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Advances in the Planning and Conceptual Design of Storm Surge Barriers – Application to the New York Metropolitan Area

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Abstract: Flood risk in coastal zones is expected to increase due to sea level rise and continued economic development and urbanization in coastal cities. In large bays, estuaries and natural harbors, storm surge barriers can be constructed as integral parts of flood risk reduction systems and be closed prior to the arrival of storms to impede storm surge and reduce the risk of flooding for the region behind the structure. The authors present an overview of world-wide constructed storm surge barriers and tabulate key design features and dimensions as well as cost data to create an inventory of characteristics (expanded upon Mooyaart and Jonkman 2017) and an improved cost model. The inventory is used to show similarities between the structures' characteristics, gate types and costs and inform feasibility type studies. The authors present a case study for the New York City region and partial results of the ongoing New York – New Jersey – Hudson River and Tributaries (NY/NJ HAT) coastal storm risk management feasibility study that seeks to recommend a plan to provide flood risk reduction to the study area.

Keywords: Flood Risk, Storm Surge Barrier, Coastal Protection, New York Metropolitan Area

1 Introduction

1.1 Flood Risk

In the aftermath of Hurricane Sandy (October 2012) and Hurricane Harvey (August 2017) storms that caused significant damages and loss of life to two major US metropolitan areas, there has been an increased level of interest by the US Federal Government to construct storm surge barriers to provide flood risk reduction. Storm surge barriers can be cost-effective alternatives to improve and fortify long stretches of coastline or perimeter flood risk reduction systems, especially when these coastlines are extensive in length, are heavily developed or urbanized and have multiple waterfront uses.

A common solution for reducing flood risk is to raise the level of existing perimeter flood risk reduction systems. This solution can be challenging to implement in geometrically constrained urbanized areas where waterfront spaces have multiple uses and serve a variety of stakeholders with considerable social and economic impacts. In large bays, estuaries, natural harbors and port entrance channels, coastal barriers constructed as integral part of a flood risk reduction systems can be a cost-effective alternative to reduce flood risk. This paper focuses on storm surge barriers. A storm surge barrier is a fully or partially closable barrier that is navigable and includes operable elements that can be closed temporarily to impede storm surge generated by coastal storms and limit water levels in the basin, thereby reducing flood risk for coastal areas surrounding the basin.

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[1] The views presented are those of the author and do not necessarily represent the views of DoD or its Components.

1.2 *Planning of Flood Risk Reduction Systems and Conceptual Design of Storm Surge Barriers*

Only a limited number of storm surge barriers have been constructed and, apart from Mooyaart and Jonkman (2017), no other systematic and complete overview of existing storm surge barriers and their characteristics are available. To further the scientific and engineering base needed to evaluate storm surge barrier concepts and costs for future flood risk reduction systems, a more complete and comprehensive overview and analysis is presented here.

A general description of a storm surge barrier, where a typical layout contains three elements; a gated section, a dam section and a navigable passage, is included here (Mooyaart & Jonkman, 2017). A navigable passage can be established with a lock or with a gated opening. A lock passage is usually closed during normal operational conditions and opens for the passage of vessels; a gated navigable passage is usually open for free passage and only closed during the occurrence of a storm surge event. Fig 1. below provides a schematic plan view of a hypothetical storm surge barrier, including a gated navigable passage and a total of three (3) auxiliary flow gates. The auxiliary flow gate sections maintain tidal exchange between the ocean and the inner basin. Furthermore, both navigation and tidal flow exchange can be provided through the navigable passage opening.

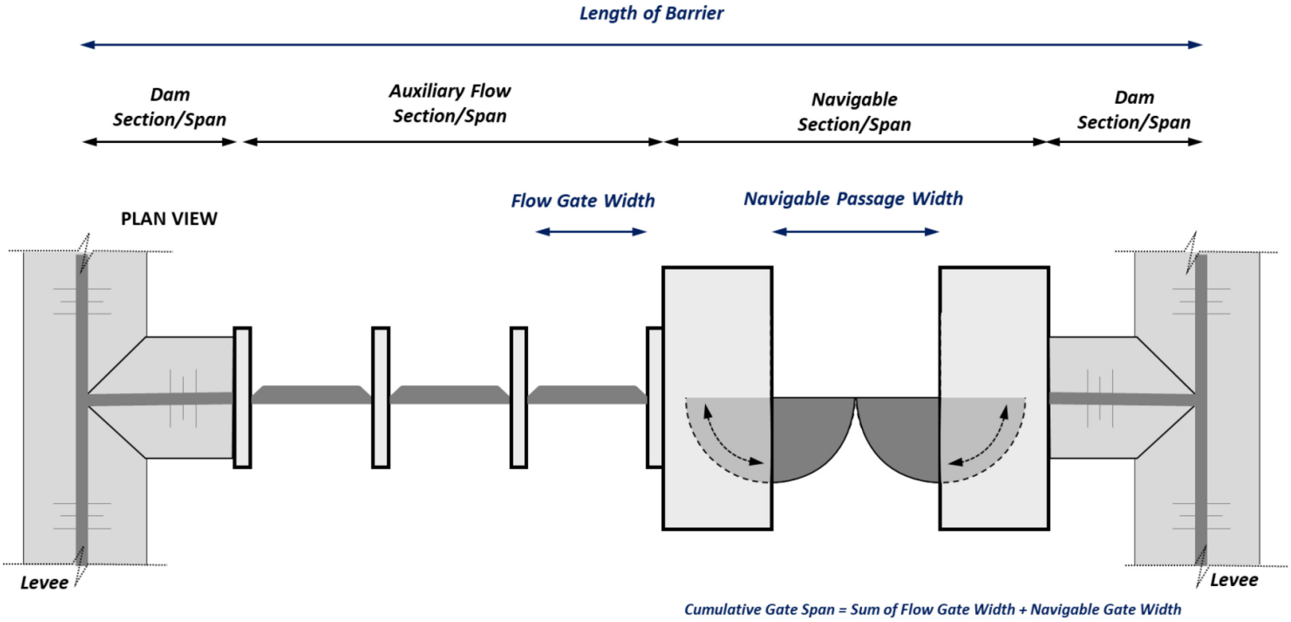

Fig. 1. A hypothetical storm surge barrier layout in plan view with gates in the closed position.

1.3 *Hydraulic Gate Types and Characteristics*

The gate types suitable for a storm surge barrier as reported by (Mooyaart & Jonkman, 2017) are inclusive of commonly used gate types or hydraulics steel structures for water control structures and coastal barriers, but more specifically tailored to the application within constructed storm surge barriers. The gate types are included in Appendix A1 and referenced throughout this paper. These gate types are utilized to close off navigable and/or auxiliary flow openings and they can be categorized by their direction of movement. The following list is evaluated: Horizontal Rolling Gates (horizontal lateral movement), Sector Gate (vertical axes rotation), Floating Sector Gate (ball joint, i.e. vertical and horizontal axes rotation), Rotating Segment Gate (horizontal axes rotation), Flap Gates (horizontal axes), Barge Gate (vertical axes), Vertical Lift Gates (vertical lateral movement), Vertical Rising Gates (vertical lateral movement) and Tainter Gates (horizontal axes rotation). It is recognized that other hydraulic gate types exist (e.g. drum gate or visor gate), which are applied in riverine and upland water control structures (PIANC, 2006) (USACE, 2014). However, those have not been utilized in a coastal setting or in constructed storm surge barriers, and as such, are omitted from consideration here.

2 Storm Surge Barriers Main Characteristics

2.1 General Characteristics

Storm surge barriers described here are based on the functional characteristics described above and based on the original selection of structures from (Mooyaart & Jonkman, 2017) where the inventory is expanded, refined and includes one additional structure (Fox Point Barrier (Rhode Island, USA). A complete overview and inventory of the selected storm surge barrier characteristics is included in Appendix A2 and a summary is provided in Tab. 1. The storm surge barriers are listed in order by construction date. The first is the Hollandsche IJssel barrier in The Netherlands and the last is the MOSE project near Venice, Italy which is expected to start operation in the coming years.

For all barriers, the considerations for flow and navigation are dominant and contingent on the local conditions. The various gate types discussed are included within the constructed storm surge barriers to accommodate these two functions, where some gate types are better suited to accommodate one, the other, or a combination of both. Storm surge barriers with long spans in estuarine environments include many auxiliary gates and large cumulative openable areas. Shorter barriers in developed harbor and industrial coastal canals include one main navigable gate with one or two auxiliary gates.

The storm surge barriers vary considerably in length (with the longer barriers being constructed in more recent years), while construction speed (defined here as length divided by construction duration) varies greatly and is not directly correlated to total barrier length (see Fig. 2).

Construction duration can be negatively influenced by environmental reviews, e.g. Eastern Scheldt, NL, St. Petersburg, RU, (Rijkswaterstaat, 1994) (Hunter, 2012), funding availability and/or budget over runs, e.g. St. Petersburg and Venice (WL Delft Hydraulics, 2005) (Lo Storto, 2015) and or unforeseen construction complexities e.g. Venice, IT or positively influenced by accelerated government mandated project delivery schedules following a national disaster, i.e. New Orleans, USA (DeSoto-Duncan, et al., 2011).

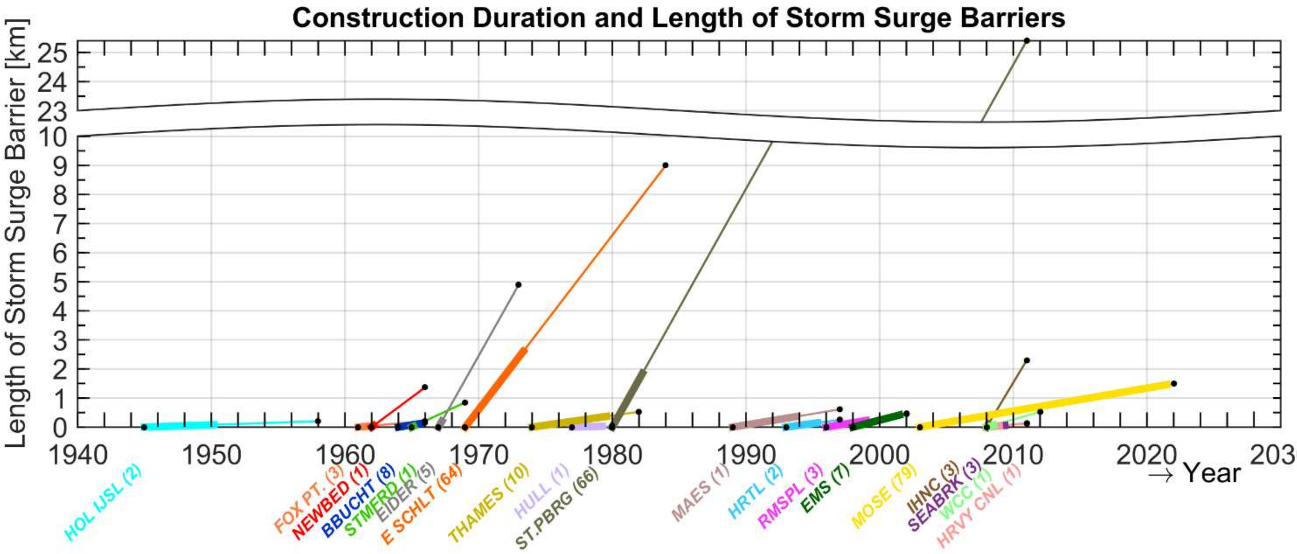

Fig. 2. Start and end year of construction of each storm surge barrier vs. total length of storm surge barrier. Increased line width indicates total cumulative gate span as fraction of total length. Total number of gates are provided between parentheses. Rather than as a function of total length, duration is better modeled as a function of the lengths of each component type (see Equation 2 in Section 3.3).

2.2 Design Considerations for Storm Surge Barriers: Navigation, Tidal Exchange and Storm Surge Impediment

All storm surge barriers provide for navigation through one or multiple passages with dimensions based on the design vessel, traffic intensity and the local hydrodynamic and meteorological conditions. To accommodate large ocean-going vessels and high maritime use, deep and wide navigable passages are required. Gate types to accommodate the navigation function are further discussed below.

Tab. 1. Overview of presented storm surge barriers. Summary of gate types within the storm surge barriers. Symbols used are as follows: Double Flap Gate (★), Flap Gate (✚), Floating Sector Gate (◆), Inflatable Gate (✕), Rotary Segment Gate (●), Sector Gate (○), Tainter Gate (✱), Vertical Lift Gate, (▼), Barge Gate (■), Vertical Rising Gate (△). The navigable gates are shaded in grey. Navigable passage through the Eider and Eastern Scheldt storm surge barrier is through a lock.

Storm Surge Barrier Name (Location)	Length	Gate Type for Gate Series$^{(\# \text{ of Gates})}$							Total Number of Gates	Cumulative Gate Span (ft)	Cross-sectional Area below Mean Sea Level (MSL)	Construction Cost (2019)	Construction Duration	Abbreviation
		Gate Series N*												
	(m)	1	2	3	4	5	6	7		(m)	(m^2)	(M€)	(yrs)	
Hollandsche IJssel (NL)**	200	▼^{1}	▼^{1}						2	80	520	138	4	HOL IJSL
Fox Point hurricane barrier (RI, USA)	213	✱^{3}							3	36	174	135	5	FX PNT
New Bedford hurricane barrier (MA, USA)	1,370	○^{1}							1	46	550	171	4	NEWBED
Billwerder Bucht barrier (Germany)	150	✚^{2}	✚^{2}						8	128	614			BBUCHT
Stamford hurricane barrier (CT, USA)	850	✚^{1}							1	27	150	109	4	STMFRD
Eider barrier (Germany)**	4,900	✱^{5}	✱^{5}						10	200	930	523	6	EIDER
Hull barrier (UK)	40	▼^{1}							1	30	130	18	3	HULL
Thames barrier (UK)	530	●^{4}	●^{2}	✱^{4}					10	369	2,488	1,427	8	THAMES
Eastern Scheldt barrier (NL)	9,000	▼^{7}	▼^{11}	▼^{6}	▼^{9}	▼^{8}	▼^{6}	▼^{15}	64	2604	18,000	5,043	17	E SCHLT
Maeslant barrier (NL)	610	◆^{1}							1	360	6,800	846	8	MAES
Hartel barrier (NL)	250	▼^{1}	▼^{1}						2	147	950	184	4	HRTL
Ramspol barrier (NL)	450	✕^{1}	✕^{1}	✕^{1}					3	225	1,050	152	5	RMSPL
Ems barrier (Germany)	476	●^{1}	✱^{1}	▼^{1}	▼^{1}	▼^{3}			7	414	2,435	440	3	EMS
St. Petersburg barrier (Russia)	25,400	◆^{1}	△^{1}	✱^{34}	✱^{30}				66	1846	9,610	7,363	27	ST.PBRG
IHNC barrier (LA, USA)	2,300	○^{1}	■^{1}	▼^{1}					3	107	520	1,363	3	IHNC
Seabrook Floodgate Complex (LA, USA)	130	○^{1}	▼^{2}						3	59	320	180	3	SEABRK
Harvey Canal floodgate (LA, USA)	120	○^{1}							1	38	330	49	3	HRVY CNL
GIWW-West Closure Complex (LA, USA)	525	○^{1}							1	69	330	406	4	WCC
Venice / MOSE-project (Italy)	1,500	✚^{18}	✚^{20}	✚^{20}	✚^{20}				79	1460	16,760	5,500	19	MOSE

Notes: * Gate series are per the order as documented in the supplemental data in Appendix A2 and not necessarily based on any designated numbering system from operating authorities. ** For the Hollandsche IJssel and Eider storm surge barriers the gates are placed in series (i.e. double gate systems).

A storm surge barrier affects the tidal exchange and minimizing impacts to the tidal exchange are an important design consideration e.g (Rijkswaterstaat, 1994). The barriers in estuarine settings (Tab. 1) include a large number of auxiliary flow gates to allow for intertidal flow exchange (see also Fig 2). Gate types for auxiliary flow are further discussed below. In instances where navigation is not locked through the storm surge barrier, the navigable passage also provides flow exchange.

The crest elevation of a storm surge barrier is typically informed by the design water level and additional requirements for freeboard. The design water level is commonly determined by using a selected safety standard, extreme value distributions of water levels and anticipated sea level rise over the service life of the structure. Furthermore, local increases in extreme water levels as a result of the construction of the storm surge barrier should be considered. The design elevation is then set by adding freeboard to the design water level. Freeboard can be based on local standards or an optimization of overtopping discharge (DeSoto-Duncan, et al., 2011). It can be emphasized that storm surge barriers function as an impediment to storm surge and that large volumes of wave overtopping are in some instances allowed i.e. Hartel barrier and Maeslant barrier designs include load cases with overflow, and for the Eastern Scheldt the design water level is practically equal to the design elevation (Fig. 3).

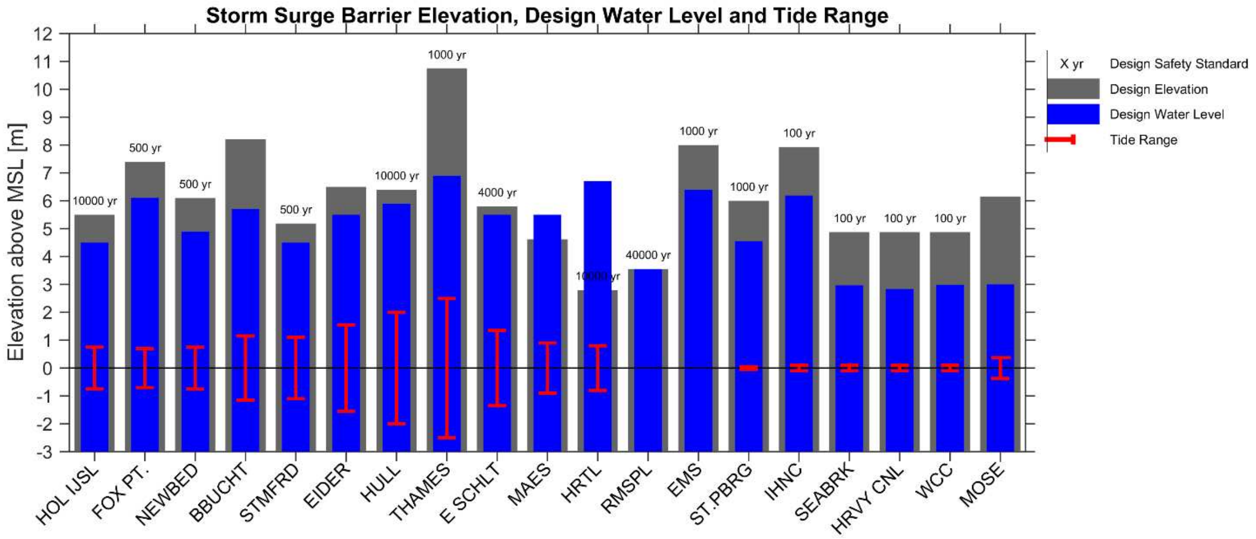

Fig. 3. Storm surge barrier elevation, design water level and tidal range. The storm surge component of the design water level can be gleaned from the graph by assessing the difference between the design water level and the maximum of the tidal range. The design safety standard is included and noted above the individual barrier elevations when available. The annual exceedance probability (AEP) is expressed with the average return period (RP) in years (RP = AEP^{-1}).

Storm surge barriers are critical components of a flood risk reduction systems, situated in exposed waters, with common geological settings (deltas and coastal or riverine sedimentary plains with typically poor quality, low strength soils). These factors in combination with the inclusion of large moveable parts translate into stringent safety and reliability criteria. Such design criteria result in redundancies, conservative safety factors to reduce the chance of failure and large foundations. This results in comprehensive requirements for operation and maintenance of the structure.

2.3 Storm Surge Barrier Gate Types, Characteristics and Application

Certain gate types have fewer limitations for navigation, while others have more. The air clearance restriction associated with tainter gates and lift gates is a typical example of a limitation for navigation. Second, while all hydraulic gate types require a foundation, gate types like the vertical rising or inflatable gate require relatively more complex sill structures which effectively limit the gate height and thereby the depth of the navigable passage. Other limitations for navigation result from the feasible span of the gate types.

Fig. 4 presents the gate type versus the span and sill elevation for all gates (both auxiliary and navigable) that are part of the selected set of storm surge barriers. The navigable gates are circled in grey. It allows one to distinguish the outliers in both span and sill elevation as well as to note that several gates, independent of type, span less than 50m and have a sill elevation less than 8m below MSL. From Fig. 4 it is clear that a floating sector gate has been selected for navigable passages where a wide maritime traffic lane needs to be maintained. Floating sector gates span an opening of over 360m and 200m at the Maeslant Barrier and St. Petersburg Barrier respectively. Other large navigable openings are spanned with a vertical rising gate or a vertical lift gate. Vertical lift gates intrinsically result in air draft restrictions. The floating sector gates are the constructed gates that accommodated the deepest sill elevations (over 16m of water depth measured from MSL), followed by flap gates. The Venice barrier includes a series of twenty 20m wide flap gates with a sill at 15m below MSL, jointly those gates span over 400m of waterway. It can further be noted that the sector gate for the, albeit a relatively narrow, navigable passage at New Bedford has a sill elevation at 12m below MSL.

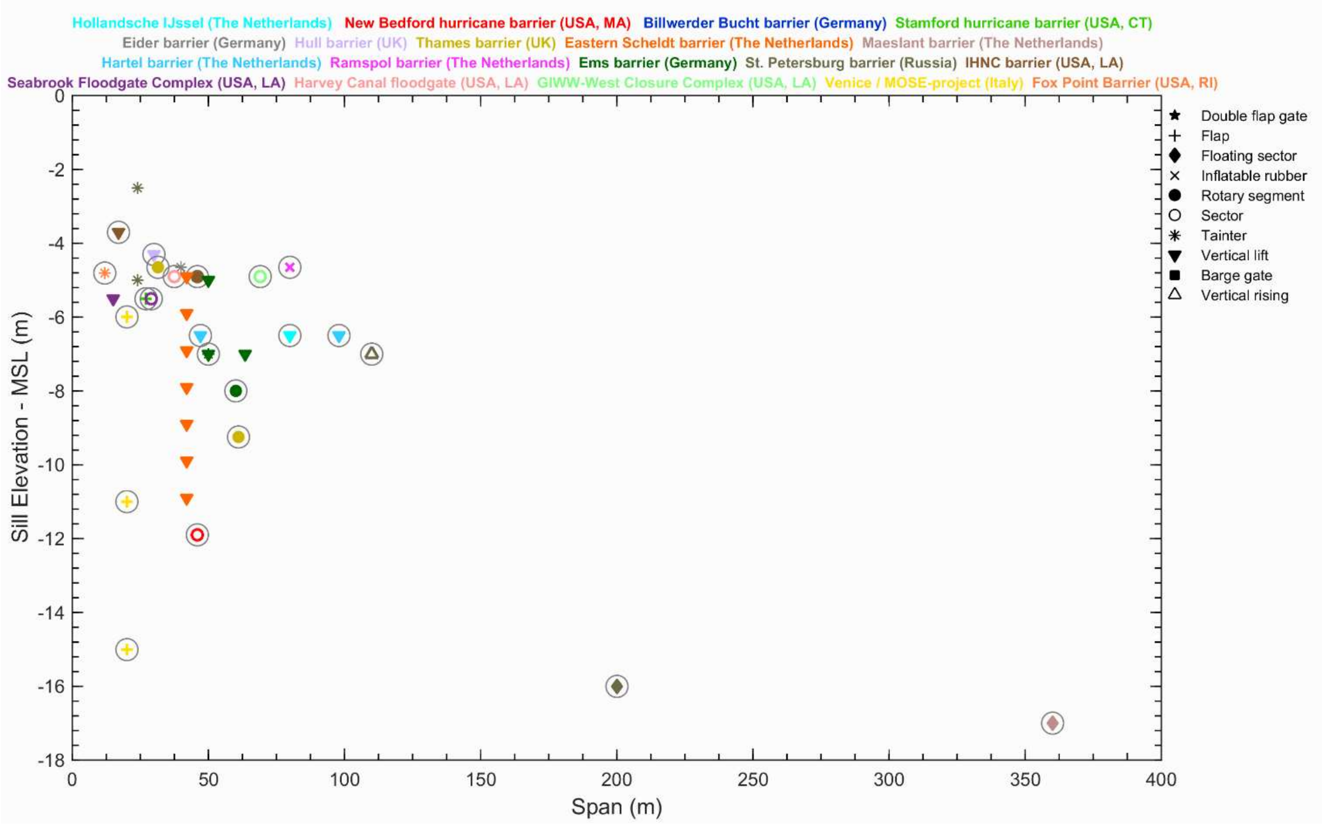

Fig. 4. Gate span versus gate sill elevation for both auxiliary flow gates and navigable gates for the storm surge barriers presented herein. Markers circled in grey are the gates of the navigable passages.

3 Parametric Model for Construction Cost and Construction Duration

3.1 Towards an Improved Parametric Model for Storm Surge Barriers

Previously, USACE-referenced models for estimating the construction cost and duration of Storm Surge Barriers (SSB's) have not incorporated the full range of available reference data or the most pertinent design information (Mooyaart & Jonkman, 2017) (USACE, 2015). As part of the NY/NJ HAT Study, the field of variables to investigate for influence upon cost was expanded. Through standard multivariable regression analysis, the work identified and employed improved models for estimating storm surge barrier construction costs and durations.

Lacking full plans or reliable cost information for all constructed barriers, some have been excluded from the list of reference barriers in this study. The eighteen (18) barriers analyzed were selected for their general applicability (size, function) and completeness of data. With more research, additional barriers may be incorporated into future studies and some measurements may be refined for those reference barriers incorporated here. All costs are presented here in 2019 Euros (see Tab. 1), the dimensional information for the reference barriers is published in Appendix A2 and details concerning escalation and currency conversion are available in Appendix A3. Components of storm surge barriers were broken up as Navigable and Auxiliary gates and Dam Lengths. "Navigable" refers to the barrier sections which can be opened for vessel traffic. "Auxiliary" refers to those which can be opened for flow but not navigation, and "Dam" portions are those which permanently close off flow.

Previous cost models treated vertical dimensions of barriers such as average height separately from horizontal dimensions such as length. In this study, vertical section areas (from sill to barrier top) for each of the three component types defined above were also analyzed for influence upon cost. In the case of the navigable and auxiliary components, note that the calculation of lengths or areas includes the structures which are necessary to the function of that section of barrier. For example, the dimensions of structures which house navigable sector gates are calculated as part of that barrier's navigable dimensions. Similarly, the adjacent structural components which connect and facilitate the function of auxiliary flow gates arranged in a series are considered part of a barrier's auxiliary length or area dimensions. Dam Area captures that area which is associated with static features of the barrier.

3.2 Cost Model

The cost and duration models generated in this study were based on linear regression analysis of a wide range of potentially influential variables. Those variables with the greatest contribution to the cost and duration of barrier construction (such as total barrier length or number of gates) were identified based on that analysis. Before multiple variables were to be considered in combination, all variable sets were tested against each other for variance inflation to guard against building a model with compounding or redundant influences.

Ultimately, the selected model meets three criteria. 1) The model should be sensitive to major design decisions which can be anticipated with moderate precision at the feasibility phase of a study. 2) It must be grounded in sound statistical analysis of the best available data. 3) The model needs to be reasonable and consistent with sound engineering judgment. For example, cost or duration should not be negatively correlated with a barrier's length and should not depend more heavily on less complex components.

The regression analysis to develop cost and duration models was performed using commonly available software. By pursuing combinations of variables which meet the first criteria above, the study progressed to identify the preferred models, i.e. those which additionally met the 2nd and 3rd criteria.

3.3 Results and Analysis

Previously identified dependence of cost upon length of dynamic components within barriers is confirmed. Mooyaart & Jonkman (2017) published their finding that overall cost can be estimated at 2.2M€ (2013 Euros) per linear meter of dynamic barrier component (auxiliary flow gates and navigable gates, taken together). This matches closely with the 2.45M€ per meter unit cost identified in this study. That's with three additional barriers in the reference data and escalated to 2019 Euros.

To identify an improved multivariable model, this study analyzed a total of sixteen (16) potential variables of influence upon the two (2) dependent variables, i.e. construction cost escalated/converted to 2019 Euros and construction duration in years, months and days. Similar to prior studies, variables such as length of dynamic features (i.e., navigable and auxiliary components), head differential and barrier height were considered. New variables analyzed include the section areas by component type defined above as well as the number of gates within a barrier. Incorporation of these additional variables into the analysis (considered alone and in combination) produces models with improved conceptual strength. For construction cost (all areas are measured in square meters and costs in 2019 Euros) and duration, the following models are recommended based on the criteria outlined in section 3.2:

$$\text{Cost} = €157{,}000 \times \text{Navigable Area} + €102{,}000 \times \text{Auxiliary Area} + €26{,}000 \times \text{Dam Area} \qquad (1)$$

$$\begin{aligned}\text{Duration} = {} & 2 \text{ Years} + 33 \text{ months} / 100\text{m of Navigable Span} \\ & + 23 \text{ weeks}/ 100\text{m of Auxiliary Flow Span} + 16 \text{ Days} / 100\text{m of Dam}\end{aligned} \qquad (2)$$

Equations (1) and (2) correspond with mean, best fit of regression curve based on most recent cost, duration and barrier feature and dimension data available. Costs and durations estimated with these models can be expected, with 50% confidence, to match or exceed actual construction costs and durations. For the cost formula, a 90% confidence interval can be defined based upon the dataset analyzed with the following slope intervals: +/- €60,000 on the Navigational area (NA) term coefficient, +/- €54,000 on the Auxiliary flow area (AA) term coefficient and +/- €13,500 on the Dam or static term (DA) term coefficient. Fig. 5. Presents actual versus modeled costs of the reference SSB's plotted along with modeled costs for the NY/NJ HAT Study case study storm surge barrier presented in Section 4.

4 Case Study for the New York Metropolitan Area

4.1 Flood Risk

Recurring impacts from coastal flooding has resulted in significant economic, environmental, and community impacts in the New York metropolitan area. Millions live in communities located in low lying, densely developed urban and suburban neighborhoods and New York City alone incurred an estimated $19 billion in damages due to Hurricane Sandy in 2012 (USACE, 2019). During coastal storms, surges propagate through New York Harbor or through the Long Island Sound and have the potential to flood the extensive low-lying areas surrounding the metropolitan area.

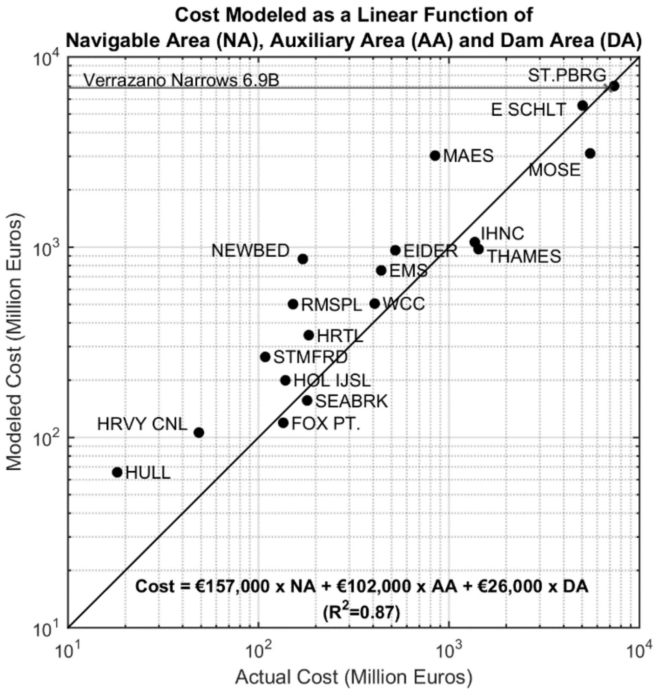

Fig. 5. Actual costs of existing barriers plotted against costs estimated by the improved model, dependent upon areas of barrier components. Estimated costs of case study barrier also shown. (2019 price levels).

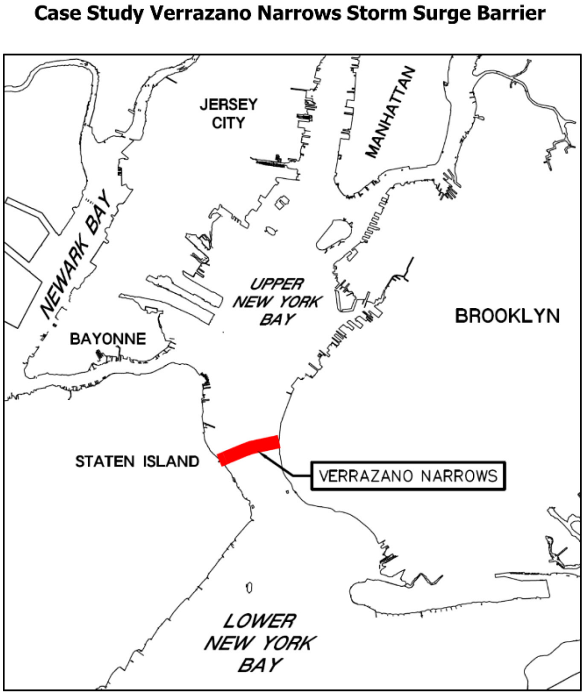

Fig. 6. Location of the Verrazano Narrows Storm Surge Barrier as Case Study for the NY/NJ HAT Feasibility Study.

4.2 Storm Surge Barrier Case Study for Verrazano Narrows

There are numerous visioning studies, reports and presentations that have addressed the concept of storm surge barriers for the larger New York Metropolitan Area, relevant reports and publications include Smith (2005), Bowman, et al. (2004), Bowman, et al. (2008), Hill, et al. (2013) , Dircke, Jongeling and Jansen (2012) and Aerts, Botzen and De Moel (2013), amongst others. USACE has formulated coastal storm risk management strategies as part of the NY/NJ HAT Feasibility Study (USACE, 2019), inclusive of storm surge barriers. These are in part informed by these previous studies. One example is provided here to illustrate how insights in storm surge barrier gate applications and the improved cost model were utilized to inform coastal storm risk management strategies for the region.

A conceptual design for a storm surge barrier at the Verrazano Narrows (Fig. 6) was part of the referenced study and includes two (2) gated navigable passages and 15 auxiliary flow gates for a total of 17 gates (Tab. 2). This provides for navigation to pass and minimizes the impacts to the tidal flow exchange. The dimensions of the gated openings are provided in the table below. It should be noted that the dimensions of the navigable passage for this barrier are larger than any gated opening among constructed storm surge barriers (Maeslant Barrier spans 360m). The data plots in section 2 provides visual aids and are used to distill characteristics of the constructed barriers and demonstrate the applicability of proven concepts within a range of parameters such as gate span or gate sill elevation.

For the main navigable passage a floating sector gate is a suitable selection as only such gate types have been used for large navigable openings while recognizing that the realization of very large gates with unrestricted air clearances remains challenging (Erbisti, 2004). For the secondary navigable passage a sector gate is selected as similar depths and spans have been constructed before. Lastly, vertical lift gates were selected for the auxiliary flow openings as these are proven suitable concepts.

Peak tidal flows for this location are approximately 36,000 m^3/s (USACE, 2019). With a cumulative flow area of 19,400m^2, peak flow velocities are expected to be 2 m/s. Previous evaluations of storm surge barriers have shown that the relation between the flow opening and the peak tidal discharge provides an indication of the maximum current velocities through openings. These can used as a proxy to assess navigability (adverse currents) or the need for extensive bed protection measures (Mooyaart & Jonkman, 2017). The projected 2 m/s is comparable to calculated peak velocities and tidal flows at the MOSE barrier. Lastly, using the presented cost model the cost estimate for the Verrazano Narrows Storm surge barrier is estimated at €6.9B (2019 price levels) with a construction duration of 18 years.

Tab. 2. Characteristics of a conceptual storm surge barrier for the Verrazano Narrows – structure elevation is set at +6.7m and a dam section of 220m is included to tie the structure to the land-based flood risk reduction system.

Gate Series	**Function**	**No. Gates**	**Sill Depth (m, MSL)**	**Width of each Gate* (m)**	**Flow Area (m^2)**	**Span** (m)**	**Notes**
A	Auxiliary Flow	1	-6	46	-279	55	Vertical Lift Gate
B	Auxiliary Flow	12	-18	46	-837	668	Vertical Lift Gate
C	Nav. Passage	1	-18	427	-7548	982	Float. Sector Gate
D	Nav. Passage	1	-14	61	-837	140	Sector Gate
E	Auxiliary Flow	2	-8	46	-349	119	Vertical Lift Gate
Total		17			-19,400	1,963	

Notes: *Total Cumulative Gate span = 1174m. **Span for navigable structures equals gate width + pier widths.

5 Concluding Remarks

Storm surge and coastal floods are one of the most damaging and dangerous natural hazards facing society (Orton, et al., 2019) and responsible for half of all hurricane related mortalities in the US from 1963 to 2012 (Rappaport, 2014). Global extreme water levels are increasing and for the New York Metropolitan area the 100-year Return Period (RP) flood is expected to be a 40yr to 11yr RP flood under the middle range of sea level rise projection in the year 2100 (Orton, et al., 2019). Storm surge barriers can be cost-effective alternatives to the improvement and fortification of long stretches of coastline or the construction of perimeter flood risk reduction systems, especially when these coastlines are extensive in length, are heavily developed or urbanized and have multiple waterfront uses.

Preparing conceptual designs for storm surge barriers remains a complex undertaking where not one single design aspect can be investigated without due consideration of all the functions a barrier needs to provide. In general, storm surge barriers should strive to minimize changes to the existing ecological conditions and minimize the environmental gradient between the flood side and protected side during normal hydrometeorological conditions, e.g. Ramspol barrier (PIANC, 2018).

Flow considerations and navigability can be assessed first to get an understanding of the required opening sizes while attempting to minimize impacts to flow exchange and the passage of maritime traffic. The gate type for both the navigable and auxiliary flow opening are informed by the required minimum width and depth of the gate and any restrictions on air clearances. The authors provided a visual aid that illustrates the use of hydraulic gate types for varying span and sill elevations. Note that a combination of different gate types can be the optimal solution and that not one optimal single design exists as alternate solutions may provide similar benefits (Dircke, et al., 2012). The authors furthermore present an improved cost model to estimate the construction cost and duration for storm surge barriers.

A final note is made regarding sea level rise and the fact that storm surge barriers do not provide flood risk reduction to sea level rise alone. Future sea level rise may increase flood risk for coastal areas and, as such, increase the closure frequency in out years. Yet a navigable storm surge barrier cannot be expected to close during frequent high tide events as it would put a large burden on operations and have economic and environmental impacts, e.g. the Thames barrier currently includes a maximum permissible number of 50 closures (Environment Agency, 2016). It is therefore recommended that during the conceptual design stage due consideration is given to an analysis of closure frequency. Ultimately a storm surge barrier design will be a tradeoff between capital costs, effectiveness and impacts on the system (environmental, risk, navigation etc.) and long-term operation and maintenance.

6 Supplemental Data

Appendixes A1, A2 and A3 are available online from the 4TU.ResearchData website. Appendix A1: Gate Types for Storm Surge Barriers, Appendix A2: An updated overview of characteristics of constructed storm surge barriers, Appendix A3: Cost estimates including cost escalation of constructed storm surge barriers. [http://doi.org/10.4121/uuid:9820d43f-9e20-48a6-a791-59e634fab30e]

Acknowledgments and Disclaimer

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