, the two units lean against each other forming a wedge pointing towards the side of higher water level. These gates are thus intended to support a water level difference in one direction only. The gates rotate on vertical axis located in the gate recesses. When open, the gates rest in the gate recesses parallel to the walls of the waterway, clearing the way for navigation. This type of gate is the most commonly used type in navigation locks and very often used in the Netherlands.



Top view

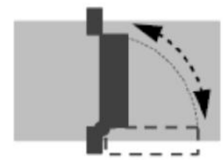
The main advantages of mitre gates include economic use of materials since required thickness is typically small, shallow gate recesses and simple operating mechanism. Disadvantages include high risk of blockage by waste, debris and ice and possibility of opening by vessel collapse against the gate.

Examples of application: several locks in the Netherlands (Small Lock of IJmuiden, Wilhelmina canal, Oranje locks, etc.), Upper Mississippi locks, Ballard locks Seattle, Gatun locks Panama.

Figure 2.3 – Small Lock of IJmuiden, The Netherlands.

2.4.4 Swinging gate

A swinging, or barge, gate is a flat gate that rotates around a vertical axis located in one side of the waterway. The gate may be buoyant or equipped with gated openings to reduce hinge and operating forces. For flood defence, swinging gates have been designed to seal the river against tidal intrusions. These types of gates can only be moved in low flows or with minimal differential head. Once in closed position, the gate is ballasted to sit onto a bottom sill.



Top view

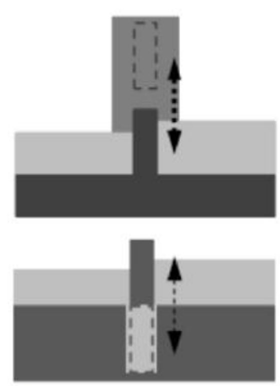
Advantages of this type of barrier include unlimited clearance for navigation, shallow gate recesses, possibility to support a water level difference in both directions and suitability for narrow waterways. Disadvantages include the heavy operating mechanism and the high risk of blockage by waste, debris and ice.

<u>Examples of application</u>: Inner Harbor Navigation Canal (IHNC), Empel lock.

Figure 2.4 – Empel Lock, The Netherlands.

2.4.5 Vertical lift gate

A vertical lift gate is a gate that opens and closes by means of vertical movement. In open position the gate is held vertically above the water, supported by two lateral towers, or stored underwater in a bottom sill. When closed, the gate is lowered (or lifted from the bottom sill, depending on the design) and sits on the bottom sill. This type of gate is suitable to support water level differences in both directions.



Cross-section

Advantages include good inspection and maintenance possibilities if gate can be held vertically above water, as well as little sensitivity to waste and ice, possibility of holding a water level difference in both directions, and less construction space required around the waterway. A big advantage of the gate stored underwater is unlimited clearance for navigation and simple lifting mechanism and supporting structure. Another advantage is preventing corrosion as oxygen cannot reach the gate when it is stored under water. For the gates held above water the main disadvantages are related to costly support towers and limited clearance for navigation. For the underwater gates maintenance and inspection cannot be performed without removing the gate from the waterway. This type of solution requires strong geotechnical foundations, which makes the underwater gates not a preferred solution in the Netherlands.

Examples of application (open gate supported above water level): Hartel barrier, Hollandse IJssel barrier, Eastern Scheldt barrier, Ems barrier, Inner Harbor Navigation Canal (IHNC), Seabrook Floodgate Complex.
Examples of application (open gate stored underwater): St. Petersburg barrier.

Figure 2.5 – Hartel barrier, The Netherlands.

2.4.6 Rotary segment gate

The rotary segment gate has the shape of a cylinder segment and rotates around a horizontal axis. When open, the barrier lies on a concrete sill on the bed of the waterway. Thus, it is possible to sail over the gate in opened position. Operation of the gate is achieved by the rotation of about 90º thus raising the gate to the 'defence' position. A further 90º of rotation of the gate positions it ready for inspection or maintenance.

Cross-section

The main advantages include large stiffness to torsion, light operating mechanisms, clearance for navigation, possibility to support water level difference in both directions, good inspection and maintenance when gate rotated above water and not visible when open. Disadvantages include sensitivity to waste and silt, risk of vibrations when gate is near closed position and considerable forces in pivoting points.

Examples of application: Thames barrier, Ems barrier.

Figure 2.6 – Thames barrier, UK.

2.4.7 Inflatable tube

An inflatable tube gate consists of a sealed tube made of a flexible material, such as synthetic fibre, rubber, or laminated plastic. It is anchored to a bottom 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. When open, the barrier is invisible, lying under water. When it closes, the barrier is inflated standing above the water level. The membranes of inflatable barriers are stored on the bottom of the waterway or in a recess in the foundation of the barrier.

Cross-section

Advantages of this type of barrier include less required maintenance (no corrosion), limited disturbance of the waterway, light weight, not visible when open. Disadvantages include limited experience with this type of gate, shorter service life (rubber) and susceptibility to abrasion.

Examples of application: Ramspol barrier.

Figure 2.7 – Ramspol barrier, The Netherlands.

2.4.8 Flap gate

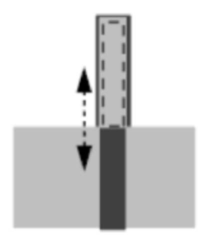
Cross-section

Flap gates consist of straight or curved retaining structures, pivoted on a fixed horizontal axis. These gates are attached to sill foundations. When open, the gates are stored submerged and flat to the bottom. The gates can be operated by filling or emptying the gates with air, or using a piston-type mechanism. In closed position, the gates rotate upwards around the horizontal hinges. Advantages of this solution include not visible when open, allowing navigation, forces are transmitted to the bottom of the waterway (stability), simple civil work. Disadvantages: sensitive to vibrations, corrosion risk in underwater hinges, sensitive to sediment transport (abrasion risk); danger if not enough clearance for shipping.

Examples of application: Venice barrier, Stamford barrier, Billwerder Bucht barrier.

Figure 2.8 – Venice barrier, Italy

2.4.9 Rolling gate



Top view

Rolling gates are flat sliding gates typically made of steel. In open position the gate is stored in a gate chamber adjacent to the waterway. The gate rolls into closed position in anticipation of a flood event. When closed, the loads are transferred to the chamber walls. It can support water level differences on both sides. Gates can roll over bottom rails or slide, depending on the design. The gates are typically partially buoyant (equipped with buoyancy chambers) for ease of movement. These designs are equipped with gated openings in the gate itself to limit the load during closure.

Rolling or sliding gates can support head differences in both directions, allow light operating mechanisms and are suitable for large waterway openings, being common in large navigation locks (ex. New set of Panama locks, new sea lock of IJmuiden - Netherlands). Some of the disadvantages include the large construction areas associated with the gate chambers, the risk of accumulation of waste and silt in the sills and eventual sensitivity to waves for the lighter gates.

Examples of application: Krammer locks, new sea lock of IJmuiden, new set of Panama locks.

Figure 2.9 – Panama lock, Panama.

2.5 Overview types of barriers

The table below presents an overview of the different types of barriers considered and respective advantages and disadvantages.

Table 2.1 Overview advantages and disadvantages of each type of barrier

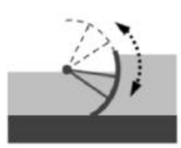
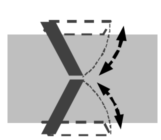
Type of barrier	Schematic	Main advantages	Main disadvantages
Sector gate – vertical axis	 *Top view*	- requires relatively light operating mechanisms; - movable under water pressure; - when open, gates do not obstruct the natural waterway characteristics; - can support head difference in both directions if designed for it.	- typically associated with high costs; - vulnerable pivoting points; - large construction area required for the gate chambers.
Sector gate – horizontal axis	 *Cross-section*	- light operating mechanisms; - can be used for flow regulation; - both overflow and underflow possible; - can support head difference in both directions if designed for it; - facilitates inspection and maintenance if possible to rotate to a position above the water column.	- considerable forces on the pivoting points; - sensitivity to waste and silt; - limits clearance when rotated upwards; - possibility of vibrations when gate is near closed position.
Mitre gate	 *Top view*	- economic use of materials since required thickness is typically small; - shallow gate recesses; - simple operating mechanism; - when open, gates do not obstruct the natural waterway characteristics.	- risk of blockage by waste, debris and ice; - sensitive to differential ground settlement; - support water level difference in one direction only; - possibility of opening by vessel collapse against the gate.

Table 2.1 Overview advantages and disadvantages of each type of barrier (continuation)

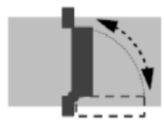
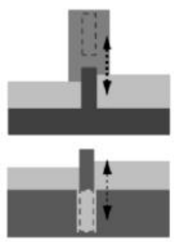
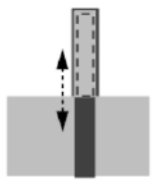
Type of barrier	Schematic	Main advantages	Main disadvantages
Swinging gate	 ***Top view***	- unlimited clearance for navigation; - shallow gate recesses; - can support head difference in both directions if designed for it; - suitable for narrow width passages.	- high risk of blockage by waste, debris and ice; - heavy operating mechanism.
Vertical lift gate	 ***Cross-section***	- can support head difference in both directions; - good inspection and maintenance possibilities for gates held vertically above water; - little sensitivity to waste and ice; - suitable for areas with limited building space; - unlimited clearance for the gates stored underwater. - preventing corrosion as oxygen cannot reach the gate when it is stored under water	- operating mechanism; - costly support towers; - clearance for navigation can be an issue for the gates held above water; - for the drop gates (stored underwater), accessibility for inspection and maintenance, and sensitivity to waste and silt can be a problem; - strong geotechnical foundation is required for the gates stored underwater.
Rotary segment gate	 ***Cross-section***	- large torsion stiffness, allows mechanisms in one side of the gate; - light operating mechanisms; - when open, gates do not obstruct the natural waterway characteristics; - can support head difference in both directions if designed for it; - facilitates inspection and maintenance when rotated above water; - not visible when open.	- considerable forces on the pivoting points; - sensitivity to waste and silt; - possibility of vibrations when gate is near closed position.
Inflatable tube	 ***Cross-section***	- less required maintenance (no corrosion); - limited disturbance of the waterway; - light weight; - not visible when open.	- limited experience with this type of gate; - shorter service life (rubber); - susceptible to abrasion.

Table 2.1 Overview advantages and disadvantages of each type of barrier (continuation)

Type of barrier	Schematic	Main advantages	Main disadvantages
Flap gate	 ***Cross-section***	- not visible when open - forces are transmitted to the bottom of the waterway (stability); - simple civil work.	- sensitive to vibrations; - corrosion risk in underwater hinges; accessibility issues. - sensitive to sediment transport (abrasion), waste and silt; - danger if not enough clearance for shipping;
Rolling gate	 ***Top view***	- can support head difference in both directions; - light operating mechanism; - suitable for large waterway openings;	- large construction area required for the gate chamber; - expensive gate guiding system; - risk of accumulation of waste and silt in the sills - sliding gates (lighter), might be sensitive to waves.

3 Facts and figures storm surge barriers

The Dutch have been fighting against water for centuries and, unfortunately, every century was marked by the devastating effects of severe storms and flooding. In 1937 several studies were conducted by the Dutch government which showed that safety in many parts of the Netherlands could not be guaranteed during storms and high sea levels. In particular, the densely populated areas near the river mouths of the Rhine, the Meuse, and the Scheldt were high risk areas due to the difficulty of building new dikes or strengthen the original ones. The first solution against severe flooding was to close all the river mouths, a proposal designated by “The Deltaplan”.

The scale and costs of the Deltaplan, together with the World War II, led to delays in the construction of the projects. With only two river mouths closed and still fully relying on dikes for protection, in 1953 a major flood caused by a heavy storm surge in the North Sea struck the Netherlands, causing 1,853 deaths, 50,000 homes lost and flooding more than 150,000 hectares of land. Shortly after this event, the Delta Commission was inaugurated to give advice on the execution of the Deltaplan. The plan would, in the long run, increase the safety of the Delta area. Although safety was the number one priority, the New Waterway and the Western Scheldt would have to stay open, because of the economic importance of the ports of Rotterdam and Antwerp.

By 1958 the first Delta work, the storm surge barrier in the river Hollandse IJssel, was already operational and by 1997, the last of a total of thirteen dams and storm surge barriers was completed: the Maeslant barrier. In this chapter a summarized description of 6 Dutch barriers (Maeslant barrier, Hollandse IJssel barrier, Eastern Scheldt barrier, Haringvliet sluices, Ramspol barrier and Hartel barrier), the Thames barrier (UK) and the Venice barrier (Italy) is presented.

Table 3.1 Overview of the barriers presented in this memo

Name	Type	Location
Maeslant barrier	Sector gate – vertical axis	The Netherlands, Hoek van Holland
Hollandse IJssel barrier	Vertical lift gate	The Netherlands, Capelle aan den IJssel
Eastern Scheldt barrier	Vertical lift gate	The Netherlands, Vrouwenpolder
Haringvliet sluices	Sector gate – horizontal axis	The Netherlands, Hellevoetsluis
Ramspol barrier	Inflatable tube	The Netherlands, Kampen
Hartel barrier	Vertical lift gate	The Netherlands, Spijkenisse
Venice barrier	Flap gate	Italy, Venice
Thames barrier	Rotary segment and sector gate (horizontal axis)	UK, London

Future challenges in operating storm surge barriers

Regarding future challenges for these barriers, knowledge management is a constant challenge for all barriers. Although the Netherlands is well-known for the challenge to fight the sea, the daily focus of Rijkswaterstaat is more on other infrastructures, such as highways, than on storm surge barriers. Employees change jobs, rules and policies change but the task for maintenance and operations stay important for the lifetime of a barrier. Also, the fact that storm surge barriers are not used frequently adds up to the challenge for constantly training and exercise to a certain required standard. Implementing innovative measures during renovations on a structure that requires proven reliability is quite challenging as well.

Nowadays cyber security is a new field of challenge since this sets certain requirements to behaviour of staff but also to contracts. Attacks on the digital systems that control water works are increasingly becoming a major concern, as more and more safety systems are computer-controlled thus being vulnerable to attack.

As for particular challenges of each barrier, the Eastern Scheldt barrier was and is facing scour that undermine the stability of the surrounding dikes. Measures to avoid this problem have been taken since 2012.

The gates of the Haringvliet sluices should be permanently open (except during extreme weather) to restore the natural freshwater-saltwater gradient. The return of natural dynamics will also positively affect the habitat quality of many migratory and coastal bird species.

For the Venice barrier, discovering the best and optimal ways of doing maintenance and operations (and budget) is a challenge. The transition of responsibilities from building to maintenance and operation will be also a challenging task.

Sea level rise is a challenge that the Environment Agency tackles with studies called Thames Barrier 2100. The possibility of a fully new barrier is explored in this study too. Within the I-STORM network countries cooperate to learn from each other during these studies.

Maeslant barrier

Maeslantkering

Location	The Netherlands, Hoek van Holland
Year commissioning	1997
Type barrier	Sector gate – vertical axis
Number gates	2
Waterway	New Waterway
Dimensions waterway	
Width	360 m
Tidal range	1.8 m
Dimensions barrier	
Width gate	210 m
Height	22 m
Sill level	-17 m below sea level
Protection level	10,000 years (design return period)
Expected using frequency	7-10 years
Actual closing events	1 (2007)[3]
Closing criterion	+3.0 m above sea level, based on forecast levels
Closing system	Fully automatic operating computer system: Decision and Support System (BOS)
Operation	Computer system follows predefined procedures and decides whether or not to close the barrier depending on water level forecast. It is a fully automatic system under constant human supervision. By using a fully automatic system, the chances of human failure during operation are reduced. A team of 15-20 people is present during operation; all team members must at least attend to 4 training sessions per season. The closure of the barrier is a high-stakes decision: on the one hand it involves economic loss of Port disruption by hindered navigation and, on the other hand, inundation of urban areas and loss of property.

[3] During the storm season of 2007 the closing criterion of the barrier was reduced to +2.60 m above sea level because the barrier had never been closed since it became operational 10 years before. A water level of +2.60 m was forecasted in November 2007, leading to the closure of the barrier.

Building company	BMK consortium: BAM, Volker Stevin and Hollandia Kloos; design and building.
Building costs	450 M€
Why was the barrier built	The dikes that were originally planned were insufficient to protect the city of Rotterdam and surrounding areas; the alternative solution was to raise and reinforce all existing dikes in the area, which would have been a much more costly solution (150M€ more) and would require additional ten years of work. A storm surge barrier was thus an attractive solution in terms of safety, environmental impact, costs and time.
Why this type of solution	The most important demand for the design was that the barrier should not hinder shipping during normal conditions, a requirement that is met with this type of solution. Additionally, the selected design allowed the construction and maintenance to be performed in dry docks located in the margins of the waterway, thus without obstructing navigation.
Functionality	The main function of the barrier is to protect the hinterland: Rotterdam and surrounding areas from high water levels originated by storm surges from the North Sea. Together with the associated Hartel barrier and the dikes in between, the Maeslant barrier forms a line of defence responsible for the protection of highly populated areas in South-Holland. The barrier allows navigation under normal conditions with unlimited clearance for vessels. The Maeslant barrier is not allowed to close for reasons other than flood risk (as, for instance, to avoid eventual oil spill from the Port of Rotterdam to reach the sea).
Characteristics protected area	Highly populated areas in the Rotterdam region (~1 million people), Port of Rotterdam, infrastructure (roads, railways), historical centres and agricultural areas. The closing criterion is a compromise between preventing potential inundation in urban areas and hindering navigation.
Reliability	Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast*. The fact that building, operation and maintenance of the barrier were all end responsibility of the Ministry of Infrastructure and Water Management (*Rijkswaterstaat*), it avoided the transference of responsibility after the construction of the barrier was finished, a step that could have decreased the barrier reliability.
Maintenance and contracting	Maintenance and management of the barrier is a responsibility of Rijkswaterstaat (RWS). Maintenance and management team consists of 15-20 people. However, it is complex to exactly define the number of people involved. The team that is responsible for all four storm surge barriers in the Rotterdam region consists of 35 people. For maintenance and contracting another number of 20-40 people are involved depending on the complexity and duration of the works. Most maintenance work is done by contracted technicians.

Responsibility and financing building vs. maintenance/operations

Rijkswaterstaat was the responsible for construction and is also responsible for operation and maintenance of the barrier. The design and building of the barrier and the first 5 years of maintenance were the responsibility of contractors, under supervision of RWS. After 5 years RWS took over ownership and management, operation and maintenance.

Long term effects on the surroundings by barrier construction

As the Maeslant barrier is a sector gate with only two gates that are always open and only close in the exceptional situation of extreme high water levels, the long-term changes to the surroundings are small in terms of changes to the water system. It was agreed that the closing criteria of the Maeslant barrier would be evaluated after its first closure. The closing event in 2007 was the first closure event under storm conditions. This event was evaluated and so was the closing criterion. The evaluation of the closing criterion did not lead to an adjustment of it. However, it did give insight into the fact that urban buildings and the invested capital increased in the period between 1998 and 2009, not only in the areas protected by closing the barrier but also in the areas that still inundate. After 2009, the awareness and need for adaptive urban planning was growing and adaptation measures are taken in spatial and urban planning.
Once every year the Maeslant barrier is closed for a closure test. At the moment the Port of Rotterdam is not facing major negative impacts due to the existence of the barrier as the closing frequency is not larger than once a year (including the test closure). With climate change/sea level rise this may change. In 2050 a closing frequency of once every 4 years is very well possible. In that case, the barrier could be seen more as a lock and the Port can be perceived as less attractive. However, the extension of the Port seawards with the Maasvlakte 2 was a strategy to deal with this eventual risk.

Effects on the surroundings during barrier closure

When the Maeslant barrier is closed (real storm surge close or test closure) both inland shipping and maritime shipping experience hindrance. During an average day around 250 ships pass the Maeslant barrier (about half inland and half maritime). During the storm closure in 2007 the water level seawards of the Maeslant barrier was much higher than expected in advance. It caused damage to the levees near the Hartel canal and New Waterway. The damage would have occurred in any case, not only because of the closure.

Hollandse IJssel barrier

Hollandse IJsselkering

Location	The Netherlands, Capelle aan den IJssel
Year commissioning	1958
Type barrier	Vertical lift gate
Number gates	2
Waterway	Hollandse IJssel
Dimensions waterway	
Width	115 m
Tidal range	1.5 m
Dimensions barrier	
Width gate	80 m
Height	11.5 m
Sill level	-6.5 m below sea level
Protection level	4,000 years (river side, design return period) 10,000 years (sea side, design return period)
Expected using frequency	2–3 times a year
Actual closing events	Average of 3 to 5 times a year
Closing criterion	+2.25 m above sea level, based on forecast levels
Closing system	Manually operated with control systems. If necessary barrier can be closed by hand from the upper level of the towers. Barrier closure based on forecast, but maximum level at barrier is allowed to be +2.25 m, so it is usually closed in advance.
Operation	There is a small team (6-8 people) that operate the barrier (leader operational team, technical experts, operators for bridge and sluices and people on board of vessel to put defence line in place).
Building company	Rijkswaterstaat was in charge for the design, building by Hollandia.
Building costs	About 20 M€ (40 M guilders at that time)
Why was the barrier built	It was chosen to build a storm surge barrier since raising the existing levees would not provide sufficient security for the hinterland against floods and would cost too much

money and time. The Hollandse IJssel connects Rotterdam with the North Sea. In the event of a flood, the river water would be unable to flow away because the rising seawater would stop it. The river would therefore easily burst its banks, flooding easily the city of Rotterdam. There were two major reasons for finding a solution for the danger of flooding: first, the Hollandse Issel flows through the lowest lying area of the Netherlands. Second, this is one of most populous areas of the Netherlands. For those reasons the building of this barrier started in 1954.

Why this type of solution

The main requirements that the barrier had to fulfil, besides a certain degree of protection against floods, were allowing navigation under normal conditions and to guarantee river flow from the Hollandse IJssel to the sea without any problems. A movable gate was thus chosen, allowing tidal exchange which helps reducing salt water intrusion in the New Waterway. In 1976 a second gate was added to the structure. The towers were built already in the 50's, but due to high costs the second gate could be realised in 1976. In addition to the surge barrier, a navigation lock was built for ships that are too high to pass under the gates.

Functionality

The main function of the barrier is to protect the hinterland from high water levels originated by storm surges from the North Sea and from river floods. The bridge & road associated with the barrier provides an important connection to the city of Rotterdam.

Characteristics protected area

Urban areas, infrastructure (roads, railways), historical centres and agricultural areas. The water of the Hollandse IJssel is used to supply drinking water for the people living in Rotterdam and its environments.

Reliability

Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast*.
The fact that building, operation and maintenance of the barrier were all end responsibility of the Ministry of Infrastructure and Water Management (*Rijkswaterstaat*), it avoided the transference of responsibility after the construction of the barrier was finished.

Maintenance and contracting

Maintenance and management of the barrier is a responsibility of Rijkswaterstaat (RWS). Most maintenance work is done by contracted technicians.

Responsibility and financing building vs. maintenance/operations

Rijkswaterstaat was the responsible for construction and is also responsible for operation and maintenance of the barrier. The design and building of the barrier and the first 5 years of maintenance were the responsibility of contractors, under supervision of RWS. After 5 years RWS took over ownership and management, operation and maintenance.

Long term effects on the surroundings by barrier

As the barrier is always open and only close in the exceptional situation of extreme high water levels, the long-term changes to the surroundings are small in terms of

construction	changes to the water system.
Effects on the surroundings during barrier closure	Due to the barrier there is some hindrance for navigation: ships have to use the navigation lock to pass the section. The barrier had a positive effect on reducing salt intrusion. The barrier also created a new possibility for transportation was very important in opening up Krimpenerwaard area in the Netherlands and in particular in the Rotterdam area.

Eastern Scheldt barrier

Oosterscheldekering

Location	The Netherlands, Vrouwenpolder
Year commissioning	1986
Type barrier	Vertical lift gate
Number gates	62
Waterway	Eastern Scheldt

Dimensions waterway

Width	9,000 m (3 tideways: Hammen, Schaar and Roompot)
Tidal range	2.7 m

Dimensions barrier

Width gate	42 m (total barrier width 3,000 m, excluding islands)
Height	6-12 m (gate height)
Sill level	-11 m to -5 m below sea level

Protection level	4,000 years (design return period)
Expected using frequency	Once per year
Actual closing events	26
Closing criterion	+3.0 m above sea level, based on forecast levels
Closing system	Manually operated; if human control fails an electronic security system acts as backup, closing the gate automatically based on measured water levels.

Operation	When a water level of +2.75 m above sea level is expected, barrier staff decides whether or not the barrier should be closed based on local data and water level forecasts in the North Sea. The situation in the Eastern Scheldt basin is factored into any decision to open or close the gates. Operating the barrier affects fisheries, the ecosystem and the water management system as well as the safety of the dikes that surround the Eastern Scheldt. If something goes wrong either in operating the gates or sounding the alert, an emergency system closes the gates automatically based on measured water levels. All gates start closing at the same time. A team of 10 people (decision team, operating team and design expert) is present during the operations.

Building company	DOSBOUW consortium: Baggermaatschappij Breejenhout, Hollandse Aanneming Maatschappij, Hollandse Beton Maatschappij, Van Oord-Utrecht, Stevin Baggeren, Stevin Beton en Waterbouw, Adriaan Volker Baggermaatschappij, Adriaan Volker Beton en Waterbouw and Aannemerscombinatie Zinkwerken. Design & build was a joint effort between market and government.
Building costs	About 2.4 B€
Why was the barrier built	Most of the Zeeland province is at or under sea level. During the 1953 flood event the existing dikes in Zeeland were in poor conditions and broke down at different locations. As a consequence, hundreds of gaps appeared in the dikes and many hectares of land were flooded. Zeeland was the Dutch province where most of the causalities were registered during the flood of 1953. To protect this region against flooding, the Eastern Scheldt barrier was built, being the largest of the 13 Delta Works constructions.
Why this type of solution	The initial idea was to close off the Eastern Scheldt with a regular dam. However, this solution would destroy the unique natural habitat in the Eastern Scheldt estuary, compromising fishing, mussel and oyster farming activities. The pressure from public opinion to leave the Eastern Scheldt open was strong enough to lead to the reconsideration of the initial closure plan. The minimum criterion was to keep people safe under all circumstances and maintain the original environment. A semi open storm surge barrier with movable gates that would only close during storm events was thus the preferred solution meeting the requirements.
Functionality	The main function of the barrier is to protect the hinterland from high water levels originated by storm surges from the North Sea. A navigation lock and two auxiliary dams, the Philips and the Oester dams, were also constructed together with the barrier: The decision to build these dams was to reduce the size of the basin behind the Eastern Scheldt barrier limiting the impact of the barrier on the tidal range and to create a tide-free shipping route between Antwerp and the Rhine. Together with the auxiliary dams the barrier forms a line of defence responsible for the protection of Zeeland region. There is also a main road on the barrier, linking the separate island in Zeeland to each other. This new possibility for transportation was very important in opening up the Zeeland areas in the Netherlands.
Characteristics protected area	The protected area comprises mainly residential areas (villages and little cities), agricultural fields and unique estuary ecosystem. The Eastern Scheldt is an important area for birds that are looking for food, or want to brood or are looking for a place to hibernate. If the Eastern Scheldt had closed, this unique saltwater environment would have been lost, together with the mussel and oyster culture. This would also have had severe economic consequences. Fishery has always been the largest source of income for the traditional fishing villages such as Yerseke and Bruinisse. People have been farming oysters in the Eastern Scheldt since 1870.
Reliability	Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship

collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast*.
The fact that building, operation and maintenance of the barrier were all end responsibility of the Ministry of Infrastructure and Water Management (Rijkswaterstaat), it avoided the transference of responsibility after the construction of the barrier was finished, a step that could have decreased the barrier reliability. People that work on design and build mostly are other people that will do the maintenance and operations. So there is always a period of lack of knowledge and experience even when in this case the Ministry is involved in all stages.

Maintenance and contracting

Maintenance and management of the barrier is a responsibility of Rijkswaterstaat (RWS). Maintenance and management team consists of 18 people. For maintenance and contracting another number of 25 people are involved depending on the complexity and duration of the works. These are most technical involved people and regarding project- and contract management. More people are involved with other kind of general expertise or very specialist expertise. Most maintenance work is done by contracted technicians. Current maintenance costs are estimated about 10-18 M€/year.

Responsibility and financing building vs. maintenance/operations

Rijkswaterstaat was the responsible for construction and is also responsible for operation and maintenance of the barrier. The building phase and the first years of maintenance and operations were the responsibility of RWS who had contractors to do the actual work.

Long term effects on the surroundings by barrier construction

The morphology of the Eastern Scheldt inlet has been changing for the past 30 years in response to the construction of the Eastern Scheldt barrier. As a result, there has been a decrease in tidal amplitudes, tidal volumes, and average flow velocities, and there is hardly any sediment exchange through the barrier. This is the so called “Sand hunger of the Eastern Scheldt”. As a result tidal flats erode and this has a negative impact on the ecology. The birds have less space to forage. The system is still far from any kind of equilibrium, and is still adapting itself to the new hydrodynamic forcing regime, even though sediment transport capacities have decreased.

Effects on the surroundings during barrier closure

Once a month each gate is closed for testing. Once the test is passed, the gates are quickly opened again to minimize the effect on tidal movements and on the local ecosystem.

Haringvliet sluices

Haringvlietsluizen

Location	The Netherlands, Hellevoetsluis
Year commissioning	1971
Type barrier	Sector gate – horizontal axis
Number gates	34 (17 double gates)
Waterway	Haringvliet
Dimensions waterway	
Width	4,500 m
Tidal range	n.a.
Dimensions barrier	
Width gate	56.5 m
Height	8.5 - 10.5 m
Sill level	-5 m below sea level
Protection level	4,000 years (design return period)
Expected using frequency	Operational on a daily basis due to its function as a sluice to discharge river flow into the North Sea.
Actual closing events	5-8
Closing criterion	+2.20 m above sea level, based on forecast levels
Closing system	Automated with human monitoring and interaction when necessary..
Operation	Rijkswaterstaat operates the gates 24 hours a day. The opening/closing operations depend on the amount of water entering the Netherlands at Lobith (Rhine) and Borgharen (Meuse). When the river water levels are too high, the locks drain the extra water. On average 30% of the discharged water goes to the New Waterway, the remaining 70% goes to the North Sea passing the Haringvliet sluices.
Building company	A consortium of companies called Nestum.
Building costs	About 600 M€

Why was the barrier built	As part of the Delta Plan, Rijkswaterstaat has built the Haringvliet sluices. It prevents dangerous high water from the sea side. The water level of the area between Stellendam and Dordrecht is also regulated by the Haringvliet sluices: the locks are operated 24 hours a day, 7 days a week. The Haringvliet sluices lie between the North Sea and the Haringvliet. They regulate the water level in a way that can be compared with the opening or closing of a tap.
Why this type of solution	Instead of damming the estuary it was decided to build sluices in order to be able to let in salt water to prevent freezing of the rivers Meuse and Rhine and to drain these rivers in case of flood. Navigation locks in the barrier allow the passage of vessels.
Functionality	When the water levels near Rotterdam are getting too high, the special drainage sluices can drain off an increased amount of water into the sea. In addition to the drainage sluices, a lock was built for ships. To preserve wildlife, a number of piers were constructed within special tunnels. Fish can use these tunnels to swim directly from the Haringvliet to the North Sea (or vice versa), even when all locks are closed. Due to European initiatives to have certain species of fish i.e. salmon the Haringvliet sluices will be more open than before from the end of 2018 onwards. This means the Haringvliet will become a little bit more salty that supports fish from sea to find their way into the Haringvliet and European rivers towards, for example, Switzerland. This again is a change in the original concept of closing all estuaries during the Delta Plan towards achieving more ecological goals. But also with consequences to maintenance and operations with its full effect are still to be discovered.
Characteristics protected area	The Haringvliet area is a protected Natura 2000 area. The area around it is not highly populated but does protect residential areas (villages) and agriculture. It is very important for water inlets too.
Reliability	Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast*. The fact that building, operation and maintenance of the barrier were all end responsibility of the Ministry of Infrastructure and Water Management (*Rijkswaterstaat*), it avoided the transference of responsibility after the construction of the barrier was finished.
Maintenance and contracting	Maintenance and management of the barrier is a responsibility of Rijkswaterstaat (RWS). Contractors do the daily maintenance.
Responsibility and financing building vs. maintenance/operations	Rijkswaterstaat was the responsible for construction and is also responsible for operation and maintenance of the barrier.
Long term effects on the	Before the closure of the Haringvliet, it was a large nature reserve. The Haringvliet

surroundings by barrier construction

became a fresh water lake after the construction of the barrier. The soil which was flooded during high tide was uncovered and was used by farmers. Consequently, many geese lost their habitat area. The tide change no longer influenced the flora and fauna. Many plants and animals that depended on the sea, died. Plants which were flooded for 12 hours during flood tide, dried up. The crabs and shrimps did not survive the transfer from a salty to a silt environment. The death of some sorts however meant the upcoming of others. Similarly, flounders and smelts were replaced by carps, perches and rock-basses. Nevertheless, the present balance was thoroughly disturbed in the years after the closure.

The aquatic ecosystem in the Haringvliet, however, greatly suffers from the quick change from salty to fresh water. In 2008 the sluices are therefore slightly opened and create a somewhat more natural delta. This means that during high and low tide limited opening of the sluices is allowed. This makes it possible for sea water to flow into the Haringvliet, creating a more natural transitional area between the salty sea water and fresh river water in the Haringvliet. The construction of the Haringvliet dam had major consequences for nature: the transition area, in which the sea and river gradually converged, suddenly changed in 1970 into a hard separation between fresh and salt water. Migratory fish could no longer pass through the locks and plants and animals that lived in this area. For example, the salmon and trout migrate from salt to fresh water to lay their eggs there. By setting the locks ajar, the migratory fish can pass through the Haringvliet locks again. There have been long discussions on the above and in 2015 the decision has been taken to open the sluices, the so called 'Kierbesluit".

By opening the sluices partly, the seawater can flow again into the Haringvliet and migratory fish, such as salmon and sea trout, can pass through the locks towards their spawning areas, which are upstream. Rijkswaterstaat, as manager of the Haringvliet locks, will continuously monitor the salt content as it is balancing different stakes. The agriculture and the intake of drinking water are depending on the fresh water supply. A measuring network of poles and buoys, equipped with measuring equipment, monitors this salt boundary. Water intake points west of this line are moved. For example, Evides Waterbedrijf and the Hollandse Delta water authority must shift their inlet points for fresh water in the area.

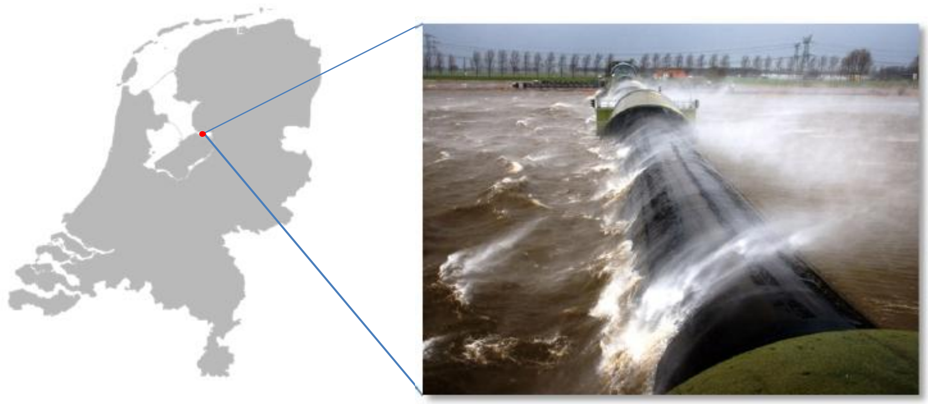
An important positive effect of the building of the Haringvlietsluices was again transportation. There is also a main road on the barrier, linking the separate island in Zeeland to each other. This new possibility for transportation was hugely important in opening up the Zeeland areas in the Netherlands.

Effects on the surroundings during barrier closure

n.a. (barrier is closed on a daily basis)

Ramspol barrier

Ramspolkering

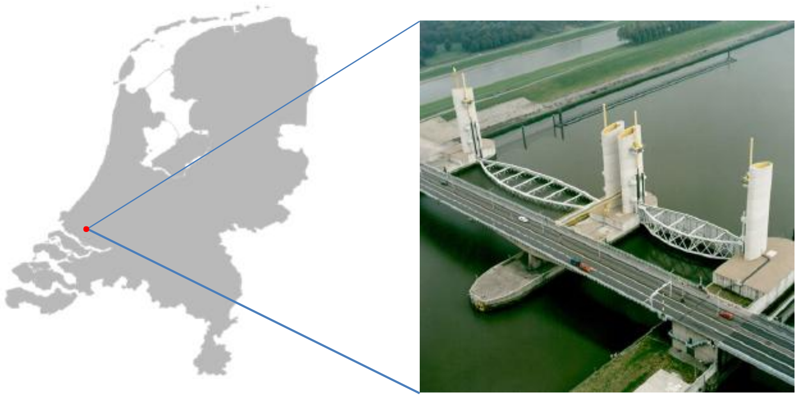


Location	The Netherlands, Kampen
Year commissioning	2002
Type barrier	Inflatable tube
Number gates	3
Waterway	Ramsgeul and Ramsdiep
Dimensions waterway	
Width	360 m
Tidal range	n.a.
Dimensions barrier	
Width gate	80 m
Height	10 m
Sill level	-4.65 m below sea level
Protection level	2,000 years (design return period)
Expected using frequency	Once per year
Actual closing events	4 times in storm situations; once in 2012 and 3 times in 2015
Closing criterion	+0.5 m above sea level
Closing system	Automatic operating system, based on measured water levels and flow direction. In an emergency situation, for a test closure or for maintenance barrier can be manually closed.
Operation	Computer system follows predefined procedures and decides whether or not to close the barrier depending on measured water levels and flow direction. When the decision is made to close the barrier, each inflatable is filled with 3,500 m^3 of air and 3,500 m^3 of water. During normal operational conditions a team of 5 people (operators and reliability specialist) is present at the barrier. In special circumstances, an incident response team is called to the barrier, including barrier manager and contractor.
Building company	Hollandsche Beton- en Waterbouw bv (HBW, later called BAM).
Building costs	48 M€

Why was the barrier built	The barrier was built to protect the hinterland in the Northwest Overijssel region (around lake Ketel) against flooding during storm surges caused by wind set up on the lake IJssel (*IJsselmeer*). The extensive dike system behind the barrier (~115 km) needed to be reinforced and raised. The construction of a barrier was thus an economically advantageous solution. As a consequence, dike improvement could be limited compared to a situation without the barrier. The barrier reduces the required design flood levels upstream the barrier to reach the specified level of protection.
Why this type of solution	An inflatable barrier is expected to have less construction, operation and management costs when compared with traditional barriers. Also, it has low impact on the landscape since in open position the barrier is stored and deflated underwater, not hindering navigation in normal conditions.
Functionality	The main function of the barrier is to protect the hinterland from storm surges from the lake IJssel. The barrier allows navigation under normal conditions with unlimited clearance for vessel.
Characteristics protected area	Urban areas (city of Zwolle and nearby villages), agricultural areas and Natura 2000 area (Zwarte Water).
Reliability	Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast.*
Maintenance and contracting	Maintenance and management of the barrier is a responsibility of Rijkswaterstaat (RWS). Most maintenance work is done by contracted technicians.
Responsibility and financing building vs. maintenance/operations	DBM type of contract: Design, Build and 10 years of Maintenance the responsibility of the contractor. In December 2002, the Ramspol storm surge barrier was opened, then under the management of the Groot Salland Water Board (now merged into the Drents Overijssel Delta Delta Water Board). Rijkswaterstaat has taken over the management and maintenance since 1 July 2014.
Long term effects on the surroundings by barrier construction	The barrier is open during normal conditions, only closing during storm surges in the IJssel lake. Therefore, the long term changes to the surroundings are small in terms of changes to the water system. The barrier is closed annually for a test closure.
Effects on the surroundings during barrier closure	When the barrier is closed (real storm surge close or test closure) shipping experience hindrance. During a closure of the barrier there is less inundation on the flood plains of the Zwarte Water it could have an impact on the existing ecosystem (cane fields) but probably minimal as this is only during extreme events.

Hartel barrier

Hartelkering



Location	The Netherlands, Spijkenisse
Year commissioning	1997
Type barrier	Vertical lift gate
Number gates	2
Waterway	Hartel canal

Dimensions waterway

Width	300 m
Tidal range	1.6 m

Dimensions barrier

Width gate	49 m and 98 m
Height	9 m
Sill level	-6.5 m below sea level

Protection level	10,000 years (design return period)
Expected using frequency	7-10 years
Actual closing events	1 (2007)[4]
Closing criterion	+3.0 m above sea level, based on forecast levels
Closing system	Fully automatic operating computer system: Decision and Support System (BOS); equally to the Maeslant Barrier an operational team monitors the systems and can interfere or overrule the control systems.

Operation	Computer system follows predefined procedures and decides whether or not to close the barrier depending on water level forecast. It is a fully automatic system under constant human supervision. By using a fully automatic system, the chances of human failure during operation are reduced. A team of 5 people is present during operation. The closure of the barrier is a high-stakes decision: on the one hand it involves economic loss of Port disruption by hindered navigation and, on the other hand, inundation of urban areas and loss of property.

[4] The Hartel barrier closed simultaneously with the Maeslant barrier during the storm season of 2007.

Building company	Van Hattum, Blankevoort and Hollandia.
Building costs	98 M€
Why was the barrier built	The shipping routes to the Port of Rotterdam via the New Waterway and the (smaller) Breeddiep are not safe during very strong winds. The Hartel canal enables an improved inland navigation connection between the Port and the hinterland during adverse weather conditions. In this way, a storm surge barrier in the Hartel canal was also necessary to avoid large amounts of sea water flowing into the Port of Rotterdam when the Maeslant barrier is closed, threatening the safety of South-Holland region. The Hartel barrier together with the Maeslant barrier and the dikes in between work together to provide a certain degree of safety to the hinterland.
Why this type of solution	The barrier consists of large movable elliptical gates suspended by lateral towers. Flow overtopping over the gates is possible without damaging the structure. Limited overtopping over the barrier is accepted and does not threaten the safety of the protected area because of the buffer areas around the river, i.e., areas that can be temporarily inundated.
Functionality	The main function of the barrier is to protect the hinterland: Rotterdam and surrounding areas from high water levels originated by storm surges from the North Sea. Together with the associated Maeslant barrier and the dikes in between, the Hartel barrier forms a line of defence responsible for the protection of highly populated areas in South-Holland. The barrier allows navigation under normal conditions with clearance for vessels of 14 m above sea level.
Characteristics protected area	Highly populated areas in the Rotterdam region (~1 million people), Port of Rotterdam, infrastructure (roads, railways), historical centres and agricultural areas. The closing criterion is a compromise between preventing potential inundation in urban areas and hindering navigation.
Reliability	Determined and demonstrated every 5 years as demanded by the Dutch Water Defence Act. Reliability determined through probabilistic maintenance and asset management where the probability of flooding is translated into performance criteria of the barrier. This requires a Fault Tree Analysis, i.e., an analysis of all the possible basic components that can fail and the relation between these components and the main event for failure. The reliability analysis requires the assessment of the reliability of the following elements: *components, system, external events* (fire, lightning, ship collision, etc.), *security, maintenance, human error* (operation and maintenance), *software, common cause failure* and *forecast.*
Maintenance and contracting	Rijkswaterstaat (RWS) established a multi-year contract (2012-2027) handing out the responsibility for management, maintenance and monitoring of operating and control systems to a contractor. With this contract, RWS handed out for the first time the maintenance responsibility of an important storm surge barrier to a contractor.
Responsibility and financing building vs. maintenance/operations	Rijkswaterstaat was the responsible for construction and was also responsible for operation and maintenance of the barrier.
Long term effects on the	The barrier is open during normal conditions, only closed during extreme storm

surroundings by barrier construction

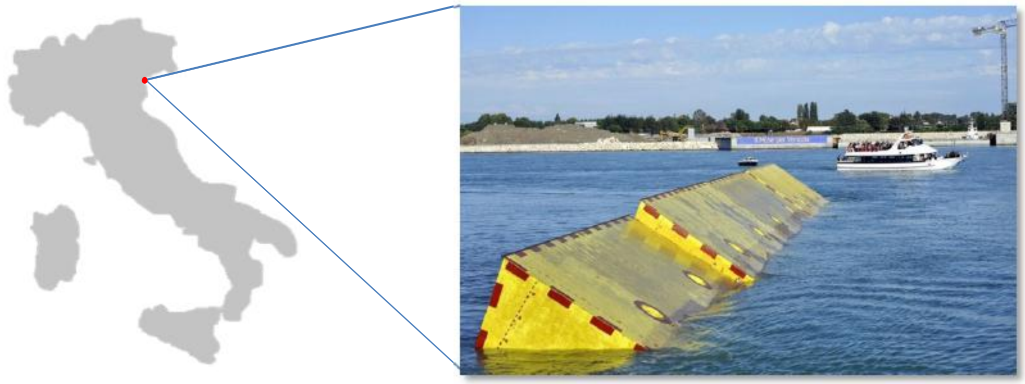
surges in the North Sea. Therefore, the long term changes to the surroundings are small in terms of changes to the water system. The barrier is closed annually for a test closure.

Effects on the surroundings during barrier closure

When the barrier is closed (real storm surge close or test closure) both inland shipping and maritime shipping experience hindrance. During the storm closure in 2007 the water level seawards of the barrier was much higher than expected in advance. It caused damage to the levees near the Hartel canal and New Waterway. The damage would have occurred in any case, not only because of the closure.

Venice barrier

MOSE (MOdulo Sperimetale Elettromeccanico)



Location	Italy, Venice
Year commissioning	Partly operational in 2014 (Lido inlet), 2016 (Chioggia) expected fully operational for testing between 2018 and 2020. Fully operational after testing period.
Type barrier	Flap gate
Number gates	78 gates (4 barriers)
Waterway	3 inlets in the Venice lagoon: Lido, Malamocco and Chioggia
Dimensions waterway	
Width	Lido inlets: 920 m; Malamocco inlet: 460 m; Chioggia inlet: 550 m
Water depth	Lido inlets: 6-11 m; Malamocco inlet: 15 m; Chioggia inlet: 11 m
Tidal range	1 m
Dimensions barrier	
Width gate	20 m
Height	18.5-29.2 m
Protection level	Not comparable with the Dutch cases
Expected using frequency	3-5 times per year
Actual closing events	n.a.
Closing criterion	+1.10 m above sea level (reference level). Criterion can change whenever necessary based on forecast and measured levels.
Closing system	Manually operated based on Decision Support System (DSS), system still in development. The I-STORM network is used to learn from each other's best experiences to decide upon the optimal system for the MOSE.
Operation	Decision to close the barrier is made by the management team based on a storm surge forecasting system with 5 components: data acquisition and archiving module, statistical forecasting model, deterministic forecasting model, error analysis module, and set of procedures and web server. The average inlet closure time is 4 to 5 hours (including gate opening and closure times, 30 and 15 minutes respectively). The MOSE Control Centre is at the Arsenale (northern area). This is the centre where the key decisions on raising and lowering the MOSE mobile barriers will be taken.

Building company	Consortium made of Italian construction companies (*Consorzio Venezia Nuova*): Consorzio Cooperative Costruzioni, Consorzio Grandi Restauri Veneziani, Consorzio Italvenezia, Kostruttiva, Venezia Lavori, Grandi Lavori Fincosit, Impresa di Costruzioni Ing. E. Mantovani, Mazzi, San Marco - Consorzio costruttori veneti, Società Italiana per Condotte d'Acqua.
Building costs	5.5 B€
Why was the barrier built	The combination of sea level rise together with land subsidence makes Venice particularly vulnerable to floods. The flood of 1966 caused massive loss of life and property. The flood was caused by the "high water" phenomenon where a combination of astronomical tides, seasonal rain and strong winds hinder water outflow from the lagoon. Venice does have some natural protection against flooding – the lagoon is enclosed by a string of barrier islands that help to shelter it. This barrier of sandbars is nonetheless breached by three inlets (at Lido, Malamocco and Chioggia), which are essential to water flow and shipping but still leave the lagoon vulnerable to high tides. Land subsidence contributes to this problem. Venice is sinking at a rate of 0.05 cm/year and the 25 cm of sea level rise occurred over the 20th century has increased the flood frequency by more than seven times. The main reasons for land subsidence in Venice are attributed to the rise in the sea level and extraction of ground water and methane gas within the vicinity of the Venetian Lagoon.
Why this type of solution	The requirement was that the barrier should not disturb the Venice landscape (tourism), for that reason the barrier needed to be invisible when not operational. Another requirement is that it should not disturb the ecosystem as the Venice lagoon is a protected Natura 2000 area (EU Habitat and Bird Directive). Venice has ports and fisheries that are important. These functions should not be disturbed too much. For the above reasons, the chosen design kept the lagoon inlets open during normal conditions. The gates are independent from each other making it possible to partially close the inlets if necessary. In open position the gates are filled with water and stored in underwater sills, parallel to the floor. When the barrier closes, the gates are filled with air causing them to rotate around the bottom hinges, rising above the water level by buoyancy. There is a gap of a few centimetres between each gate, which will only allow small amounts of water through and obviates the need for seals.
Functionality	The main function of the Venice barrier is to protect the lagoon and the hinterland from floods. Together with the barrier construction, the 3 lagoon inlets have been strengthened with new concrete walls and embankments. In order to keep the average number of closures per year to a manageable level, the lower parts of Venice are being raised to at least +0.87 m above mean sea level. The navigation lock in the Malamocco inlet allows vessels to reach the ports in the Venice Lagoon when the gates are closed. The Venice barrier is designed to cope with 60 cm of sea level rise in a century.
Characteristics protected area	Main protected areas include Venice and its lagoon that is an UNESCO World Heritage property and a Natura 2000 area (protection of the ecosystem), nearby towns, villages and inhabitants, iconic historic, artistic and environmental heritage.
Reliability	Operation and maintenance process will be developed using a probabilistic approach (LPAM: Living Probabilistic Asset Management). This approach allows managing optimally performance, risks and costs and it joints performance requirements and

performance levels.

Maintenance and contracting

Operation and Maintenance Activities have been defined and they have been assigned to the "Manager of Operation and Maintenance Process". The Manager of Operation and Maintenance Process has to operate in order to ensure:
· maintenance and performance level required either for the system, data network and operational and emergency resources;
· continuous technological improvement of all elements of the systems;
· planning, whether possible, new techniques designed to improve overall performance;
· Adequate training of all workers on operational procedures and safety procedures.
Maintenance of the gates will take place at the Arsenale. The organization has several spare parts that will put in place for the flaps that need maintenance or revision. In a periodical planning every flap will be maintained or renovated if necessary every five years. The exact planning will be defined during building and testing period.

Responsibility and financing building vs. maintenance/operations

The Ministry of Infrastructure and Transport – Venice Water Authority is the responsible for the construction of the barriers. The construction work and first 5 years of operation is the responsibility of CVN consortium (*Consorzio Venezia Nuova*) under close supervision from the Ministry of Infrastructure and Transport. After 5 years the Ministry of Infrastructure and Transport will take over ownership. After handover, it is not yet clear who will be appointed for management and maintenance. This appointment will be made by the Italian Government.

Long term effects on the surroundings by barrier construction

As the Venice barriers are built in a N2000 area, the MOSE project is not only a flood protection project also a lot of attention has been paid to the environment and the ecosystem in particular. Environmental protection measures have been taken: to protect the lagoon from pollution and environmental reclamation and morphological restoration measures. Besides Maintenance and Operational management also environmental management and monitoring is important. This is to guarantee the preservation of the internal morphological characteristics of the lagoon, counteracting the effects of waves and currents that cause erosion of tidal flats, salt marshes, lagoon bottoms and inhabited areas. These actions are ultimately finalized to the overall preservation of lagoon habitats.

Effects on the surroundings during barrier closure

Closing off the inlets during high tides will retain pollution inside the lagoon, a negative impact that will depend on the duration that the barriers are closed. It is expected that the barriers will close for a short duration for which the disruption of tidal flows should be minimal. When the barriers are closed the vessels can still enter the lagoon though the Malamocco navigation lock.

Thames barrier

Location	United Kingdom, London
Year commissioning	1984
Type barrier	Rotary segment gate and sector gate with horizontal axis
Number gates	10 (6 rotary segment and 4 sector gates)
Waterway	Thames river
Dimensions waterway	
Width	520 m
Tidal range	7 m
Dimensions barrier	
Width gate	30 - 61 m
Height	20 m
Sill level	-9.25 m to -4.65 m
Protection level	Not comparable with the Dutch cases
Expected using frequency	A couple of times a year
Actual closing events	179
Closing criterion	The Thames barrier closes if water level forecast is above 4.87 m at London Bridge. The criterion is based on a combination of factors including forecast height of the tide and river flows. Met Office issues tidal alerts for areas around the coast against set trigger levels. If an alert is received for sheerness, depending on river flow the barrier closure procedures start without any further decision. The results of 3 models are combined to highlight the need for closure taking into account forecast accuracy.
Closing system	Manually operated based on forecast levels
Operation	Over 80 staff people operate and maintain the Barrier and the associated flood defences. Conditions can be forecast up to 36 hours in advance. The decision to close the barrier is taken by the Barrier Controller. This decision is based on the predicted height of the incoming tide estimated by the Storm Tide Forecasting Service (STFC) – part of the Meteorological Office – together with information from the Barrier's own sophisticated computer analysis. When the decision to close is made,

	the barrier is normally closed just after low tide, which is usually around 4 hours before the incoming surge tide peak will reach it. Closing after low tide creates an empty 'reservoir' space for the river flow to fill up. The gates are operated in stages, sequence varies. The river water is held back from the estuary until the tide turns, meaning that the gate must remain closed until the water on both sides of the barrier are at the same level.
Building company	Costain Group, Hollandsche Beton Maatschappij, Tarmac Construction
Building costs	£535M
Why was the barrier built	The barrier was built to protect greater London region from fluvial floods and storm surges generated in the North Sea associated with high tide events. London suffered dramatic flooding a number of times during the 20th century. In 1953, the North Sea flood resulted in several hundred deaths, forced thousands to evacuate their homes, and caused substantial damage. This flood event led to rethinking of London's flood strategy. Without the barrier the river embankment walls would have to be considerably raised to provide the same protection level as the barrier.
Why this type of solution	In normal conditions the barrier is open; the gates are stored in underwater sills allowing unlimited clearance for navigation. When closed, the gates rotate around horizontal axis about 90 degrees to the defence position. The gates can be raised beyond the defence position allowing water to flow underneath so that the water levels upstream and downstream can slowly equalize.
Functionality	The main function of the barrier is to protect the hinterland: London and surrounding areas from high water levels originated by storm surges from the North Sea. The associated Barking and Dartford Creek barriers are closed before the Thames barrier. Together, the barriers form a line of defence responsible for the protection of highly populated areas in London region. The barrier allows tidal exchange and navigation under normal conditions with unlimited clearance for vessels.
Characteristics protected area	Highly populated areas in London region (~1.25 million people), £200 billion worth of property and infrastructure, 30 mainline & 68 Underground / DLR stations, many historic buildings and environmental sites, 400 schools,16 hospitals & 8 power stations, London City Airport. The closing criterion is a compromise between preventing potential inundation in urban areas and hindering navigation.
Reliability	Requirement that the barrier must be totally reliable under criteria from UK Government. Design criteria serve as a guide and no figures are set as to certain heights or return periods. Equipment is chosen using tried and tested technology. The Thames Barrier has much duplication, redundancy and segregation of its systems to avoid CCFs (Common Cause Failures). Change control procedure ISO9001 is used to solve interdependency problems through documentation and communication changes. The Thames Barrier has an impact resistant design, for example gate mechanisms are protected from ship strikes by the concrete piers. It has comprehensive fire and security systems. Remote condition monitoring makes it easier to assess difficult to access areas and critical components.There is frequent training and practices of operational procedures. Constant plant monitoring through Control Tower. The original Failure Mode and Effect Analysis (FMEA) considered call out or warning failure, failure to close or a combination of the two as the main risks.

Maintenance and contracting	Maintenance and management of the barrier is a responsibility of the Environment Agency. Part of the work is done with in house staff but most maintenance work is done by contracted technicians.
Responsibility and financing building vs. maintenance/operations	The local government (Greater London Council) was the entity responsible to build the barrier. In 1996 the Environment Agency took over the responsibility for operation and maintenance of the barrier. The cost of operating and maintaining the barrier and the associated defences is approximately £6 million a year, plus £5 million on walls and embankments (2001 costs).
Long term effects on the surroundings by barrier construction	The Thames barrier is a semi open gate: always open and only close completely in the exceptional situation of extreme high water levels. Due to the semi open design the water system did change.
Effects on the surroundings during barrier closure	In case the Thames barrier closes it is mostly just a couple of hours and impact on the regime and environment are marginal. However recent floodings (2014, 2015) showed that different flooding events could coincide and the extreme situation occurred that the barrier was closed for days/weeks. As floodings were major most focus was on that not on the impact of regime and environment. Before closing the Barrier, operation team informs with a 6 hours' notice the Port of London Authority. They in turn inform shipping by radio and notice boards upstream and downstream of the site are illuminated. Navigation lights on the barrier itself also indicate imminent closure. Although the gates can take only minutes to close against the threatened surge, in reality more time is allowed to reduce the possibility of a reflective wave being created. No shipping is allowed within 1 mile of Thames barrier when closed. Even with closing the barrier, floodings can occur as fluvial dominated closures are becoming more the rule than the exception. The Environment Agency sends out warnings to the citizens on flood risks.