Maintenance by Design: Managing Storm Surge Barrier Upkeep

Embedding Flexibility Across the Storm Surge Barrier Life-Cycle

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by

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Cover photo: Render of Bolivar Roads Gate System at Texas Gulf Coast (USACE, 2021a).

Preface

With the increasing impact of climate change on densely populated coastal deltas, the reliability of storm surge barriers is more critical than ever. This Thesis explores how a *Maintenance by Design* approach can contribute to a storm surge barrier that is not only safe today but can also adapt flexibly to changing physical- and socio-economic conditions over the next century.

Since September 2022, I have been pursuing the Double Degree program at Delft University of Technology, combining the *MSc. in Civil Engineering (CE)* (Track: Hydraulic Engineering) with the *MSc. Construction Management and Engineering (CME)* (Track: Projects & People). For my graduation project, I had the great opportunity to work as Intern at Arcadis N.V., focusing on the Coastal Texas Study project. As part of this Thesis, I spent three months, February through April 2025, at Texas A&M University in Texas. Discussions with local stakeholders provided essential tacit context for this research.

The idea for the research topic was lighted up by earlier experiences. During my part-time traineeship at Mourik Infra N.V., I worked on flood risk projects and innovative dike projects, where I saw how maintenance challenges often surface only after completion. As a Water Ambassador, I participated in the Taskforce Deltatechnology, which promotes co-creation between governments and market parties in addressing flood protection challenges, and I came to understand the importance of public support. Meanwhile, my political and policy experiences through the Delft municipality student party STIP and the IDEA League Challenge Programme with students from RWTH Aachen, ETH Zurich, Politecnico di Milano, and Chalmers University of Technology gave me insight into the complex political and economic trade-offs behind major infrastructure decisions. These combined experiences, both technical and policy-oriented, convinced me that a multidisciplinary approach is essential to make large-scale flood defense infrastructure future-proof.

As a result of this Double Degree program, the two Theses, each worth 30 ECTS, overlap by 20 ECTS, resulting in a combined Thesis total of 40 ECTS. Consequently, this Thesis includes distinct sections for both CE and CME, each carrying a weight of 10 ECTS, as validated by the Thesis committee. In essence, the assessment committee evaluates both the common section and the degree-specific sections (CE or CME) using the Master Thesis grading sheet. Within the further outline of this report, the specific parts are indicated by label marking: “CE”, “CME” or “CE + CME”. This subdivision is included in the research scope and -questions, which form the basis for elaborating the specific parts (“CE”, “CME” and “CE + CME”).

This Thesis is aimed at engineers, asset managers, policymakers, and academics involved in the design, management, or governance of storm surge barrier and other coastal infrastructure. By explicitly linking design decisions to maintenance and institutional frameworks, I aim to bridge the gap between engineering and policy. Writing this Thesis meant immersing myself in the unique nature of storm surge barriers, where engineering meets governance. Site visits along the Houston Shipping Channel showed how technical design choices immediately trigger policy, legal, and financial considerations. The process revealed that designing a barrier is not just a technical task, but a balancing act between physical constraints and political realities.

S.D. (Sander) van der Geer
Delft, July 2, 2025

“Thus, the task is not so much to see what no one yet has seen, but to think what nobody yet has thought about that which everybody sees.”
— Arthur Schopenhauer

Acknowledgment

Writing this Thesis has been both a challenging academic experience and a personal journey of growth. I would like to sincerely thank my responsible supervisor, ir. Leon Hombergen, for his continuous support and valuable feedback throughout this process. His high standards and attention to detail have played a big role in shaping this Thesis. Our conversations often went beyond the academic content, helping me see things from new and meaningful perspectives. I am also very grateful to my Thesis committee members, prof.dr.ir. Marcel Hertogh and prof.dr.ir. Bas Jonkman, for their constructive feedback and helpful suggestions, which really improved the quality of my work.

A special thanks goes to ir. Arno Kemper and ir. Kasper Stoeten from Arcadis N.V. for their support and the resources they provided. I am also thankful for the help I received from staff at Texas A&M University. In particular, I would like to thank prof.dr. Sam Brody, dr. Jens Figlus, dr. Yoonjeong Lee, and dr. Baukje Kothuis for their guidance and support during my time in Texas. This experience reminded me that research is never a solo effort, but one that depends on the insights of many people.

I am also extremely grateful for the financial support from Arcadis N.V., Mourik Infra N.V., the Bay Area Coastal Protection Alliance, and the FAST fund TU Delft. Their contributions made it possible for me to spend three months in Texas to collaborate and conducting research.

I want to thank my family for their endless support, and my friends for keeping me grounded, whether through encouragement or the occasional welcome distraction. My fellow students and peers, especially ir. Bruining van Dongen, also played an important part in this journey, making the experience richer and enjoyable. This Thesis reflects not only my hard work but also the incredible support I have received from many people, both academically and personally. This journey has shown me how important it is to keep asking questions and to value different perspectives when tackling societal topics.

Finally, I acknowledge the use of ChatGPT (GPT-4o & o3) from OpenAI [https://chat.openai.com/] to identify improvements in the writing style, to support Python programming to create the plots included in this Thesis, to help brainstorm topics, to aid my understanding of a concept, topic or course materials, and to review my writing at the final stage. I acknowledge also the use of DeepL Translate [https://DeepL.com/] to generate translations of key terms from my first language into English in the writing process.

Abstract

Millions of people live in low-lying, flood-prone economic hubs like Rotterdam, Singapore, Houston, and Sydney. These areas are increasingly threatened by relative sea level rise, storm events, and river flooding. Traditional flood defenses, such as dikes, are often unfeasible in dense urban settings. As a result, engineers have turned to movable storm surge barriers that stay open under normal conditions for navigation and water exchange but close during extreme events to block storm surges. Fewer than fifty such barriers exist worldwide, limiting operational know-how, which remains tacit and globally scattered. The main challenge begins after construction: barriers like the proposed Bolivar Roads Gate System on the Texas Gulf Coast must deliver absolute reliability over a 100 year lifespan while physical and socio-economic drivers evolve unpredictably, impacting the functional performance.

Traditional barrier design practice often cannot cope with these volatile physical- and socio-economic drivers, as exemplified by the maintenance difficulties of the Maeslant Barrier, and suffer from fragmented governance. These limitations lead to performance issues that are intensified by the long lifespans and structural complexity of these structures. The objective of this Thesis is to integrate operational and maintenance requirements into early design and planning, aiming for organizational stability and adaptable operations throughout the life-cycle, using the Bolivar Roads Gate System at the Texas Gulf Coast as a case study. The research investigates options for flexibility in barrier design to remain adaptable over its lifespan. It examines how drivers like relative sea level rise and increases in vessel drafts affect operations and maintenance, and how design and maintenance choices can support long-term performance and institutional resilience in dynamic coastal settings.

The study applied De Neufville and Scholtes (2011) four-phase Flexibility in Engineering Design method. Phase 1 defined the Bolivar Roads Gate System reference design to establish the solution space for Phases 2 and 3. Comprising: (1.1) boundary condition mapping, (1.2) stakeholder analysis, (1.3) constructing a functional breakdown structure, and (1.4) inventory of barrier components through a system breakdown structure. Phase 2 linked system drivers in the Houston-Galveston Bay Region to barrier performance, informing options for flexibility in design explored in Phase 3. System drivers were assessed through (2.1) historical-, (2.2) projected trend magnitudes, and (2.3) impacts on barrier functional performance. Lastly, (2.4) four expert-informed delta scenarios were developed to identify the critical system driver under many/limited changing climate conditions and socio-economic growth.

Phase 3 mapped (3.1) dependencies between the critical system driver identified in Phase 2 and barrier components, informed by expert interviews. Combined with (3.2) components-cost share resulting in (3.3) a risk-susceptibility factor per component, with the sill scoring highest. Finally, (3.4) four conceptual adaptable sill designs were developed, with an (3.5) Asset Management Strategy. Phase 4 defined the public client's accountability in storm surge barrier delivery by synthesizing insights from the previous phases. Including: (4.1) project complexity mapping, a "make" or "buy" assessment using the Kraljic Matrix, and (4.2) synthesis of findings into a conceptual project delivery method.

The study shows that system drivers affecting barrier performance are only partly predictable, as each barrier design reveals location-specific vulnerabilities to volatile and random physical and socio-economic drivers over time. However, options for flexibility in design allows for limited foresight, as the barrier "has the option to change". Instead of precise forecasts, system drivers were identified using heuristics like historical trends and expert judgment. The scenario analysis for the Houston-Galveston Bay Region identifies eight dominant system drivers: Temperature; Hydrodynamics & Morphology; Relative Sea level Rise; Hurricanes; Multi-Stakeholder Dynamics; Politics, Policy and Law; Organizational Shifts; and Economic Growth (i.e., Increased Vessel Draft). Relative Sea Level Change and Increasing Vessel Drafts pose the greatest risks to functional performance, but differ in volatility: sea level rises slowly, while economic growth is unpredictable (i.e., hard to measure and quantify), and may exceed design limits within decades, making it the critical driver.

The results exhibit that storm surge barriers are long-lived, rarely used, but must stay reliable, making maintenance planning challenging due to uncertain drivers and design-specific needs. The research unveils that without strong, consistent maintainability requirements, maintainability principles (e.g., component interchangeability) often disappear from the design. In response, the study findings argue that barriers must be designed and planned with maintenance intervals tailored to component lifespans: fixed (100 years), movable (50–100 years), and electrical (8–15 years), as each component has different degradation rates (further elaborated in Figure 4.9 in Chapter 4). Position shorter-life components in locations that are easy to reach, ensuring frequently serviced parts can be accessed without disassembly, hence a maintainability-first approach. Results further lay out that a maintainability-first approach must pair with state-based maintenance policy, given uncertain component degradation, and required reliability regarding the high consequences of failure. Involving regular inspections and degradation action thresholds to prevent failures. Combining preventive maintenance for critical components, corrective for low-risk ones, and failure-based repairs during emergencies like storms.

These research findings reveals a design dilemma: build for required reliability and risk design obsolescence, or, as with Bolivar Roads, anticipate uncertain system drivers like future vessel drafts at higher upfront cost. Results highlight the need for design options to adapt to these types of volatile and random conditions. Thereby "having the optionality to change", prioritizing components most sensitive to system drivers and costly to change later. The study shows that flexibility must be built into permanent fixed components like the sill and foundation, or they must be over-engineered to support future upgrades of shorter lived movable and electrical parts. In contrast, movable and electrical parts manifest flexibility through multiple planned replacements over the barrier lifespan.

What might options for flexibility in fixed components at Bolivar Roads look like? This study proposes an adaptable sill, allowing future deepening to accommodate increased vessel drafts (see Figure 1; further elaborated in Figure 6.30 in Chapter 6). Comprising a two-stage structure: permanent sill blocks founded on piles and a graded open filter, covered with caisson modules. Stage 1, the caissons sets the crest at $-18.3\,\mathrm{m\,NAVD}$. When deeper drafts are needed, stage 2 is activated: the ballast is removed, caissons are floated off, and the underlying sill blocks, precast to $-25.3\,\mathrm{m\,NAVD}$, become the new crest. As stated above movable and electrical components must be retrofitted accordingly. Stability is ensured by a pile foundation and a four-layer open granular filter placed between the sill blocks and subsoil. Above this, loose rock bed protection is applied. Implementing a complementary Asset Management Strategy with a "Flexibility Logic" across the strategic, tactical and operational asset management levels, through a flex-reserve fund, and five-yearly stress-tests with multi-actor risk dialogues, ensures the adaptable sill can be reconfigured quickly (further elaborated in Figure 6.33 in Chapter 6).

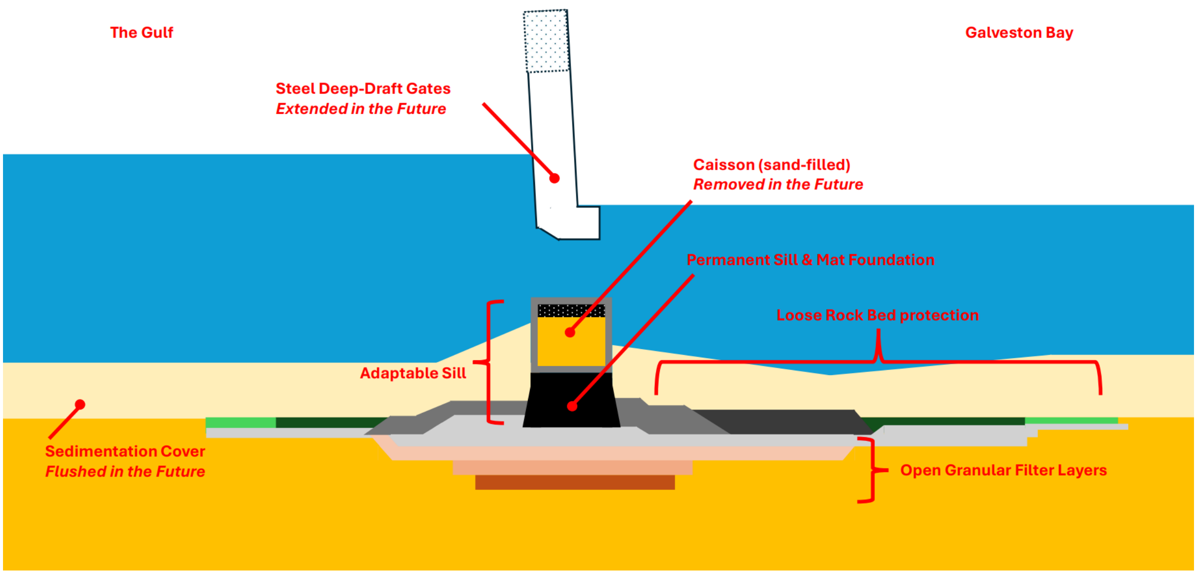

Figure 1: Schematic of Adaptable Sill design Floating Sector Gates section Bolivar Roads Gate System at Bolivar Roads Texas Gulf Coast – side view (further elaborated in Figure 6.30 in Chapter 6).

The study shows that barrier performance are shaped by volatile drivers, especially unpredictable, non-linear socio-economic ones influenced by Institutional Logics. That is the behavior, culture, and interactions of actors across institutions. Together with barriers' 100 year lifespans and high reliability demands, public clients face an "Make" or "Buy" dilemma regarding the procurement of design-build-operations-maintenance and the governance of options for flexibility in the barrier design: retain in-house for accountability or outsource for innovation and risk-bearing capacity of market parties.

The contract strategy analysis (further elaborated in Figure 6.34 in Chapter 6) reveals regarding the design phase, given the multidisciplinary scope, detailed design must go to qualified first-tier suppliers, while the public client maintains a small, skilled in-house team to manage interfaces, oversee contracts, allocate risks, and validate deliverables. Hence, being the system integrator, which requires an increase in in-house capacity. In the build phase, due to cross-disciplinary needs, the client must continue to retain interface and risk management, supported by a temporarily expanded in-house team. Physical execution can be outsourced via integrated design-build contracts, enabling market expertise while preserving continuous client-led system integration. Concerning operating a barrier, given the high failure stakes, operational authority and staffing must stay in-house. Routine- and variable minor maintenance can be outsourced, while major variable maintenance are contracted separately. The client again continuous to retain interface management and risk allocation to ensure continuity and accountability. Lastly, governance of the adaptable sill must remain with the client, as activation depends on unpredictable policy windows, though execution can be outsourced once activation is approved.

Synthesizing results, this study concludes that to integrate operational and maintenance needs into design and planning, ensuring organizational stability and adaptable system operations throughout the lifespan, storm surge barriers require a bimodal strategy: managing the barrier through two distinct yet complementary modes (see Figure 2). *Mode 1 - Maintainability* follows a traditional, linear approach focused on the predictable reliability like component degradation, routine maintenance, and risk minimization. Emphasizing the need to deliberately design the barrier with maintenance intervals of its components in mind. Complemented by a state-based maintenance policy, combining preventive-corrective- and failure-based maintenance. *Mode 2 – Flexibility* addresses the non-linear, unpredictable volatility and randomness exhibited by system drivers by embedding options for flexibility in design that allow the system to adapt over time. Accepting instability but "having the design options to change." The adaptable sill, for example, enables the barrier to accommodate deeper vessel drafts rather than resist them. Mode 2 complements Mode 1 by preserving performance under long-term uncertain conditions. This dual strategy depends on the public client acting as system integrator. This requires a differentiated governance structure where the client is exposed to the outcomes of its decisions.

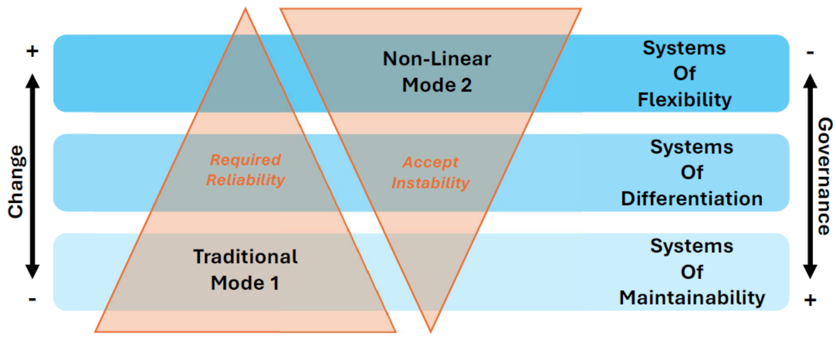

Figure 2: Managing storm surge barrier upkeep via a bimodal strategy: Mode 1 - Maintainability for required reliability and Mode 2 - Flexibility for evolving physical- and socio-economic uncertainties.

These findings call for a shift in how we think about barrier development: instead of trying to eliminate uncertainty during design (i.e., solely Mode 1), we should also focus one creating barriers that are adaptable under changing conditions, hence Mode 2. To conclude, storm surge barriers must be treated as living systems: built for immediate reliability yet pre-equipped with design options that let them evolve. Embedding options for flexibility in the hardest-to-replace elements and pairing it with state-based maintenance policy gives public clients a practical way to keep flood safety, performance, and accountability intact amid the uncertain physical and socio-economic shifts of the coming century.

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Abbreviations

Abbreviation	Definition
AM	Asset Management
CBRA	Coastal Barrier Resource Act
DB	Design-Build
DDB	Design-Bid-Build
DBFM/O	Design-Build-Finance-Maintain and/or Operate
DBO	Design-Bid-Operate
EPA	Environmental Protection Agency
EPC	Engineering Procurement and Construction
ES	Engineering Systems
FBS	Functional Breakdown Structure
FEMA	Federal Emergency Management Agency
FTA	Fault Tree Analysis
GCPD	Gulf Coast Protection District
GLO	Texas General Land Office
HSC	Houston Shipping Channel
LEPC	Local Emergency Planning Committees
LTS	Large Technological System
MCA	Multi Criteria Analysis
NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NWF	National Wildlife Federation
O&M	Operations & Maintenance
PDCA	Plan-Do-Check-Act
PDM	Project Delivery Method
ProBo	Probabilistisch (Risicogestuurd) Beheer en Onderhoud
RCT	Relational Contract Theory
ROA	Real Options Theory
RSLC	Relative Sea Level Change
RWS	Rijkswaterstaat
SBS	System Breakdown Structure
SE	System Engineering
SSB	Storm Surge Barrier
STS	Sociotechnical Systems Theory
SWEG	Shallow Water Environmental Gates
TCE	Transaction Cost Economics
TDEM	Texas Division of Emergency Management
TPWD	Texas Parks and Wildlife Department
U.S.	United States
USACE	U.S. Army Corps of Engineers
VLG	Vertical Lift Gates
VUCA	Volatile Uncertain Complex and Ambiguous

Nomenclature

Symbol	SI-unit	Definition
$B_{\text{crit,Iz}}$	[−]	Critical Izbash stability coefficient
C	[$m^{1/2}$/s]	Chézy coefficient
C_L	[−]	Lane's coefficient
D_0	[m]	Effective propeller diameter (vessel)
D_{50}	[m]	Median grain size
D_{n50}	[m]	Nominal median grain size
F	[N]	Force
H	[m]	Design water level
H_s	[m]	Design wave height
P_D	[W]	Maximum installed engine power (vessel)
T	[s]	Wave period
U	[m/s]	Depth-average flow velocity
$UKC_{c,\min}$	[m]	Minimum under-keel clearance
f	[−]	Darcy friction coefficient
g	[m/s^2]	Gravitational acceleration
k_h	[−]	Flow-velocity-profile factor
k_r	[m]	Equivalent bed roughness
k_{sl}	[−]	Side-slope factor
k_t	[−]	Turbulence factor
n_f	[−]	Soil porosity
n_s	[−]	Slope factor of failure plane
p	[Pa]	Pressure
p'_{max}	[Pa]	Ultimate bearing capacity (soil)
r	[−]	Turbulence factor
u_{cr}	[m/s]	Critical velocity for sediment-motion initiation
$\bar{u}$	[m/s]	Depth-average velocity at end of scour protection
$\dot{u}_b$	[m/s]	Maximum orbital flow velocity
Δ	[−]	Relative buoyant density
Θ_{cr}	[−]	Shields parameter (critical)
α	[−]	Turbulence factor
γ	[−]	Safety factor
ρ	[kg/m^3]	Density of salt water
ρ_c	[kN/m^3]	Density of concrete
ρ_w	[kg/m^3]	Density of fresh water
ϕ	[rad]	Internal friction angle
ϕ_{sc}	[−]	Stability-correction factor
ψ_{cr}	[−]	Critical mobility parameter

1 Introduction

This chapter introduces the challenges of designing and maintaining a storm surge barrier (SSB) in dynamic coastal systems. Hence, the reason of this Thesis. Section 1.1 outlines the increasing flood risks, and SSBs as possible solution. Section 1.2 outlines SSB maintenance challenges. Section 1.3 presents the research objective. Section 1.4 defines the research question. The chapter concludes with the research scope, approach and applied theories (Sections 1.5 and 1.6).

1.1. Societal Context

Coastal flood risks are rising due to shifting climate conditions and increasing economic activities. This section introduces the societal context of this study, outlining global flood risks (Section 1.1.1) and introducing the challenges in the Houston-Galveston Bay Region case study (Section 1.1.2).

1.1.1. The Coastal Delta at Risk

A significant part of the global population lives in low-lying, flood-prone coastal regions, deltas, and along riverbanks (Small and Nicholls, 2003; Jonkman and Schweckendiek, 2015). Over 600 million people inhabit these zones globally (Neumann et al., 2015). A number expected to surpass 1 billion by 2060 due to population growth and coastal migration (Merkens et al., 2016). Many reside in expanding estuarine cities (Haasnoot et al., 2020), like New Orleans in the Mississipi River Delta (U.S.), the Venetian Lagoon (Italy), Singapore Strait (State of Singapore), and the Port Jackson ria in Sydney (i.e. drowned river valley in Australia).

Coastal regions are vital for social and economic development but highly vulnerable for flooding. For example, Rotterdam, located in the Rhine-Meuse delta, is Europe's largest seaport and a key economic hub, yet exposed to natural hazards from the North Sea (Trace-Kleeberg et al., 2023). Coastal deltas face risks like erosion, hurricanes, saltwater intrusion, and flooding from storm surges and river runoff, risks heightened by climate change and sea level rise (Small and Nicholls, 2003; Mooyaart and Jonkman, 2017). Growing human populations and socio-economic activities further increase their vulnerability (Small and Nicholls, 2003). To illustrate, the city of Singapore has built itself up as an Asian financial hub, being one of the world's largest centers for wealth management and commodities trading (Khalaf, 2013). However, located in South-east Asian the city is prone to monsoons and typhoon-hits (The Straits Times, 2024).

These interplay's of environmental conditions and socio-economic activities heightens flooding risks (Du et al., 2020), further driven by extreme storm surges, sea level rise, and increased rainfall (IPCC, 2023). Intensifying storm surges threaten coastal cities, causing severe damage and loss of life (Jonkman and Schweckendiek, 2015). As seen in the 1953 Netherlands flood disaster (see Figure 1.1, Hamerslag and Bakker, 2023) and after Hurricane Katrina in New Orleans in 2005 (see Figure 1.2, Jonkman and Schweckendiek, 2015). These factors contribute to projected global annual flood losses of $60-63 billion by 2050 (Hallegatte et al., 2013; Jevrejeva et al., 2018).

Figure 1.1: Flood disaster 1953 the Netherlands (Zeeuws Archief, 2020).

Figure 1.2: Floodwaters from Hurricane Katrina in New Orleans (Kailath, 2016).

Economically, heightened flood risks drive significant investments in flood mitigation (Brekelmans et al., 2012). For instance, after Hurricane Katrina in 2005, the U.S. Army Corps of Engineers (USACE) built the Lake Borgne Storm Surge Barrier in New Orleans at a cost of $1.3 billion (Huntsman, 2012). Coastal defense measures, including locks, weirs, and SSBs, support habitation and economic activities by reducing risks to populations and assets (Jonkman, Hillen, et al., 2013; Kamps, van den Bogaard, et al., 2024). But rising sea levels and intensifying climate impacts, such as waves, precipitation, and storm surges, require ongoing adaptation of these systems.

Elevating existing flood defenses is a common strategy to mitigate flood risks but is challenging in densely populated areas due to space constraints and social impacts (Mooyaart and Jonkman, 2017). As climate models suggests that flood risks intensify beyond 2050 and 2100, robust infrastructure, including hard measures like SSBs, becomes essential (IPCC, 2023; Du et al., 2020).

SSBs provide technically and economically viable solutions for flood protection in coastal areas with extensive coastlines and limited space (Aerts, 2018; Mooyaart and Jonkman, 2017). By way of illustration, the Delta Works (The Netherlands) involved constructing large, complex barriers that significantly shortened the coastline, transforming a 700 km volatile boundary into a straight 80 km stretch (van der Ham et al., 2018). Therefore, cities like Houston and New York are incorporating SSBs into their plans to mitigate flood risks (USACE, 2021a; Morang, 2016).

SSBs are large structures with movable gates (Mooyaart and Jonkman, 2017), typically located in estuaries, rivers, or lakes (Nogueira and Walraven, 2018). These barriers remain open under normal conditions to allow tidal exchange and navigation (Mooyaart and Jonkman, 2017). The Maeslant Barrier in the Rhine-Meuse delta exemplifies this design (see Figure 1.3), minimizing navigation impacts (Trace-Kleeberg et al., 2023). During storms, SSBs close to block surges, preventing catastrophic damage (Zhong et al., 2012).

Figure 1.3: Maeslant barrier, Rotterdam (I-STORM, 2021).

SSBs must meet stringent safety standards, protecting against 500-year flood events in the United States (U.S.) (Morang, 2016) and 10,000-year events in The Netherlands (Mooyaart and Jonkman, 2017). Currently, 50 SSBs operate globally, including the Hartel Barrier (Netherlands), and Thames Barrier (UK) (Nogueira and Walraven, 2018). Experts are connected through I-STORM, an essential international knowledge network (I-STORM, 2021). Knowledge sharing is necessary, given the limited number of SSBs and scarce academic research, hence expertise in this field is rare (Mooyaart and Jonkman, 2017). This Thesis aims to advance understanding, analysis, and propagation of SSB knowledge, contributing to the academic discourse.

1.1.2. The Flourishing Houston-Galveston Bay Region

Many flood-prone coastal areas are considering SSBs to reduce flood risks. The Houston-Galveston Bay Region on the Texas Gulf Coast, home to over 7 million people (including 4 million in Greater Houston), is exploring SSB construction (USACE, 2021d), see Figure 1.4. A significant portion of the population resides in flood-prone zones (Kothuis et al., 2015), and the estuarine system supports diverse ecosystems like marshlands, oyster reefs, and intertidal zones (USACE, 2021d).

The Houston-Galveston Bay region relies on industries like fisheries, tourism, and maritime trade (USACE, 2021d). Its population is projected to exceed 8 million by 2045, increasing housing demand (USACE, 2021e). The Houston Ship Channel supports $802 billion in trade annually, handling over 8,000 vessels (USACE, 2021d). The Port of Houston processes 247 million tons of cargo yearly, contributing over $500 billion to the U.S. economy (USACE, 2021b; Kothuis et al., 2015). While Houston's petrochemical sector accounts for 40% of national capacity (USACE, 2021d). Hence, the economic importance of the Houston-Galveston Bay Region.

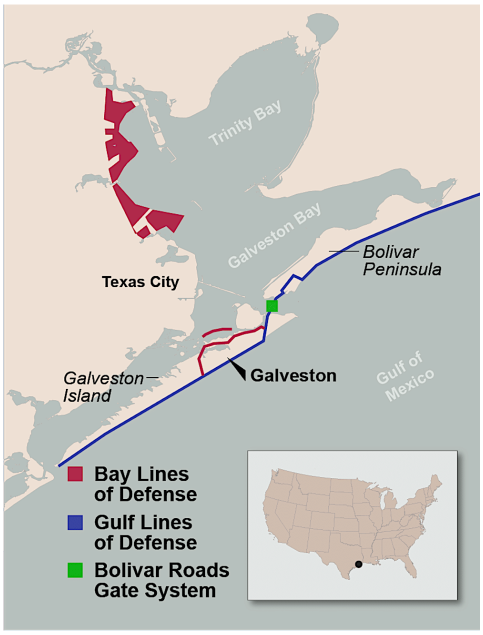


Figure 1.4: Proposed Coastal Texas Project (USACE, 2021a).

Hurricanes frequently impact the Gulf and the Houston-Galveston Bay Region (USACE, 2021a), causing significant damage. Hurricane Ike (2008) caused $28 billion in damages, and Hurricane Harvey (2017) totaled $150 billion (Sohn et al., 2020). Without interventions, annual flood damages in the region could reach $2.1 billion (USACE, 2021a). To cope with these flood risks, the Coastal Texas Protection and Restoration Feasibility Study, led by the U.S. Army Corps of Engineers (USACE) and Texas General Land Office (GLO), aims to address coastal hazards and enhance ecosystem resilience (USACE, 2021a). This $30 billion project (anno 2021), integrates environmental, social, and economic factors, with the Bolivar Roads Gate System, a proposed SSB, as a key component to mitigate hurricanes and storm surges (USACE, 2021a). Natural features like wetlands, oyster reefs, and marshes act as storm surge buffers while providing ecological services (USACE, 2021b).

The Coastal Texas Protection and Restoration Study faces uncertainties across environmental, economic, social, and technical dimensions. Environmental groups worry the SSB may disrupt wetlands, crucial for storm surge buffering and fisheries (USACE, 2021a). Economically, delays and disruptions to key industries, such as maritime and petrochemical industry, pose risks. Socially, the project faces local opposition, due to housing pressures from population growth, and unequal impacts on vulnerable communities (USACE, 2021e). Technically, concerns about the Bolivar Roads Gate System's long-term reliability, overall stakeholder coordination, and the plan's lack of operational clarity add to the challenges (Merrell et al., 2021). Resulting in disagreements over design and scope, which further complicate stakeholder consensus. Hence, this Thesis aims to advance understanding, analysis, and propagation of knowledge on the Bolivar Roads Gate System project, contributing to the practical implementation of this mega-project.

1.2. Problem Statement: Managing Storm Surge Barrier Upkeep

SSBs, like the proposed Bolivar Roads Gate System, are costly, long-lived structures with life spans of around 100 years (Walraven et al., 2022; Hamerslag and Bakker, 2023). Operating only under specific conditions (Mooyaart and Jonkman, 2017), their reliability and availability must be ensured throughout their life-cycle (Kharoubi et al., 2024).

Over this extended period, it is essential to maintain the barrier in optimal condition to ensure it continues to meet the specified requirements. It must provide the necessary level of safety while doing so at an acceptable cost. Over this period, changes in regulations, technology, and climate may affect the structure (Kamps, van den Bogaard, et al., 2024). In addition to the aging of the civil structure, the mechanical components, and the electrical systems, currently two challenges arise: the relatively short life-cycle of software regarding the rapid increase in high-tech innovation, and the limited institutional memory of the Operations & Maintenance (O&M) organization (Merrell et al., 2021). This makes the O&M of a barrier a complex undertaking, necessitating an object specific approach.

Current design plans prioritize construction, often neglecting how changing conditions, such as population growth, impact O&M (Nogueira and Walraven, 2018). This is critical, as O&M ensures the reliable functioning of SSBs. As well, changing conditions frequently lead to subsystem obsolescence. As seen in the Ramspol Barrier, where custom-made components caused O&M challenges (Walraven et al., 2022). Thus, changing conditions and high-reliability demands make O&M of SSBs both critical and complex (Jordan et al., 2019). To illustrate, local water level thresholds dictate closures and maintenance timing (Walraven et al., 2022; Trace-Kleeberg et al., 2023), while projected rising sea levels will increase closure frequency, duration, and narrow maintenance windows (Cumiskey et al., 2019; Trace-Kleeberg et al., 2023). Also, higher water levels accelerate deterioration (Haasnoot et al., 2020), adding to the total O&M costs, such as €15–20 million annually for the Maeslant Barrier (Trace-Kleeberg et al., 2023).

The changing conditions often require SSBs to be upgraded to meet new safety standards and increased operational demands for reliability and availability (Jonkman et al., 2016). But, many barriers, such as those in the Netherlands, were designed for a 100 year lifespan with conservative sea-level rise projections (Hamerslag and Bakker, 2023). Updated predictions suggest these barriers may reach their functional end of life sooner than anticipated (Hamerslag and Bakker, 2023).

Furthermore, barriers are often not designed to adapt to these dynamic conditions, complicating O&M (Walraven et al., 2022). Understanding the impact of external factors, such as sea-level rise and socio-economic changes, on SSBs design is crucial for its long-term functionality. That being so, current life-cycle methods often overlook uncertainties like environmental and societal challenges (De Neufville and Scholtes, 2011). As well, SSB performance suffers from fragmented governance, shifting policies, and funding uncertainties (Walraven et al., 2022), with past disputes highlighting the need for stability in O&M (DeSoto-Duncan et al., 2011).

In summary, SSBs exhibit unique characteristics that impact O&M, often leading to subsystem obsolescence. However, current design and planning processes prioritize the design-build phase, with minimal focus on operations-maintenance, leading to the following problem statement:

Traditional design approaches of storm surge barriers in coastal systems fail to address future external uncertainties and governance fragmentation, leading to performance issues that are intensified by the longevity and complexity of these structures.

1.3. The Objective: Maintenance by Design

Design decisions for SSBs, like the Bolivar Roads Gate System, heavily impact the O&M phase (Walraven et al., 2022). Leveraging the unique characteristics of SSBs (Kharoubi et al., 2024), and lessons from existing barriers, potential issues can often be anticipated, mitigated, or avoided (Walraven et al., 2022). Incorporating options for flexibility in design, such as adapting the SSB sill beam for increasing ship drafts (Ross, 2005), and prioritizing maintainability is a means to adress future external uncertainties and governance fragmentation. The research problem is addressed through the following main objective:

The objective of this research is to enhance the integration of maintenance and operational needs into the design and planning process of storm surge barriers, ensuring organizational stability and adaptable systems operations throughout their life-cycle in dynamic coastal environments.

This objective seeks to address the knowledge gap on uncertain system drivers affecting the design-build-operations-maintenance phases of SSBs. It focuses on O&M requirements to ensure organizational stability, continuity, and reliability. By bridging this gap, the study aims to clarify how system drivers, like climate change and socio-economic developments, impact these phases and how options for flexibility in SSB design strategies can enhance resilience against the impact of these system drivers. The Bolivar Roads Gate System serves as case study (refer to Section 1.1.2).

1.4. Research Question

This study focuses on movable SSBs in coastal areas, which are reinforcing for economic development (refer to Section 1.1.1). However, increasingly affected by storm surges, wave impacts, and sea-level rise (Bosboom and Stive, 2023). SSBs are selected due to their unique characteristics, including infrequent use under high-reliability demands (Walraven et al., 2022). Unlike navigation locks, designed for continuous operation with higher maintenance needs (Molenaar, 2020).

Major movable SSBs are typically designed for lifespans of around 100 years (Hamerslag and Bakker, 2023), such as the Eastern Scheldt Barrier with a 200-year design starting in 1986 (Nogueira and Walraven, 2018), and the Maeslant Barrier, which took over six years to build (Trace-Kleeberg et al., 2023). Physical- and socio-economic changes over these lifespans significantly affect O&M processes (Haasnoot et al., 2020; Trace-Kleeberg et al., 2023). These are expected to accelerate after 2050 and 2100 (IPCC, 2023). Hence, this research examines dominant uncertain physical- and socio-economic system drivers influencing the design-build-operations-maintenance of the Bolivar Roads Gate System up to 50 years, with a look through 150 years post-construction (see Figure 1.5).

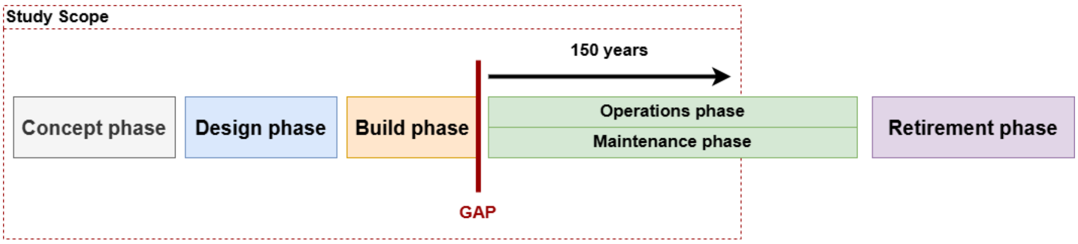


Figure 1.5: The lifespan of SSBs, with the time period of the research highlighted.

Following the research objective (refer to Section 1.3), this study aims to integrate options for flexibility in SSB design to address the impact of system drivers. This way optimizing the O&M phase. Thereby, Asset Management (AM) is crucial for SSBs, enabling O&M under budget constraints and uncertainties (Almeida et al., 2022). Leading to structured decision-making, which balances performance, risk, and resources to address (Shah et al., 2017). Given fragmented AM roles (Bakker and Cook, 2011), Institutional Logics can provide meta-level context by defining factors that guide legitimacy, as well as implicit and explicit values within organizations (Thornton et al., 2015).

Additionally, contracting strategies align stakeholder interests (Turner, 2017), establish governance mechanisms (Bakker and de Kleijn, 2018), and encourage long-term relational norms (Macaulay, 1999). These factors may integrates O&M into the design process, ensuring its continuity and stability throughout the SSB lifespan under changing conditions (Walraven et al., 2022). The main research question is formulated as follows:

How can flexibility in design, asset management, institutional logic and contracting form a integrated project delivery method to enhance operations & maintenance resilience and long-term performance of a storm surge barrier in a coastal system?

To address the main question, sub-questions are formulated for exploratory and explanatory purposes, enabling analysis through qualitative and quantitative methods. The study begins with SQ1, followed by SQ2, SQ3, and SQ4 in parallel, with their findings informing SQ5.

SQ1 What is the distribution of potential future scenarios for physical and socio-economic system drivers that the Bolivar Roads Gate System in the Houston-Galveston Bay Region may encounter over the next 150 years? (CE + CME)
SQ2 How can operational and maintenance requirements be most efficiently and effectively integrated into the barrier design and planning process to ensure optimized continuity and stability over the next 150 years? (CE + CME)
SQ3 Which specific component of the Bolivar Roads Gate System, as well as the overall system, offer design flexibility to address uncertainties over the next 150 years, and which components are anticipated to manifest flexibility? (CE)
SQ4 How do institutional logic, policies and contracting impact the flexible capacity and life-cycle of the storm surge barrier? (CME)
SQ5 What key findings, practical insights, and policy recommendations from the project delivery method enhance the operational resilience and increase the value of the Bolivar Roads Gate System? (CE + CME)

1.5. Scope and Research Approach

The design-build-operations-maintenance of a SSB are influenced by various system drivers. Integrating O&M requirements into the design and planning process, requires considering all these drivers. However, the long lifespan of SSBs makes it impossible to predict all future conditions with certainty. Integrating O&M into design and planning relies on anticipating future developments rather than precise long-term predictions (De Neufville and Scholtes, 2011). This research addresses uncertainty by developing strategies for a range of potential outcomes. After identifying a dominant system driver, one options for flexibility in design will be developed within the Bolivar Roads Gate System's current conceptual design as presented by the USACE in the Coastal Texas Study Report (USACE, 2021a). The research approach is visualized in a Flow Chart (see Figure 3.2 in Chapter 3), and elaborated on in Chapter 3, below briefly.

First, a functional analysis and physical decomposition of the Bolivar Roads Gate System's conceptual design (USACE, 2021a), provides a structured framework to identify system drivers influencing the SSB. Just a simple list of potential drivers risks missing critical interactions, complicating impact evaluations (Vader et al., 2023). The research scope and activities:

I *Perform a functional analysis and physical decomposition of the conceptual design of the Bolivar Roads Gate System (USACE, 2021a) (i.e., dictated to CE + CME);*

- The functional analysis establishes the SSB's functions and O&M requirements. This way providing criteria to evaluate system driver impacts. The physical decomposition identifies flexible design opportunities and breaks down the SSB into structural components, enabling precise identification of dominant external drivers.

Hydraulic structures, like SSBs, serve multiple functions, such as flood protection, navigation, and river discharge (Hamerslag and Bakker, 2023). Their performance, however, is influenced by system drivers. For example, sea-level rise can increase barrier closure frequency (Cumiskey et al., 2019).

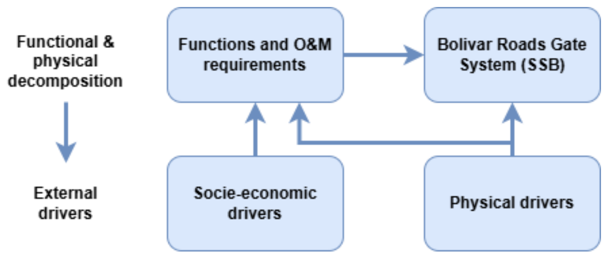


Figure 1.6: Framework of Vader et al. (2023) adjusted by S.D. van der Geer.

Using the baseline functions and O&M requirements, along with the constructued physical decomposition of the Bolivar Roads Gate System, enables evaluation of system drivers impacting its functional performance (see Figure 1.6). This analysis highlights potential effects on organizational stability and operational continuity (Vader et al., 2023; De Neufville and Scholtes, 2011), while identifying future scenarios (e.g., navigation changes, policy shifts) to understand potential outcomes. The research focus:

II *Identify and qualitatively analyze external drivers influencing the SSB's functional performance and O&M requirements. Compile and evaluate these drivers, then determine the most significant one through qualitative or quantitative analysis as needed (i.e., dictated to CE + CME);*

- Apply the method from Vader et al. (2023), combining qualitative evaluations with the semi-quantitative approach of De Neufville and Scholtes (2011) when qualitative insights are insufficient. This method identifies key drivers of the SSB by analyzing historical trends.

Maintaining SSB safety levels requires planning within an Asset Management (AM) framework (Jordan et al., 2019). AM ensures O&M activities are performed within budget and operational constraints (Kharoubi et al., 2024). For instance, during storm season (October 1st to April 14th), maintenance on the Maeslant Barrier is suspended (Trace-Kleeberg et al., 2023).

AM organizations face challenges like shifting operational conditions, limited resources, and knowledge weakening over an SSB's lifespan (Kharoubi et al., 2023). Evolving environmental conditions have also caused frequent subsystem obsolescence (Walraven et al., 2022). Identifying options for flexibility in design for the Bolivar Roads Gate System through functional analysis and physical decomposition enables adaptation to uncertain system drivers. This possibly ensures continuity in O&M activities and safeguards long-term performance (Walraven et al., 2022).

III *Identify the component, and develop an adaptable alternative (e.g., adaptable sill design) of the Bolivar Roads Gate System's conceptual design, based on functional analysis and physical decomposition, that provides the optimal flexibility to address the dominant system driver from the qualitative and quantitative analyses (i.e., dictated to CE);*

- Reassess the design space by assessing the dominant external driver with the Engineering System Matrix (ESM) method of Bartolomei et al. (2012), and the risk-susceptibility of Hu and Cardin (2015). This analysis will identify the most suitable options for flexibility in SSB design. Thereby considering SSB characteristics, uncertainty types, and modification costs. The outcome will be a worked out conceptual flexible design element, leveraging the Hydraulic Design Method by Voorendt (2022).

Flood defense AM faces technical and organizational challenges due to unique assets, multiple stakeholders, financial complexities, and high flood risk (den Heijer, Rijke, et al., 2023). Roles and responsibilities are often fragmented within and across organizations (Bakker and Cook, 2011), and large-scale projects, like SSBs, often lack alignment between delivery and long-term operation processes (Davies et al., 2009). Managing SSBs relies heavily on the expertise and engagement of personnel (Kuhn et al., 2021). Flexibility opportunities are not just technological but also social, extending design benefits into the future (De Neufville and Scholtes, 2011). Thus, clear guidance and strong support are essential for asset managers to implement flexibility as conditions evolve.

IV *Develop guidance for a project delivery method (PDM) based on the conceptual flexible design component, leveraging the standardized mega-project processes of Davies et al. (2009), and contracting strategies as described by Bakker and de Kleijn (2014) and Bakker and de Kleijn (2018). This guidance will align with the existing project organization (i.e., dictated to CME);*

- Review current AM principles and formulate prescriptive strategies. Analyze institutional logic, contract, and procurement strategies to guide stakeholder arrangements. Monitor key conditions to determine when and how to implement design flexibility, adapt to changes, and develop organizational maturity (De Neufville and Scholtes, 2011). Extract recommendations from practical insights gained from the Bolivar Roads Gate System case to propose a PDM.

1.6. Application of Research Theories

As discussed in Section 1.1, SSBs are unique prototypes with distinct characteristics operating in dynamic environments. They function as both components of a broader flood defense system (Jonkman, Hillen, et al., 2013), and as systems of subsystems. Mooyaart and Jonkman (2017) states this requires collective analysis to assess potential failures. Beyond flood protection, SSBs are multifunctional, supporting navigation, delta development, and economic growth (Meyer and Nijhuis, 2013). Their design and operation involve diverse stakeholders with sometimes competing interests.

Engineering Systems Theory systematically addresses this technical complexity, social intricacy, and processes of large-scale systems. Applied to the Bolivar Roads Gate System, it provides a broad view of domains (e.g., environmental), components, and interrelationships. This way enabling identification of complexities, path dependencies, and system changes (refer to Appendices A.1 and A.1.1).

- *Engineering Systems*: is a multidisciplinary framework examining the intersection of engineering, management, and social sciences in complex systems (Bartolomei et al., 2012). It develops theories to analyze, design, deploy, and manage systems, focusing on how components interact to form a cohesive whole (De Neufville and Scholtes, 2011);
- This field integrates work from Technology and Policy, Systems Engineering, Decision Analysis, Operations Research, Engineering Management, Innovation, Entrepreneurship, and Industrial Engineering (De Neufville and Scholtes, 2011; Bartolomei et al., 2012). Engineering Systems aids in understanding uncertainties and interdependencies across life-cycle phases (Design, Build, Operate, Maintain) of storm surge barriers. It views the barrier as a complex system with interacting components and supports sub-questions 1, 2, and 3.

Institutions, such as the U.S. Army Corps of Engineers (USACE), are human-established structures of rules and norms regulating behavior within systems like the Bolivar Roads Gate System (North, 1991). Institutional Logic Theory examines institutional creation, change, and persistence, emphasizing the implicit role of culture (Thornton et al., 2015). Institutional Logics can conflict, coexist, or blend, helping navigate governance challenges (Coenen et al., 2023). This is vital for O&M resilience (Kuhn et al., 2021), and the long-term performance of the Bolivar Roads Gate System (refer to Appendix A.2).

- *Institutional Logic*: is a concept in sociological and organization studies. It focuses on how broader belief systems shape the cognition and behavior of actors (Coenen et al., 2023);
- Institutional Logic examines how organizations like the USACE, influence long-term arrangements and design flexibility of the SSB. This theory supports sub-questions 1, 2, 4, and 5.

SSBs, as public infrastructure, require substantial investments for construction (Mendelsohn et al., 2022) and O&M (Aerts, 2018). Organizations managing such mega-projects face dynamic complexities (Bosch-Rekveldt et al., 2011), including a disconnect between delivery processes and long-term operations (Davies et al., 2009). Contract Theory addresses complexities, can align stakeholder interests (Turner, 2017), and establishes governance mechanisms (Bakker and de Kleijn, 2018) for the Bolivar Roads Gate System (refer to Appendix A.3).

- *Contract Theory*: provides a framework for addressing the dynamic complexities of mega-projects by guiding stakeholder arrangements and governance mechanisms;
- Contract Theory addresses the disconnect between project delivery and long-term operations, aligns stakeholder interests, and develops governance structures for the Bolivar Roads Gate System. It informs sub-questions 2, 4, and 5.

1.7. Reading Guide

Chapter 2 (Literature Review) identifies knowledge gaps in current understanding of SSBs; Chapter 3 (Methodology & Theoretical Framework) introduces the *“Flexibility in Engineering Design”* framework, and outlines the four-phased methodology; Chapter 4 (Phase 1: A Baseline Design of the Bolivar Roads Gate System, dictated to SQ2) analyzes the baseline design of the Bolivar Roads Gate System; Chapter 5 (Phase 2: The Shape of Uncertainty, dictated to SQ1) examines system drivers that affect SSB functional performance; Chapter 6 (Phase 3: Options for Flexibility in Design, dictated to SQ3) develops adaptable SSB design options and a corresponding AM strategy; Chapter 7 (Phase 4: Implementing Flexibility, dictated to SQ4) proposes a PDM that defines public accountability; Chapter 8 (Discussion) reflects on the methodology and research findings; Chapter 9 (Conclusion) answers the main research question and SQ5; Chapter 10 (Recommendations) offers directions for future research.

2 Literature Review

This chapter sets the Literature Review. Thereby investigating SSB knowledge gaps, connecting the research objective from Chapter 1 to existing body of knowledge. These findings further frame the research focus. The Literature Research Methodology is detailed in Appendix B. These findings collectively construct the Theoretical Framework in Chapter 3.

The Literature Review builds upon the study's theoretical theories: Engineering Systems (ES), Institutional Logics, and Contract Theory (refer to Appendix A). Section 2.1 examines SSB objective in mitigating flood risks. Section 2.2 describes design considerations, supporting guidance for options for flexibility in SSB design. Section 2.3 examines Operations & Maintenance (O&M) strategies for SSBs, focusing on the infrequent yet critical operations. Section 2.4 reviews existing Asset Management (AM) frameworks, emphasizing risk-based approaches in the Netherlands and the U.S.. Section 2.5 explores stakeholder practices in SSB projects, offering insights for the Bolivar Roads Gate System. Section 2.6 assesses applied project delivery method (PDM) on global SSBs.

2.1. The Unique Characteristics of Storm Surge Barriers (SSB)s

SSBs are large, movable flood defenses that close off estuarine areas during storm surges (Mooyaart and Jonkman, 2017). Unlike conventional hydraulic works, SSBs operate infrequent under high-reliability demands within socio-technical networks (Kharoubi et al., 2024; Walraven et al., 2022). Designed for lifespans up to 200 years (McRobie et al., 2005), they must adapt to system drivers, like intensifying storms. Relative sea level change may necessitate more frequent closures and tighter maintenance periods (Trace-Kleeberg et al., 2023).

SSBs require decision-making across multiple subsystems like structural, mechanical, and control systems, while governance constraints determine Operations & Maintenance (O&M) (Kharoubi et al., 2024). Resulting in balancing robust over-engineering for extreme storm events with being adaptable to uncertain future conditions (De Neufville and Scholtes, 2011). Investments in design robustness increase performance (DeSoto-Duncan et al., 2011), but they risk design lock-in (Walraven et al., 2022). In contrast, options for flexibility in design support adaptation but increase governance complexity and O&M costs, depending on system scale (Aerts, 2018). This trade-off has implications for the design process, as early-design decisions must balance immediate safety with adaptability.

Existing research analyzed individual barriers, covering costs (Jonkman, Hillen, et al., 2013), design configurations (Mooyaart and Jonkman, 2017), sea-level rise impacts on maintenance (Trace-Kleeberg et al., 2023), and closure frequency (Chen et al., 2020; Mooyaart et al., 2025). These studies highlight the complexity of SSB design and operations, requiring multi-disciplinary expertise. Despite case-specific insights, system-level analyses integrating design, governance, and O&M remain underexplored as stated by Walraven et al. (2022). This gap limits the ability to develop combined strategies of design and O&M that ensure long-term functionality, leading to fragmented decision-making.

While SSB design and O&M separately are widely studied, few works integrate both over the long SSB lifespan. Moreover, Kamps, van den Boomen, et al. (2024) states that maintaining organizational learning, stable O&M budgets, and technical expertise over time remains a challenge. Further, SSBs increasingly rely on electrical control systems that become obsolete faster than mechanical components (Walraven et al., 2022). Yet research on SSB component life-cycle management is limited. Although adaptive design thinking is increasingly encouraged, the trade-off between robust construction and phased adaptation remains unclear (De Neufville and Scholtes, 2011). Furthermore, comparative case studies could clarify how different SSB design and O&M strategies perform across environmental and economic contexts. This highlights the need for an integral approach.

2.2. Design Considerations of SSBs

SSBs are typically located in coastal zones where natural processes, such as tides, and waves, interact with densely populated urban areas and vital economic infrastructure (Small and Nicholls, 2003; Mooyaart and Jonkman, 2017). This heightens both their importance and design complexity. This increasing complexity stems not only from intensifying physical processes (e.g., rising sea levels and more frequent storms) but also from socio-economic developments such as rapid urban expansion in low-lying areas (Neumann et al., 2015). SSBs serve as effective flood mitigation tools (IPCC, 2023), however, an over reliance on these “hard” infrastructure solutions may create a false sense of security. Thereby delaying necessary adaptive land-use changes and reducing long-term resilience (Haasnoot et al., 2020). SSBs can be integrated into multi-layered defense strategies, combining structural measures (e.g., levees and dunes) with ecological interventions (e.g., wetland restoration).

Designing an SSB involves balancing multiple, and often competing, criteria. Four key considerations are identified in the literature: navigation and flow section, structural foundation requirements, safety standards, and probabilistic risk assessment (Mooyaart and Jonkman, 2017; Jonkman et al., 2016). First, navigation and flow sections, determined by vessel dimensions and tidal requirements, directly influence gate geometry and costs. Wider openings improve tidal exchange and environmental connectivity, but they significantly raise structural complexity and construction costs. Second, structural foundations must withstand loads from gate movement, waves, and seismic forces, particularly in soft delta soils (Jonkman and Schweckendiek, 2015).

Third, barriers must meet strict safety standards, which vary: U.S. barriers target 100- to 500-year return events (Morang, 2016). In contrast, Dutch barriers aim for 10,000-year events (Mooyaart and Jonkman, 2017). This variation reflects differing risk tolerances and socio-political priorities. The Dutch approach, though more conservative, may offer greater long-term protection. However, at higher upfront cost. Fourth, probabilistic methods like Fault Tree Analysis (FTA) may assess SSB failure modes (Jonkman et al., 2016), all giving guidance to design. Research on functional performance of SSBs identify closure or opening failures as critical risks (Mooyaart et al. (2023)). These failure modes are driven by gate design, control systems, and human decisions. These operational failures highlight a growing awareness that design must account for human-system integration.

While probabilistic modeling is a standard approach to quantify SSB failure risks, these models often oversimplify reality by assuming static conditions. Thereby overlooking dynamic institutional and human factors. To illustrate, most studies quantify physical parameters (i.e., tidal ranges, surge heights, wave forces) (Mooyaart and Jonkman, 2017), but treat human and institutional factors as secondary. Yet, operational reliability depends on forecasting, maintenance, and governance. Despite the centrality of these factors in real-world operations, they are often treated as secondary in technical models. This reveals a disconnect between design and socio-institutional realities, a gap identified by recent studies of Walraven et al. (2022) and Hamerslag and Bakker (2023).

In summary, while considerable attention has been paid to the technical and hydrodynamic design of SSBs, gaps remain in understanding how social, institutional, and operational dimensions shape their long-term O&M performance. Limited attention to adaptive maintenance, retrofitting, and human-system integration hampers O&M integration in design and planning processes. Addressing these gaps possible could enhance operational resilience and adaptability in the face shifting condtions.

2.3. The Operations & Maintenance Phase of SSBs

SSBs close during rare, but extreme storm events, requiring high-reliability despite infrequent use (Mooyaart and Jonkman, 2017). This contradiction, demands absolute operational performance during rare events. This makes reliability not just a design issue but an organizational challenge. Unlike navigation locks, SSBs demand sustained readiness and knowledge retention (Walraven et al., 2022; Kamps, van den Boomen, et al., 2024). The interdependence of electrical, hydraulic, and mechanical subsystems means that even minor faults can cascade (Lewin et al., 2003), increasing the stakes for continuous O&M planning. To maintain operational readiness, strategies such as routine servicing, condition-based inspections, and targeted upgrades needs to be employed, tailored to the failure profiles of critical components (Walraven et al., 2022). Hybrid and failure-based models offer economic efficiencies (Schiereck and Verhagen, 2019; Vrijling et al., 2015), but their limited applicability to high-risk components, like the Maeslant Barrier ball-joints, underscores the need for predictive systems that account for deterioration patterns.

Maintainability design factors may minimize downtime and streamlines repairs across a system's life-cycle (Dhillon, 1999). For SSBs, interchangeable parts, accessible components, and testable subsystems may reduce operational failure during extreme weather events. Early integration of maintainability principles not only supports preventive O&M strategies but may also facilitates long-term adaptable design options. Such as retrofits in response to sea-level rise. Designing for accessibility ensures rapid inspections and component swaps (Dhillon, 1999). This is especially important in regions with short storm warning times, where delays in inspection or repair can compromise barrier functionality. This aligns with "Maintenance by Design" concept, where operational and maintenance needs drive engineering decisions (Walraven et al., 2022).

While studies model risks related to hydraulic systems (Mooyaart et al., 2023; Mooyaart et al., 2025), they often treat these elements in isolation from organizational and human factors. For example, inter-organizational collaboration. SSB structural and mechanical studies often overlook governance, which is deemed essential for O&M. This gap reveals a divide, where engineering and policy operate in isolation, reducing the effectiveness of integrated O&M. Maintenance research details best practices, it prioritizes specific tasks (e.g., repainting, part replacement) over an overall O&M strategy development. Following this, just a few studies assess climate change impacts on O&M. Recent work by Trace-Kleeberg et al. (2023) and Vader et al. (2023) attempts to address these limitations, but findings remain fragmented and lack standardized metrics for maintenance regime effectiveness.

The constant separation of technical and institutional perspectives hampers the development of integrated O&M strategies. In light of escalating climate stressors and aging infrastructure, integrated maintenance approaches are increasingly essential within design and planning processes of SSBs. Although each SSB presents unique challenges, the lack of transferable frameworks for maintainability knowledge sharing constrains cross-project learning. Bridging this gap could enhance the integration of O&M considerations in early design.

2.4. Asset Management (AM) of SSBs

SSBs follow life-cycle phases, from concept development to retirement, aimed at balancing technical-, functional performance, and economic value (Bakker and de Kleijn, 2018; Hamerslag and Bakker, 2023). This approach is formalized in AM. AM uses risk-based planning to align O&M with regulatory standards and performance requirements (Kharoubi et al., 2023). Due to site-specific complexities, SSBs need tailored AM approaches (Herder and Wijnia, 2012). This need for tailoring reflects the environmental, and socio-political differences across coastal regions. This complicates efforts to apply generic AM models. For example, the Netherlands Probabilistisch (risicogestuurd) Beheer en Onderhoud (ProBo) framework, applies Plan-Do-Check-Act (PDCA) cycles and FTA to uphold safety requirements (van den Bogaard and van Akkeren, 2011). These systems are heavily data-dependent, creating challenges in terms of cost, data quality, and technical capacity. Also, the U.S. Army Corps of Engineers (USACE) prioritizes risk-based maintenance (Connelly et al., 2016; Leitch and Ellsworth, 2016), yet the USACE framework tends to under represent the socio-technical dynamics that are critical to SSB functional performance, as highlighted by proceding literature findings.

Both ProBo and the USACE frameworks demonstrate strength in systematic risk evaluation, offering structured metrics for decision-making and resource prioritization. This approach promotes rational fund allocation and enhances transparency in measuring infrastructure performance. They embed iterative improvement cycles, adapting to evolving operational contexts. Despite these strengths, risk-based AM remains limited by high data demands and the need for regular calibration. Additionally, institutional inertia can hinder improvement, favoring static procedures (van den Bogaard and van Akkeren, 2011). These frameworks tend to emphasize short-term safety and economic efficiency at the expense of long-term O&M. AM frameworks often treat options for flexibility in design as secondary (Ajah and Herder, 2005). However, accelerating climate change could leave SSBs obsolete faster than expected. The literature calls for explicit “future-proofing” (Trace-Kleeberg et al., 2023), embedding systematic re-evaluation to adapt SSBs to emerging physical- and socio-economic system drivers.

While ProBo and USACE use iterative risk-based approaches, neither fully integrates design and O&M. For example, embedding options for flexibility in design in early planning could facilitate mid-life upgrades.This narrow focus limits responsiveness of these AM frameworks to transformations in ecological shifts or urban expansion. Implementing advanced AM systems like ProBo necessitates organizational restructuring, clearly defined roles, and ongoing workforce training (van den Bogaard and van Akkeren, 2011). Guidance for managing these cultural shifts remains under-explored.

2.5. Multi-Actor Management in Flood Defense Asset Management

Social complexity in SSB projects arises from diverse stakeholder goals (den Heijer, Podt, et al., 2023), fragmented authority (Bakker and Cook, 2011), and high safety standards. Public agencies prioritize safety, while businesses focus on economic continuity (Coenen et al., 2023). Thereby creating role conflicts in coastal planning (Vonk et al., 2020). Multi-actor management can give guidance on collaboration through structured *“network management”* (de Bruijn and ten Heuvelhof, 2008). Aligning flood safety with various stakeholder goals. This requires a high degree of organizational maturity, where clarity in role distribution across strategic, tactical, and operational levels reduces friction and inefficiencies (den Heijer, Rijke, et al., 2023). For example, an *“asset owner”* (i.e., government ministry) sets safety targets, an *“asset manager”* (i.e., regional authority) plans maintenance, and a *“service provider”* (i.e., contractor) executes maintenance tasks while informing decision-making.

Multi-actor management reduces coordination failures and creates shared ownership (de Bruijn and ten Heuvelhof, 2008). Emphasizing participation and cooperation over top-down approaches (Cumiskey et al., 2019). However, political inertia resists authority redistribution, and multi-actor processes demand skilled facilitation. Success depends on trust, which is often weak in fragmented environments (den Heijer, Rijke, et al., 2023). de Bruijn and ten Heuvelhof (2008) warns multi-issue coalitions may delay action. In flood defense, emergencies, like SSB operations, require rapid decision-making that multi-actor frameworks struggle to accommodate.

Studies advocate adaptability in multi-actor management, however, few detail how to embed this across an SSB’s life-cycle. Gaps remain in contract strategies, performance metrics, and leadership structures. Multi-actor frameworks assume extended negotiations, yet flood-risk scenarios demand rapid intervention. Research highlights decision-making maturity at strategic, tactical, and operational levels, but empirical studies on organizational progression remain under-explored. Addressing these gaps is important to optimizing flood defense AM. Because, in complex settings, like the Bolivar Roads Gate System, structured collaborative governance can enhance resilience. Through clear accountability and timely decision-making.

2.6. Project Delivery Methods (PDM) for SSBs

Contracts like lump-sum, or reimbursable determine risk allocation and incentives (Bakker and de Kleijn, 2014; Smith, 2002). For SSBs, scope uncertainties and changing conditions pose unique challenges, fixed-price contracts may limit options for flexibility in design. More suitable PDMs, includes design-bid-build (DBB), design-build (DB), Engineering, Procurement, and Construction (EPC), and relational models (e.g., alliances), emphasizing stakeholder collaboration (KPMG, 2010).

Strong client-contractor relationships can give guidance to options for flexibility in design. This way sharing the risks of SSBs evolving demands. These mega-projects face changing technological and organizational complexities. These are compounded by long-lasting schedules and unique socio-economic stakes (Bosch-Rekveldt et al., 2011; Hertogh and Westerveld, 2010). As highlighted by proceeding literature findings. To cope with these complexities, Davies et al. (2009) states to standardize risk management, digital design, and logistics to keep in check cost overruns. Also system integrators must align specialized suppliers with long-term operational needs for long-term asset performance (Davies et al., 2009).

SSB case studies highlight PDM trade-offs. The Maeslant Barrier (Netherlands) used Design-Build with a short-term maintenance clause. Thereby neglecting long-term O&M needs (Kamps, van den Bogaard, et al., 2024). Also, The Lake Borgne Surge Barrier (U.S.) prioritized fast-track DB for immediate protection. Introducing future design inflexibilities (Huntsman, 2012; Schwartz and Schleifstein, 2018). The Ipswich Tidal Barrier (UK) employed NEC3 contracts. Promoting cost-sharing and proactive risk management (Usborne, 2019). Resulting in cost savings and proactive issue resolution. The Singapore's Marina Barrage, built via DBB, benefited from strong oversight by the public agency. Integrating flood protection, water supply, and recreation (Moh and Su, 2009). These cases show rigid contracts limit adaptability, critical for infrastructure facing long-term uncertainty. Incentive-based models support iterative design but require strong governance to prevent scope creep and budget inflation (Bakker and de Kleijn, 2018).

Thus, Design-Build and integrated contracts combine responsibilities, but few SSB projects embed O&M from the start. Research on DBO and DBFM/O for SSBs is limited, underscoring the need to investigate the integration of maintainability and design options into contracts. Many agreements remain rigid, lacking renegotiation, re-scoping, or design options. In addition, contract effectiveness studies are often descriptive rather than evaluative. A guidance framework assessing project complexities, and maintainability across PDMs could improve valuing of options for flexibility in design. Advancing PDMs that embed options for flexibility in design, maintainability, and stakeholder alignment seems essential given SSBs complexity, and long lifespan.

2.7. Summary and Conclusions

The Literature Review highlights a storm surge barrier (SSB) as large, long-lived, and complex infrastructures in dynamic coastal environments. Literature separately covers design, Operations & Maintenance (O&M) disputes, and risk-based Asset Management (AM), but gaps remain in integrating these over an SSB life-cycle. First, technical and organizational fragmentation hinders coordination between design, operations, and maintenance. Thereby reducing adaptability to changing conditions, leading to rigid, lock-in SSB designs. Second, probabilistic models and risk-based frameworks (e.g., ProBo) enhance reliability but often overlook institutional, contractual, and stakeholder factors. Literature showed that these are important for continuous performance. Third, while multi-actor collaboration research stresses structured engagement, most frameworks lack guidance on embedding options for flexibility in design together with governance into daily project delivery.

These findings show the significance of an integrated and life-cycle oriented approach regarding the unique SSB characteristics. Hence, not solely focusing on mitigating all possible uncertainties in the preliminary design. In other words, SSB design must incorporate maintainability and operational insights from the outset. Thereby preventing early design-locking. Addressing these gaps requires guidance on (I) embedding maintainability principles to cope with subsystem obsolescence, (II) integrating multi-actor management processes that align diverse stakeholders, and (III) crafting PDMs that accommodate the unique SSB characteristics by determining clear accountability allocation.

This Thesis contributes new knowledge by developing a PDM specifically tailored for SSBs. Thereby linking options for flexibility in SSB design to AM, and project delivery. In doing so, this research aims to explore the under-researched disconnect between construction-phase decisions and operational-phase challenges. Through the Bolivar Roads Gate System case study, it can offer empirical insights on how to structure governance, accountability allocation, and options for flexibility in design over time.

3 Methodology & Theoretical Framework

This chapter presents the *“Flexibility in Engineering Design”* Framework, and explains how variables guide the sub-research questions. Next, this chapter presents the overall methodological approach. Building on the Theoretical Framework, it outlines the four-phase research design based on the *“Flexibility in Engineering Design”* Framework. Each research phase is briefly introduced to show its role within the overall approach. Specific methods of data collection, -analysis, and -design (i.e., Phase 3) are detailed per phase in the corresponding chapters. The methodology is evaluated and justified in the Discussion (refer to Chapter 8).

3.1. Flexibility in Engineering Design Framework

Building on the theories introduced in Section 1.6 namely Engineering Systems (ES), Institutional Logic, Contracting, and the insights from the Literature Review in Chapter 2, this study acknowledges that a storm surge barrier (SSB) consist of subsystems (e.g., fixed, movable, and electrical parts), and is subject to evolving system drivers. According to De Neufville and Scholtes (2011), systems such as SSBs can be classified as Engineering Systems (ES). As elaborated by Bartolomei et al. (2012) such systems are characterized by technical sophistication, social complexity, and integrated functionality (refer to Appendix A.1).

This study adopts the ES definition by De Neufville and Scholtes (2011) due to its emphasis on the holistic analysis of technical, social, and institutional interdependencies, characteristics that typify SSBs. The Institutional Logic framework proposed by Coenen et al. (2023) complements De Neufville and Scholtes (2011) perspective by addressing governance challenges intrinsic in socio-technical systems (refer to Appendix A.2). Contract Theory, as discussed by Bakker and de Kleijn (2018), provides a viewpoint to examine embedded project complexities in the delivery of SSBs (refer to Appendix A.3).

To meet the research objective, this study applies the *“Flexibility in Engineering Design”* framework developed by De Neufville and Scholtes (2011), which outlines a four-phased approach to develop options for flexibility in ES. This framework, supplemented with Institutional Logic and Contract Theory, is particularly suited to the SSB context given the high stakes of coastal flood protection, long system lifespans, substantial public investment, and evolving governance environments. The four-phases, inline with the research activities of Section 1.5 (see Flow Chart in Figure 3.2) are:

1. *Baseline Design (Activity I):* establishes the reference design space for the Bolivar Roads Gate System by clarifying design considerations, interconnected subsystems (e.g., gated-, dam-, and lock sections), and Operations & Maintenance (O&M). This phase forms the solution space for analyzing system drivers in later stages and informs all sub-questions (SQs), in particulair *SQ2*;
2. *The Shape of Uncertainty (Activity II):* identifies physical and socio-economic system drivers that may affect the barrier’s operational performance over its life-cycle, addressing *SQ1* through SQ4;
3. *Options for Flexibility in Design (Activity III):* explores opportunities for design adaptability and develops alternative concepts to respond to the identified uncertainties, supporting *SQ3* and SQ4;
4. *Implementing Flexibility (Activity IV):* provides guidance for the project delivery through system integration, contractual-, and governance approaches, addressing SQ2, *SQ4*, and SQ5.

Figure 3.1 presents a condensed version of the Theoretical Framework. It highlights the main variable types and the relationships structuring the four phases. This visualization demonstrates how each variable set contributes to answering the sub-research questions (i.e., SQ1–SQ5). This framework streamlines the broader Theoretical Framework described in Appendix C. In Appendix C all relevant variables are stated for application in the methodological approach (see Flow Chart in Figure 3.2).

3.2. Methodological Approach

To recall, coastal regions like Houston-Galveston Bay face growing flood risks from hurricanes, yet SSBs, though protective, are often designed and planned with short-term focus. Thereby neglecting O&M. To investigate this problem the following research question was investigated: *"How can flexibility in design, asset management, institutional logic, and contracting enable an integrated delivery method for resilient, long-term operations & maintenance of a coastal storm surge barrier?"* To answer the research question this study applied the *"Flexibility in Engineering Design"* Framework (refer to Section 3.1), resulting in the following methodological approach, which is inline with the activities of Section 1.5 (see Flow Chart in Figure 3.2). Below briefly and detailed per phase in corresponding chapter.

Phase 1: Baseline Design (Activity I) aimed to characterize the Bolivar Roads Gate System to define the solution space for Phases 2 and 3. This characterization constrained the identification of system drivers in Phase 2 and the exploration of options for flexibility in design in Phase 3. The analysis used secondary qualitative and quantitative data (e.g., Coastal Texas Study Report (2021)) validated through primary interview data. Phase 1 applied the Systems Engineering (SE) methodology outlined by de Graaf (2014). Activities included: (I) boundary condition mapping, (II) stakeholder analysis, (III) functional analysis using Functional Breakdown Structure (FBS), and (IV) function allocation to SSB components through a System Breakdown Structure (SBS). For a detailed description of the Phase 1 methodology refer to Section 4.1.

The goal of *Phase 2: The Shape of Uncertainty (Activity II)* was to identify causal relationships between system drivers in the Houston-Galveston Bay Region and the performance of Bolivar Roads Gate System, focusing on Floating Sector Gates. These relationships informed the options for flexibility in design explored in Phase 3. The analysis used secondary qualitative and quantitative data (e.g., environmental reports, economic trends) validated through primary interview data. Building on the solution space defined in Phase 1 the method of Vader et al. (2023) was applied. System drivers were assessed through (I) historical trends, (II) forecast uncertainties, and (III) impacts on SSB performance, resulting in a shortlist of dominant drivers. Lastly, (IV) four delta scenarios were developed to identify the most critical system drivers. For a detailed overview of the Phase 2 methodology refer to Section 5.1.

Phase 3: Options for Flexibility in Design (Activity III) aimed to establish causal relationships between the governing system drivers identified in Phase 2 and barrier components most affected, with a focus on designing an adaptable component. A topic still underexplored in current literature. Building on the outputs of Phases 1 and 2 this phase used primary interview data alongside secondary sources, including construction costs, technical specifications from the Coastal Texas Study Report, and technical manuals. Applying the Engineering System Matrix (ESM) framework from Bartolomei et al. (2012), (I) dependencies between dominant system drivers and SSB components were mapped. Interview data were thematically analyzed to assess these dependencies. (II) Combined with unit-cost shares using the risk-susceptibility method of Hu and Cardin (2015), this resulted in a ranked list of flexible SSB component options. Finally, (III) four conceptual sill designs were developed based on the Hydraulic Design Method. For a detailed description of the Phase 3 methodology refer to Section 6.1.

The goal of *Phase 4: Implementing Flexibility (Activity IV)* was to characterize the public client's accountability in the project delivery of storm surge barriers by synthesizing insights from the previous phases. This phase relied on secondary data including academic literature on project complexity, dynamic project conditions, and lessons from past mega-projects. Three qualitative steps were conducted: (I) project complexity mapping based on Hertogh and Westerveld (2010), (II) a "Make" or "Buy" assessment using the Kraljic Matrix, and (III) integration of findings into a conceptual project delivery method (PDM). For a detailed overview of the Phase 4 methodology refer to Section 7.1.

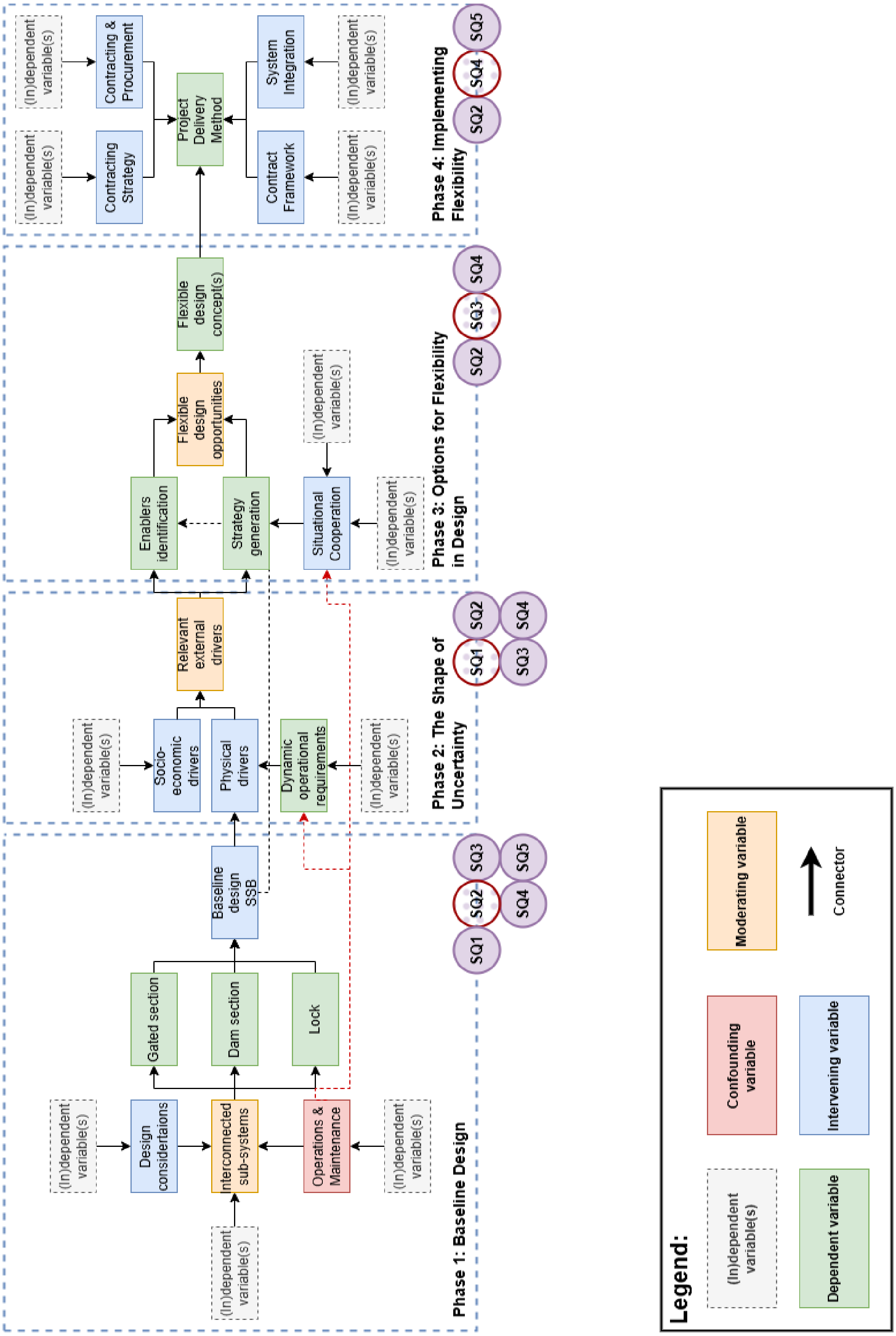


Figure 3.1: Compressed version Theoretical Framework (refer to Appendix C).

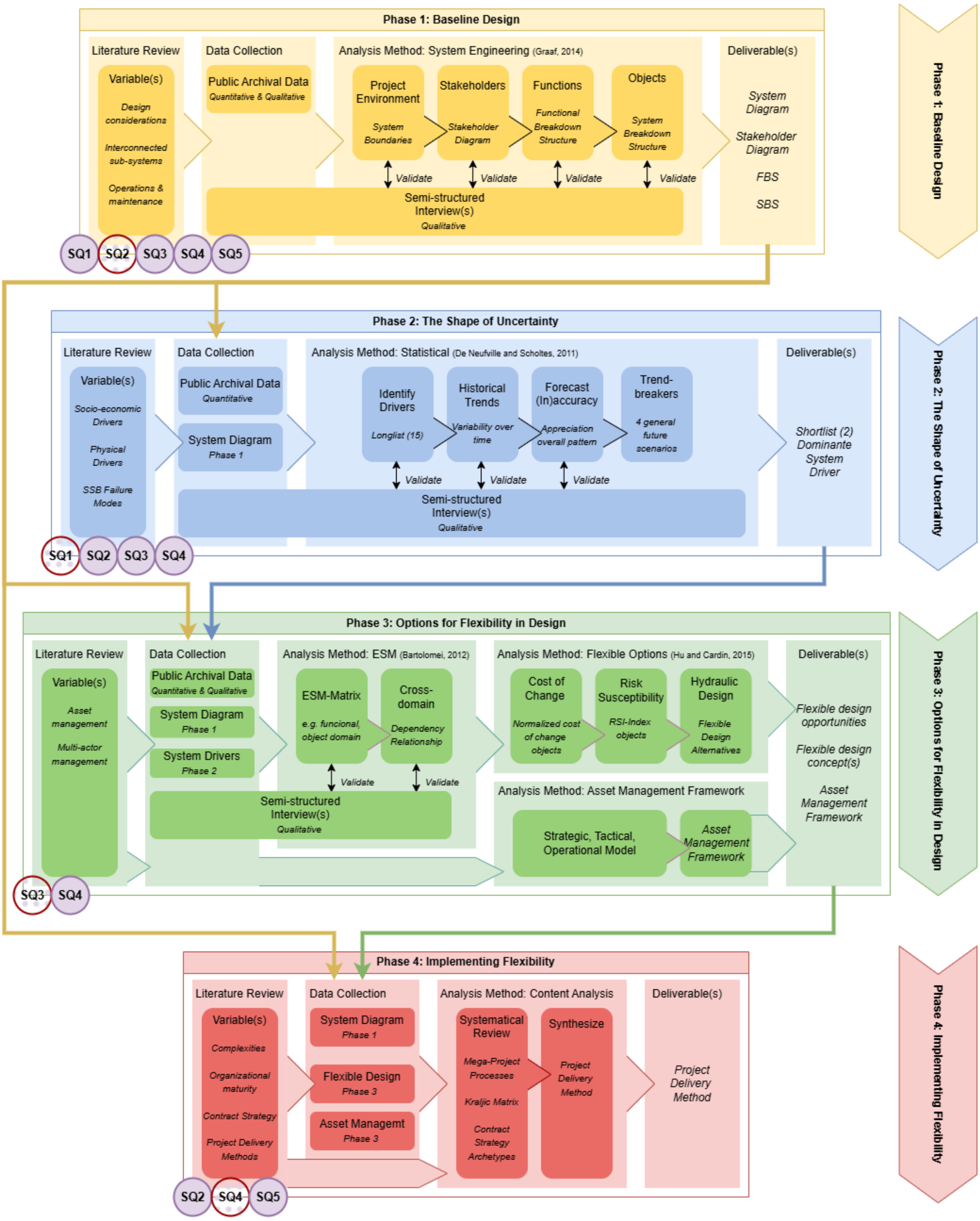


Figure 3.2: Research Design - Flexibility in Engineering Design.

4

Phase 1: A Baseline Design of the Bolivar Roads Gate System

The goal of Phase 1 is to conduct a system analysis of the Bolivar Roads Gate System (i.e., dictated to CE + CME). This serves as the solution space for research Phases 2 and 3. This chapter set the base for answering sub-questions (SQ's) 1 to 5, particular SQ2. Thereby defining the system's technical, functional, environmental, and social dimensions. Based on the Literature Review (refer to Chapter 2), storm surge barrier (SSB)s are unique: they have a long lifespan, operate rarely but must ensure high reliability. This creates a difficulty how to define a maintenance policy early in the design process, as future impact of system drivers on the functional performance remains partly unknown. Each design layout reveals different maintenance demands. This chapter explores which maintenance policy best fits SSBs, considering failure consequences and component degradation.

This chapter begins with the methodology (Section 4.1), followed by an analysis of the environmental and socio-economic context of Bolivar Roads (Section 4.2). Stakeholder dynamics are mapped (Section 4.3), after which the functions of a SSB, specifically for Bolivar Roads, are defined (Section 4.4). The chapter then presents the physical breakdown of the Floating Sector Gates (Section 4.5), linking the Functional Breakdown Structure (FBS) to the System Breakdown Structure (SBS), and concludes with an exploration of the needed maintenance policy (Section 4.6), based on the FBS and SBS.

4.1. Research Methodology

The baseline design was important for structuring the design space and guiding subsequent research phases 2 and 3. Phase 1 activities included: (I) data collection, (II) mapping environmental, (III) -social, (IV) -functional, (V) -process, and (VI) -technical domains. This to identify components sensitive to system drivers in subsequent Phase 2. Systems Engineering (SE) by de Graaf (2014) structured this analysis. Thereby, integrating social, environmental, and technical factors into a comprehensive System Diagram, based on the current conceptual Bolivar Roads Gate System design as presented in the Coastal Texas Study Report (USACE, 2021a).

The SE approach, less common in coastal flood protection than in aerospace contexts, emphasized cross-domain interactions in line with Engineering Systems (ES) theory (refer to Appendix A.1). Combining interviews with quantitative data reduced the risk of overlooked design aspects. Expert feedback helped validate the baseline concept. These combined findings were integrated into the System Diagram, FBS, and SBS. Please refer to Appendix D.1 for an elaboration on the research methodology of Phase 1. Below stated briefly.

4.1.1. Data Collection Method

Information from archival data established the technical and functional domains of the baseline design. While expert interviews validated system boundaries, uncovered stakeholder priorities, and clarified operational practices, refer to Figure 4.1.

Existing Data

Phase 1 leveraged mainly public archival data, especially USACE feasibility studies and academic articles on SSBs (refer to Appendix D.1). Sources comprised technical, environmental, social, or functional aspects of the proposed design. Priority was given to post-2019 materials to reflect the current situation (anno 2025). Though earlier documents offered historical context. Only data providing sufficient detail on design parameters, system boundaries, or stakeholder perspectives were included. By that, prioritizing peer-reviewed publications and official agency reports for accuracy.

Semi-Structured Interviews

To complement archival data, semi-structured interviews, together conducted with Phase 2 and 3, provided expert insights on operational constraints, maintenance, and stakeholder dynamics in the Houston-Galveston Bay Region. Participants were selected based on expertise in SSBs. Particularly those involved in the Bolivar Roads project. Through thematic analysis of these interviews (i.e., identify common themes) the System Diagram, FBS, and SBS were validated. Refer to Appendix G for the interview transcripts and elaboration on the thematic analysis.

4.1.2. Applied Method

Phase 1 applied Systems Engineering by de Graaf (2014) to structure the baseline design, refer to Figure 4.1. The activities involved (I) analyzing the project environment (i.e., environmental constraints), (II) conducting stakeholder analysis (i.e., dynamic mapping), (III) defining SSB functionality (i.e., FBS), and (IV) developing the SBS to link functions to physical components. Archival data informed these steps through source review. Interviews validated and enriched findings. The key deliverables: baseline System Diagram, stakeholder diagram, FBS, and SBS, combined gave a conceptual view of the Bolivar Roads Gate System. This way providing the solution space for subsequent research phases.

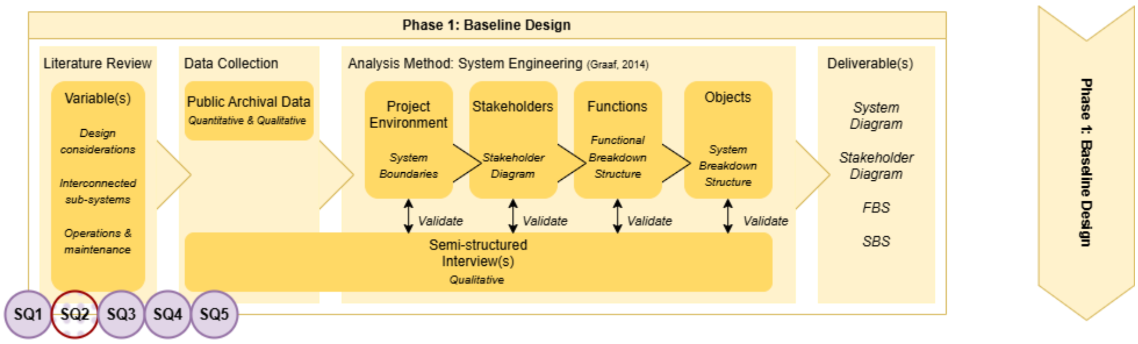


Figure 4.1: Research methodology Phase 1: Baseline Design.

4.2. Environmental and Socio-Economic Landscape of Bolivar Roads

Galveston Bay, located in Texas, serves as an important economic, and environmental hub within the Gulf Region. The Gulf Coast faces increasing challenges, including flooding, and rapid urbanization (refer to Section 1.1.2). Given the complexity of the region's interdependent components such as coastal morphology, understanding their interactions is important. Mapping these relationships provides insights into the potential impacts on the functions of the proposed flood risk measures. A system mapping will be outlined below to assess its implications. Refer to Appendix D.2 for the definitions of the main components in the System Diagram (see Figure 4.2).

4.2.1. A Dynamic Landscape of Land, Water, and Change

The Galveston Bay Region consist of Brazoria, Chambers, Galveston, and Harris counties (USACE, 2021e). Covers 9713 square kilometers of which 1399 square kilometers comprised Bay area (Moretzsohn et al., 2002). Land use consists of 41% urban, 31% agricultural, and 28% undeveloped areas (USACE, 2021e). Moreover, the estuarine system contains marshlands, oyster reefs, and intertidal zones (USACE, 2021d). Over 20% of the area lies at or below 1 meter in elevation (Kothuis et al., 2015; refer to Appendix D.2). The region has a humid, semitropical climate during summer, with an average annual temperature of approximately 20.5°C and typically mild winters (NOAA, 2025a).

The coastline measures 374 kilometers, with average bay depths of 3 meters (Phillips, 2004). A micro-tidal range of 0.4-0.6 meters (Bosboom and Stive, 2023), and wind-driven conditions. The region is heavily influenced by urbanization, erosion, and land subsidence (USACE, 2021b). Tidal exchange with the Gulf primarily goes through Bolivar Roads (Lester and Gonzalez, 2005), with flow velocities below 2 m/s under normal conditions (NOAA, 2025b). Freshwater inflows from, like Trinity River (refer to Appendix D.2), minimally impact salinity compared to tides (USACE, 2021d). Flow friction and inertia within Galveston Bay can be considered negligible (Jonkman, van Ledden, et al., 2013).

The area is prone to hurricanes, which make landfall every ~8 years (Keim et al., 2007) causing surge levels up to 6.1 meters in the Houston Shipping Channel (HSC) (i.e., serves as maritime route connecting the port to the Gulf) (refer to Appendix D.2), and up to 7 meters along the coast (Gilmore and Englebretson, 1997). Subsurface investigations around Bolivar Roads show unconsolidated clays from $0–150$ m NAVD, and sandy formations from $150–215$ m NAVD (Petitt and Winslow, 1957). Deeper boring indicating thick sand strata at around -40 m NAVD (McClelland Engineers, 1985).

4.2.2. Houston's Economic Pulse

Socio-economic activity in the region includes port operations, local businesses, and tourism. These are susceptible to storm surge and hurricanes (i.e., Atlantic Hurricane Season June 1 to November 30) affecting residents and increasing insurance and healthcare costs (USACE, 2021a), refer to the System Diagram (see Figure 4.2). Low-income communities experience heightened impacts in the region, while wetland degradation weakens natural flood defenses (USACE, 2021a).

The Bolivar Roads estuarine opening supports economic sectors including the HSC. The HSC handles over 8,000 deep-draft vessels and generated $802 billion annually (USACE, 2021d). The Port of Houston processes 247 million tons of cargo. Contributes $40 billion to the petrochemical industry, and supplies 40% of the nation's capacity (USACE, 2021d). Hence the economic importance, which was heavily emphasized by the interviewees. Commercial fishing adds over $1 billion annually, and tourism contributing to economic growth (Kothuis et al., 2015, Interview D). Population is projected to rise from 5.6 million (2020) to 7.8 million by 2045, increasing demands on land-use (USACE, 2021e).

4.2.3. The Interplay of Land and Water

The wetlands, oyster reefs, and marsh habitats provide natural buffers against storm surges while supporting fisheries, recreation, and biodiversity (USACE, 2021b). Relative Sea Level Change (RSLC) of up to 0.6 to 2.4 meters by 2100 (USACE, 2021d), increasing hurricane intensity (Colbert, 2022), and changing weather patterns (USACE, 2021d) heightens flood and erosion risks. As underscored by several interviewees, the Bolivar Roads Gate System needs to addresses flood safety, economic needs, and ecological conservation. Thereby blocking storm surge entry into the Bay (USACE, 2021d). But also containing hydrodynamic processes such as sedimentation flux (Interview A; Jonkman, van Ledden, et al., 2013). These changing morphological features (e.g., intertidal zones) are important for ecological balance (USACE, 2021d). Also planned inland dikes and dams will further reinforce flood safety resilience (USACE, 2021a), refer to the System Diagram in Figure 4.2.

4.2.4. Defending Galveston Bay

Without intervention, average annual flood damages in Galveston Bay are projected to reach $2.1 billion (USACE, 2021a). The Coastal Texas Study recommended the Bolivar Roads Gate System. This is a 43-mile beach and dune system, and habitat restoration to support natural defenses (USACE, 2021d). This concept, known as the "Coastal Spine", positions protective structures along the bay's exterior to protect Galveston Bay and the HSC. Supplemented by the Clear Lake and Dickinson Bay Gate Systems, non-structural improvements, and shoreline protections (USACE, 2021d).

This way coping with future scenarios indicating potential impacts on hydrodynamics, sediment distribution, and ecosystem balance due to evolving conditions. Key policies, including the Coastal Barrier Resources Act (CBRA), the Clean Water Act, and the Endangered Species Act (USACE, 2021d), governs floodplain development and protects ecological resources in the Houston-Galveston Bay Region, refer to the System Diagram in Figure 4.2.

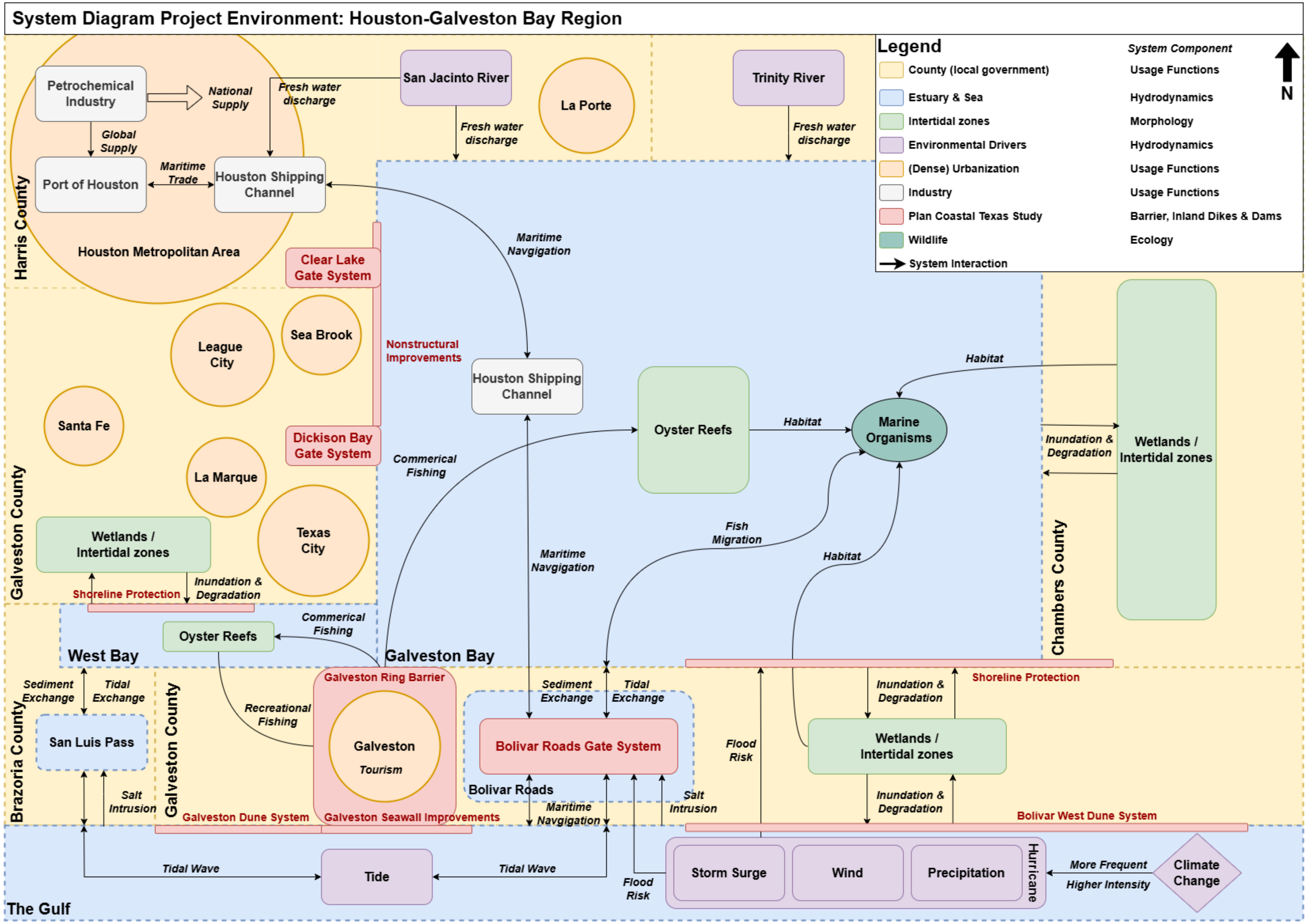


Figure 4.2: System Diagram of the Houston-Galveston Bay Region.

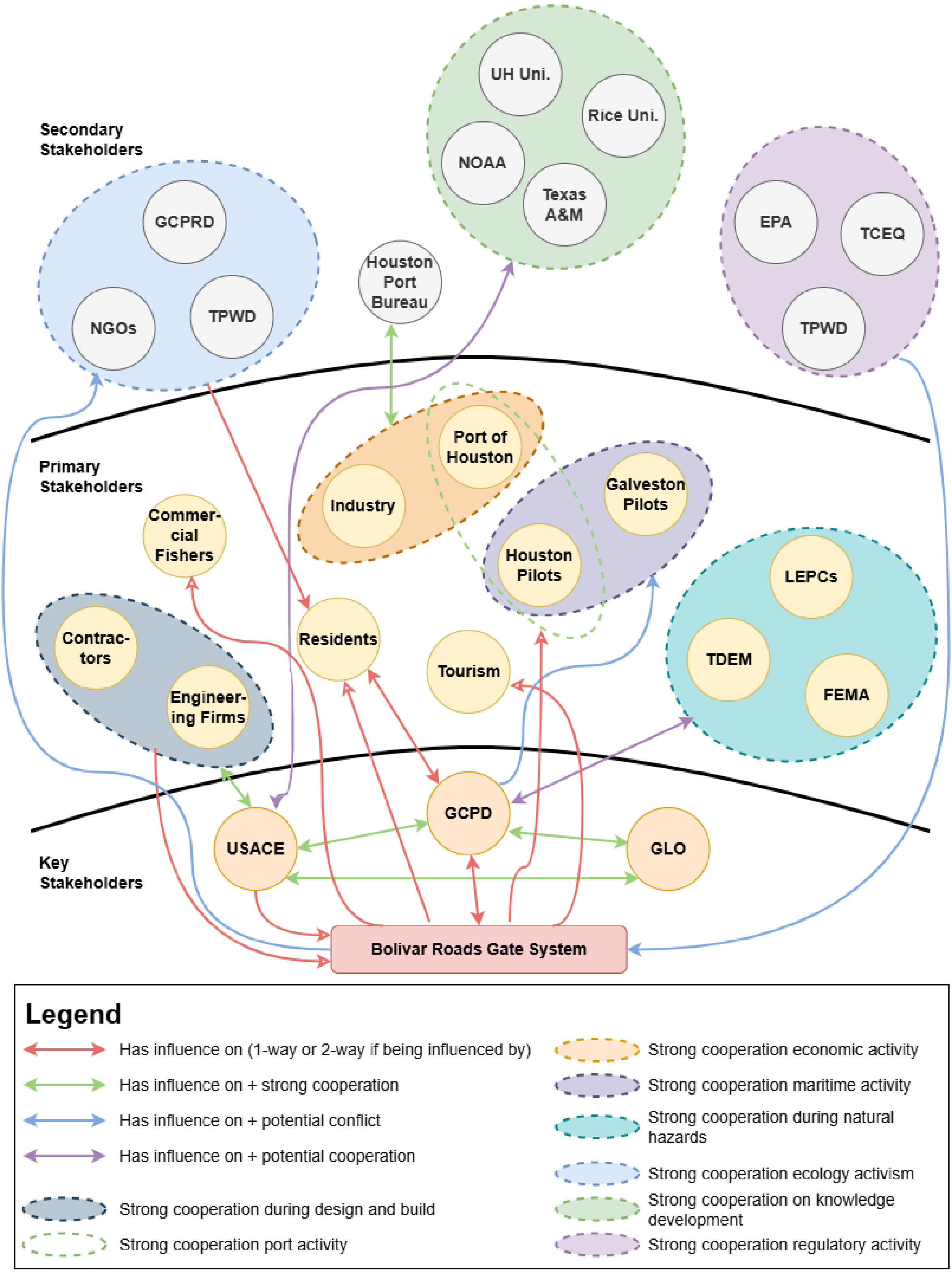


Figure 4.3: Stakeholder socio-gram – Houston-Galveston Bay Region.

4.3. Stakeholder Dynamics of the Bolivar Roads Gate System

The successful execution of the Bolivar Roads project depends on coordination efforts among various stakeholders in the project domain detailed in Section 4.2. For this research, stakeholders were selected based on their interactions, power dynamics, and interests in the project. Section 4.3.1 first identifies briefly who the stakeholders around the project are. Eventually in Section 4.3.2 it outlines what their influence is or whether, and to what extent, they are influenced.

4.3.1. Who Shapes the Bolivar Roads Gate System?

Multiple NGOs (e.g., Galveston Bay Foundation, National Wildlife Federation (NWF)) advocate for sustainable coastal practices. They emphasize minimal ecological disruption (GBF, 2025; NWF, 2025). Federal agencies like the National Oceanic and Atmospheric Administration (NOAA) and Environmental Protection Agency (EPA) enforce environmental regulations, conduct flood risk analyses, and oversee project compliance (EPA, 2025; NOAA, 2025a). Conservation-focused stakeholders such as the Texas Parks and Wildlife Department (TPWD), prioritize habitat protection (e.g., marshlands, oyster reefs, barrier islands) to enhance natural storm surge defenses (TPWD, 2025).

The approximately 6 million residents in Brazoria, Chambers, Galveston, and Harris counties are impacted by events like Hurricane Ike (2008). They support flood protection efforts (USACE, 2021b, Interview D). Academic institutions (e.g., Texas A&M University) provide research on coastal resilience and environmental assessments in the region (Merrell et al., 2021). The Port of Houston requires designs minimizing navigation disruptions (USACE, 2021b; Interview A), as do the Houston and Galveston Texas City Pilots (Interview F), who navigate 21,000 ships annually (GHBP, 2023). Commercial fishers, tourism operators, and recreational stakeholders, are reliant on healthy ecosystems, so may exert political pressure to enforce ecosystem restoration (Interview D).

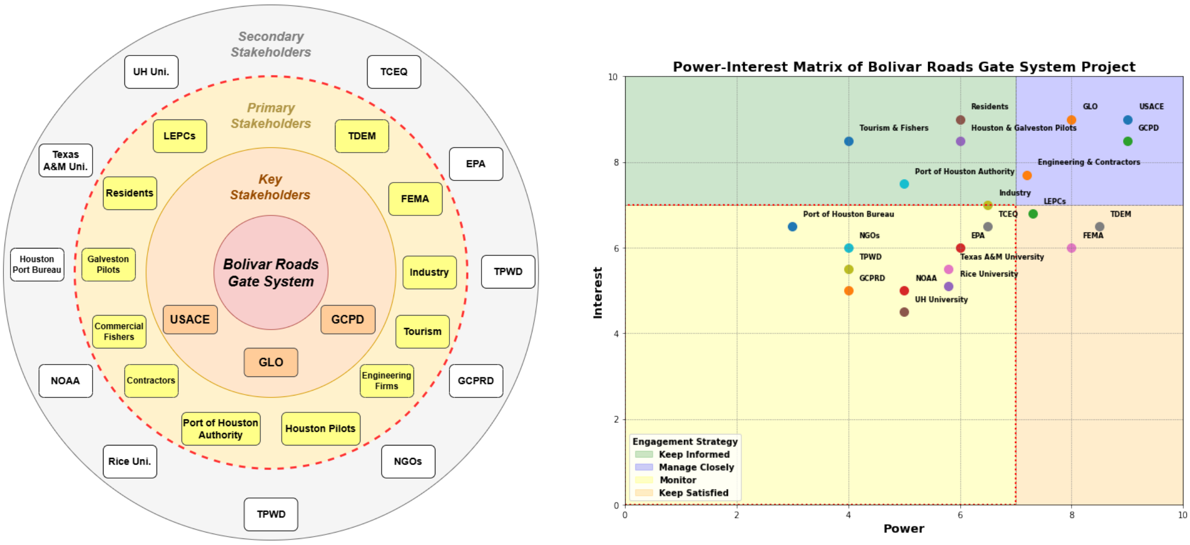
The U.S. Army Corps of Engineers (USACE) leads as the federal sponsor, with the Texas General Land Office (GLO) and Gulf Coast Protection District (GCPD) as non-federal partners overseeing the design, construction, and operation of the Bolivar Roads Gate System. They strive to balance economic and environmental goals (GCPD, 2025; Interview E). Engineering firms and contractors will likely manage design, construction, and O&M, ensuring compliance with technical and operational standards. Federal Emergency Management Agency (FEMA) and Local Emergency Planning Committees (LEPC)s integrate flood safety measures into hurricane evacuation planning, relying on the SSB's safety features to shape evacuation protocols (FEMA, 2024; LEPC, 2024).

4.3.2. The Political and Economic Forces

The stakeholder environment of the Bolivar Roads Gate System is broad, shaped by varying levels of power, interest, and influence among federal agencies, state partners, local communities, industry, and advocacy groups (see Figure 4.4a; refer to Appendix D.3). The socio-gram (see Figure 4.3) and Power-Interest matrix (see Figure 4.4b) illustrates how stakeholders interact, exert influence, and adapt strategies over time, with the rationale detailed below.

Key stakeholders, including USACE, GLO, and GCPD, hold both high power and interest as sponsors of the project. They oversee design, contractor selection, regulatory compliance, and operations. USACE ensures federal engineering standards and GLO and GCPD aligning the project with Texas coastal management goals. These entities also respond to environmental regulators (e.g., EPA) and socio-economic concerns. While regulatory agencies may have lower day-to-day engagement, their permitting authority significantly influences project timelines and environmental requirements.

Primary stakeholders, including the Port of Houston, Houston- and Galveston Pilots, and major industries, are important due to their economic impact. Their reliance is on uninterrupted shipping and need for flood protection. Their high interest (see Figure 4.4b) results from the system's direct effect on their operations. They yield moderate to high power through political, legal, and public advocacy. The Pilots, guiding over 20,000 vessels annually, may influence design as navigation is impacted. Despite lacking formal regulatory authority, these stakeholders may leverage economic and public pressure to shape project outcomes, see Figure 4.3.



(a) Stakeholder onion-diagram.

(b) Stakeholder power-interest matrix.

Figure 4.4: Stakeholder Dynamics Houston-Galveston Bay Region.

Local residents, commercial fishers, and tourism operators have high interest due to the project's flood safety, environmental, and economic impacts. They lack authority, but they can mobilize public opinion to influence policy. Particularly on property values and ecological health. Their ability to shape legislative approvals and permits, grants them moderate influence beyond their official power (see Figure 4.4b).

By contrast, secondary stakeholders including NGOs (e.g., Galveston Bay Foundation), academic institutions (e.g., Rice University), and regulatory entities (e.g., EPA), have specialized but limited direct power (see Figure 4.4b). They rank lower in power but NGOs can influence design through public campaigns, or media. Particularly on environmental issues (see Figure 4.3). Conversely, academic institutions contribute surge modeling and resilience research. This may shape operational protocols. Due to the indirect relationship to the barrier, these stakeholders are less prioritized in subsequent research.

Stakeholder dynamics evolve throughout the project life-cycle. Shifting from design to construction, operation, and maintenance. Initially outlying concerns can become critical due to unforeseen impacts or political shifts. Lessons from existing barriers, such as the Eastern Scheldt Barrier, which changes its design due to environmental concerns (van der Ham et al., 2018), highlight the need for adaptive engagement strategies to address changing public views. So, the Bolivar Roads Gate System requires long-term flexibility, balancing flood protection with emerging national and international security concerns. To illustrate, political shifts, including NATO's revived defense spending focus on critical infrastructure (Milne, 2025), can rapidly alter stakeholder influence.

Ultimately, in this volatile, uncertain, complex, and ambiguous (VUCA) environment, power, interest, and influence must be continually reassessed due to political shifts such as changes in increased oil drilling due to Donald Trump's administration (The Economist, 2024), which is against the Paris Agreement 2016. New environmental regulations, or threats to maritime infrastructure, can reshape funding, permitting, and stakeholder dynamics. The barrier's strategic role may also attract military or homeland security interest, particularly under hybrid warfare scenarios. Outlying stakeholders, like NGOs, can gain influence if issues such as habitat restoration or cybersecurity emerge. High-power entities may see engagement decline due to shifting federal priorities.

4.4. Storms, Ships, and Gates: A Functional Analysis

This section introduces a functional framework for SSBs, with an application to the Bolivar Roads Gate System. The analysis focuses on defining basic- and supporting functions. By examining the functions of SSBs alongside their Operations & Maintenance (O&M) this section provides an understanding of how the Bolivar Roads Gate System operates, and needs to be maintained.

The identification of these functions is based on variables elaborated in the Theoretical Framework (refer to Chapter 3). Each function is labeled in the text using the notation (Fx.x.x.x). Thereby also establishing a direct link to stakeholder interactions within the project environment. These functions are summarized in Figure 4.5 (refer to Appendix D.4), which presents the Functional Breakdown Structure (FBS) of a SSB, as such the Bolivar Roads barrier.

4.4.1. Guarding the Bay

The primary objective of an SSB is to prevent storm surges from entering estuaries and inland waterways, protecting communities, industries, and ecosystems. In the case of the Bolivar Roads Gate System, anticipated to be located at the Bolivar Roads estuarine opening, the SSB serves as a first line of defense component in the wider “Coastal Spine” against hurricane-induced storm surges (Foxhall et al., 2022; USACE, 2021a).

4.4.2. Core Functions of Storm Surge Barriers

This section inventories the basic functions of a SSB and their interactions. Evaluating how effectively it achieves its primary objective as stated in Section 4.4.1. By analyzing the basic functions of SSBs this study provides an understanding of the SSB design and operational performance. In the case of the Bolivar Roads Gate System, the functions of “Providing a Road Connection”, “Biodiversity”, “Recreational”, and “Monumental Value”, as identified in the Literature Review (refer to Chapter 2), are not embedded in the current conceptual design of the SSB. To broaden the scope of analysis, these functions are still considered in the FBS emphasizing SSBs in general.

Flood protection (F1.1)

The primary function of a SSB is flood protection (F1.1) (Interview A-B). This is achieved by closing the estuarine of from the sea to mitigate the entry of storm surges. In the case of Galveston Bay, particularly during hurricane-induced storm surges (USACE, 2021a; Foxhall et al., 2022). This function has a direct impact on various stakeholders, including residents, industries, and emergency agencies, by enhancing public safety, ensuring economic stability, and strengthening disaster preparedness.

Several secondary functions support flood mitigation. These include retaining extreme water levels (F1.1.2) which helps minimize shoreline erosion (F1.1.2.1), dampening wave impact (F1.1.1), and reducing inland flood safety standards (F1.1.3) by acting as the first line of defense (de Jong et al., 2012). To illustrate, high safety standards at Bolivar Roads benefits inland structures such as the Galveston Ring Barrier and the Clear Lake Gate Systems.

Navigation (F1.2)

Another basic function of SSBs is facilitating maritime navigation (F1.2), ensuring the efficient transit of vessels through the structure. This function is important for supporting the Houston-Galveston economic and logistical networks. Particularly the Port of Houston and its associated industries, which rely heavily on maritime transport (USACE, 2021e). This was highlighted by multiple interviewees.

The direct benefits of this function include maintaining safe and uninterrupted vessel movement, which is vital for economic stability (Interview F). Other sub-functions include accommodating passage for large vessels (F1.2.2) such as New-Panamax ships, ensuring navigational safety (F1.2.3), and reducing disruptions to maritime traffic (F1.2.4). These measures help prevent economic losses and maintain supply chain stability.

Water Exchange (F1.3)
The final basic function of SSBs is to facilitate water exchange (F1.3). In the case of the Bolivar Roads Gate System, this involves enabling the exchange of water between the Gulf and Galveston Bay (USACE, 2021d). This function is important for maintaining the health of the ecosystem, as stated by several interviewees. Water exchange in turn supports the economic and recreational activities of residents, tourism operators, and fishers.

Several sub-functions contribute to this activities including tidal flow (F1.3.1) to sustain ecological balance (F1.3.1.1), ensuring sediment transport (F1.3.4) for the health of marine ecosystems, facilitating fish migration (F1.3.2) to support biodiversity (F1.3.1.2), controlling salt intrusion (F1.3.3) to protect freshwater habitats, accommodating river discharge (F1.3.5), and maintaining hydraulic pressure balance (F1.3.6) to ensure the structural integrity of the barrier.

4.4.3. Keeping the Barrier Strong

The supportive functions of the SSB enhance its basic functions by ensuring operational reliability. These functions play an important role in maintaining the systems preparedness to perform its basic functions. A summary of these supportive functions is presented in Figure 4.5.

Managing Operations (F1.5)
The management of SSB operations (F1.5) is essential for ensuring the system fulfills its flood protection function. This includes monitoring water level forecasts, issue pre-warning messages, mobilize staff and prepare closure (F1.5.2). When forecast confirms, halt navigation and start closing operation. This requires ICT-systems and control of gate movements (F1.5.2.1) to regulate water flow and mitigate storm surge impacts.

To maintain system reliability, training programs should be implemented to equip operational teams with the necessary skills to manage barrier operations (Kamps, van den Bogaard, et al., 2024). In case of the Bolivar Roads, currently (anno 2025), GCPD is designated as the responsible entity for overseeing system performance and maintenance (Interview E). An adaptive Asset Management (AM) organization (F1.5.1) should be established to operate at strategic, tactical, and operational levels, which is further elaborated in the AM Strategy in Phase 3 (refer to Section 6.5).

Maintaining Structural Integrity (F1.6)
The maintenance of SSBs (F1.6) is important for ensuring their functionality, reliability, and long-term performance. This involves system upgrades (F1.6.1), repairs (F1.6.2), regular inspections (F1.6.3), and servicing (F1.6.4). All of which are integral to the sustained operations of SSBs.

SSB maintenance (F1.5) exists of regular minor, variable minor (i.e, frequency more than 1x every 1-3 years), and variable major (i.e., frequency less than 1x every 1-3 years) of mechanical-, civil-, electrical engineering, and industrial automation, demolition / removal, and certifications. For instance, the Maeslant Barrier has a probabilistic maintenance approach, ProBo, which utilizes Fault Tree Analysis (FTA) to assess component reliability. Following Literature Review findings (refer to Chapter 2) maintainability (F1.6.5) focuses on minimizing maintenance requirements while ensuring long-term system performance. Maintainability design factors (F1.6.5.x) provide guidance for integrating O&M requirements into the barrier's functional design.

4.4.4. A Functional Blueprint for SSBs

The Functional Breakdown Structure (FBS) structures the SSB's functions within a framework, defining "what" the SSB must accomplish to fulfill its objective. It distinguishes between basic and supporting functions. This general FBS can also be adapted for other SSBs worldwide, see Figure 4.5.

Future research will focus on the supporting functions as they are directly related to the research objective (refer to Section 1.3). In Subsection 4.5.2, the System Breakdown Structure (SBS) will elaborate on "how" these functions are physically implemented within the conceptual design of the Bolivar Roads Gate System. By specifying object-specific elements, this approach establishes an understanding of the SSB linking its functional requirements to its structural components.

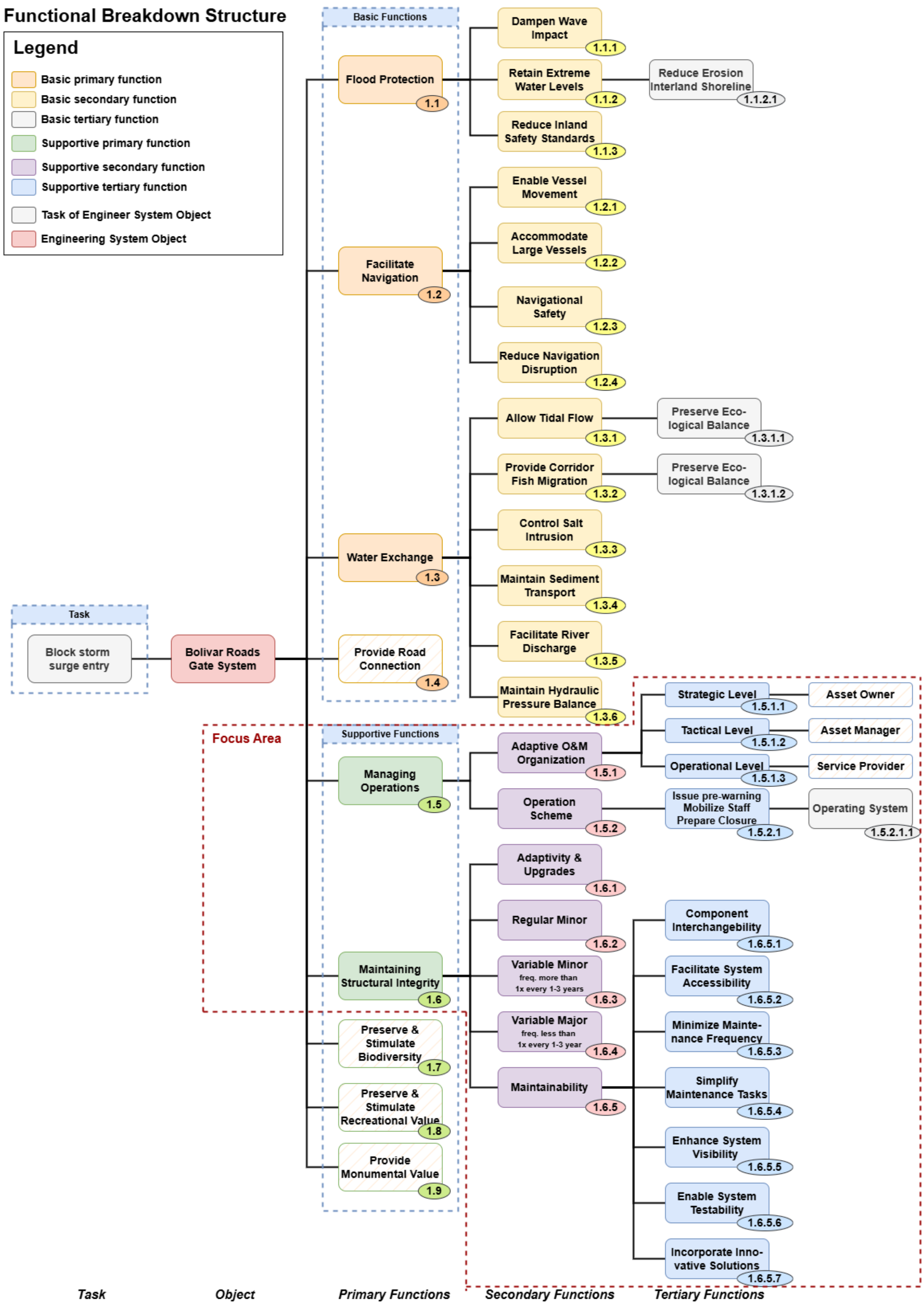


Figure 4.5: Functional Breakdown Structure (FBS) Bolivar Roads Gate System in Houston-Galveston Bay Region.

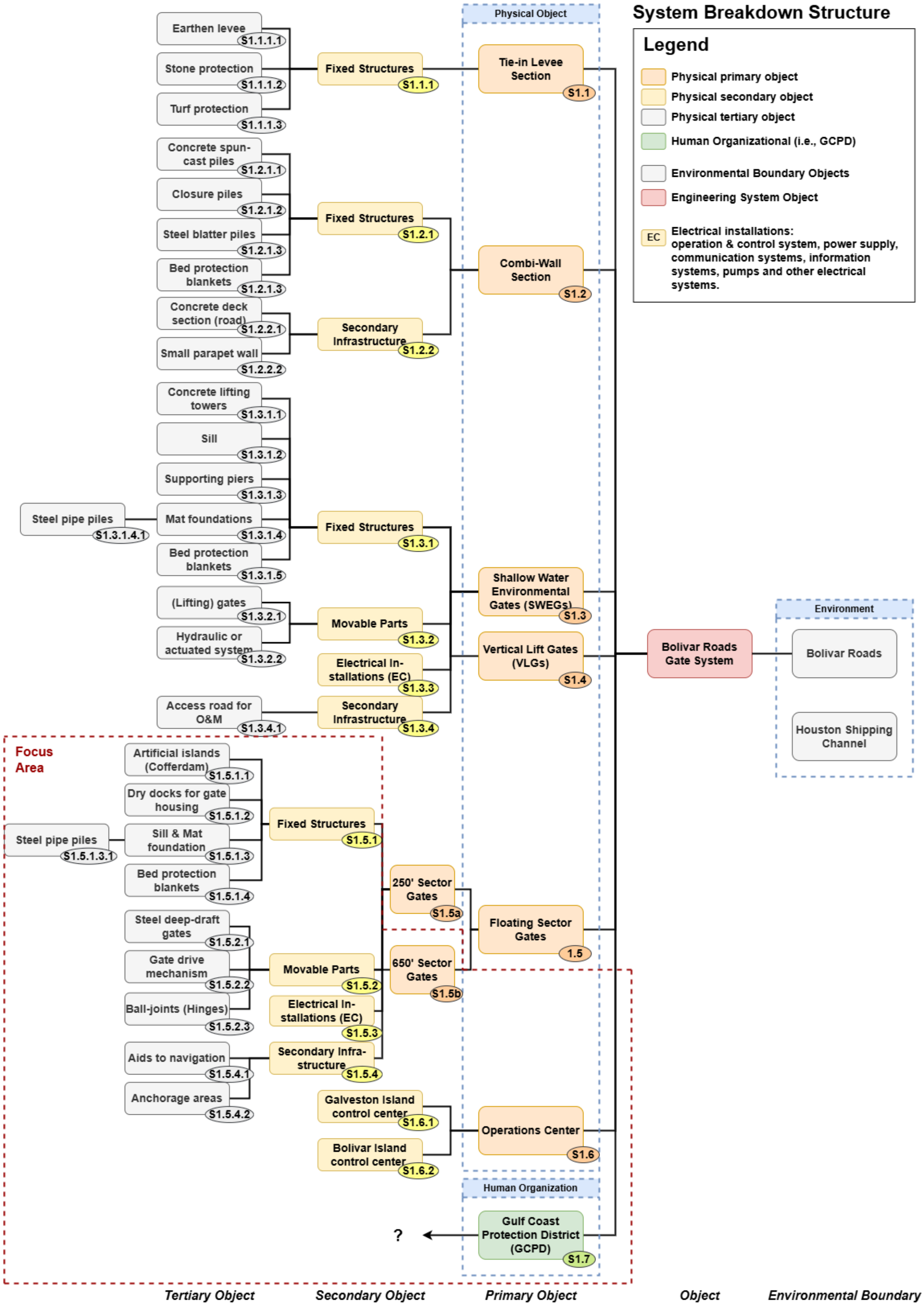


Figure 4.6: System Breakdown Structure (SBS) of the Bolivar Roads Gate System in Houston-Galveston Bay Region.

4.4.5. Investigating the Floating Sector Gates

In the broader context of the SSB, the FBS (see Figure 4.5) provides a breakdown view of what the barrier must accomplish (i.e, basic functions) and how it must be supported (i.e., supportive functions).

Within the SSB configuration, the choice is made to focus on the Floating Sector Gates. This choice stems from the potentially higher vulnerability compared to other sections. Such as the Vertical Lift Gates (VLG)s, or Shallow Water Environmental Gates (SWEG)s (see Figure 4.7; refer to Appendix D.5). Although the entire barrier must perform reliably to block storm surge entry, the sector gates form a bottleneck (Interview A-F). If either of the two gates fails, the region's level of flood protection and economic activity could be impacted. In other words, the barrier must always function reliably! This vulnerability becomes even more pronounced when the function Facilitate Navigation (F1.2) is considered. Since the sector gates cross the HSC, a malfunction or extended downtime would affect not only flood safety but also the continuous flow of maritime traffic, which was emphasized by multiple interviewees.

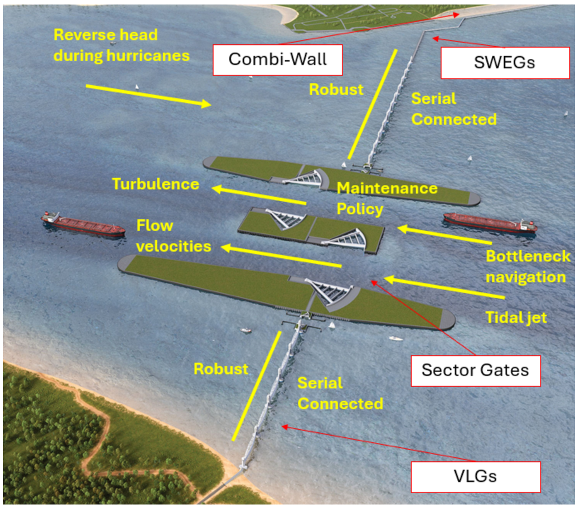


Figure 4.7: Functional breakdown on the Bolivar Roads Gate System (USACE, 2021a, adjusted by S.D. van der Geer).

The Floating Sector Gates alter hydrodynamics at Bolivar Roads by narrowing the flow profile. Intensifying tidal jets and turbulence, particularly on the Bay side, as seen at the Eastern Scheldt Barrier (de Jong et al., 2012). These changes pose risks to shipping safety, hence increase collision potential (Burkley et al., 2022; Interview F), and accelerate localized bed erosion (de Jong et al., 2012; Interview A). The Floating Sector Gates present more pronounced maintenance challenges (F1.6), as they must remain accessible for maritime traffic, allowing only one gate to be down at a time. This limits testing opportunities (Schelland and Smaling, 2022; Interview F). Their location on artificial islands complicates maintenance access. Thereby making repairs, inspections, and upgrades more difficult. This isolation may hinders both scheduled servicing and emergency response.

The Floating Sector Gates are also an interesting subject of study given the "lessons learned" from similar types of barriers such as the Maeslant Barrier. This barrier share a similar design with large movable sector gates but face different climatic and operational conditions. The Maeslant Barrier endures North Sea storms in autumn and winter (Rijkswaterstaat, 2019), while Bolivar Roads must withstand Gulf hurricanes and tropical storms (Stoeten, 2013). These differences affect storm intensity, surge duration, and tidal influences, shaping differences in design and operational schedules (F1.5). North Sea storms last about 24 hours, whereas hurricane effects can persist for 5 to 10 days (NOAA, 2025a).

The Maeslant Barrier's ball joints, and rubber supports are difficult to inspect or replace. Requiring full component disassembly (Walraven et al., 2022; Schelland and Smaling, 2022). This leads to high maintenance costs, challenges that may also arise at Bolivar Roads. The gate arm truss structure, comparable in size to the Eiffel Tower, demands complete enclosure for coating applications, making maintenance labor intensive (Schelland and Smaling, 2022). Taking a gate arm truss out of service compromises flood safety, a risk mirrored at Bolivar Roads. Failure of one floating sector gate significantly impacts navigation and flood protection. Operational testing in the busy HSC may disrupt maritime traffic, highlighting potential conflicts between Facilitate Navigation (F1.2).

In summary, while all sections of the Bolivar Roads Gate System are essential for Flood Protection (F1.1), the Floating Sector Gates stems the most complex. Their location in a high-traffic shipping channel, complex maintenance needs, and high failure impact make them a priority for further study.

4.5. A Closer Look at the Sector Gates

This section provides a physical breakdown of the Bolivar Roads Gate System. Focusing on the Floating Sector Gates that span the HSC between Bolivar Peninsula and Galveston Island (see Figure 4.7). The analysis centers on the function-fulfillers for the objective outlined in Section 4.4.1. Drawing on the relevant variables from the Theoretical Framework (refer to Chapter 3), a System Breakdown Structure (SBS) is developed. This SBS verifies that each function is assigned to a specific design element, highlighting any missing function-fulfillers, and assesses maintainability in the system's design. The objects are labeled (Sx.x.x.x).

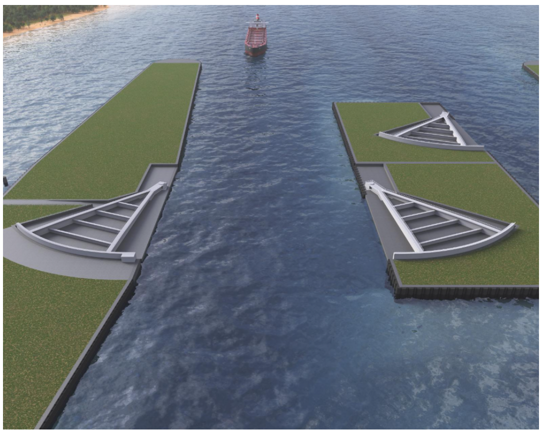
4.5.1. The Structural Blueprint of the Floating Sector Gates

The physical decomposition of the Floating Sector Gates is based on the conceptual design from the Coastal Texas Study Report (USACE, 2021a). This design is developed by USACE and GLO in 2021. As the official project framework, this design provides a reliable basis for analyzing the system. The Bolivar Roads crossing consists of several key components: the Tie-in Levee Section, the Combi-Wall Section, the Shallow Water Environmental Gates (SWEG), the Vertical Lift Gates (VLG), and the Floating Sector Gates (see Figure 4.5).

Although the primary analysis is centered on the Floating Sector Gates, all system components are included in the SBS to provide a comprehensive overview (Figure 4.6). Refer to Appendix D.5.1 for a description of the other sections. The physical decomposition maps the functions from the FBS (see Section 4.4), to their corresponding physical components, or "function fulfillers", ensuring the systems functional requirements are integrated into its design.

Floating Sector Gates (S1.5)

HSC, the busiest deep-draft channel in the U.S., necessitate robust navigation infrastructure. To ensure safe passage for commercial and recreational vessels, the USACE incorporated two-types of sector gate configurations at the Bolivar Roads crossing. These gates remain open year-round for uninterrupted navigation (F1.2.4) and natural flow (F1.3), closing during storm surge.



(a) Conceptual rendering of deep-draft navigation gates (open) (USACE, 2021d).

(b) St Petersburg flood protection barrier (RHDHV, 2025).

Figure 4.8: Floating Sector Gates designs.

The crossing features two smaller sector gate complexes (S1.5a), each with a $38\,\mathrm{m}$ (i.e., $125\,\mathrm{ft.}$) wide opening and a sill elevation of $-12.2\,\mathrm{m}$ (i.e., $-40.0\,\mathrm{ft.}$) (NAVD88), positioned on either side of the Artifical Islands (S1.5.1.1). These gates enhance navigational safety by reducing interactions between recreational vessels and deep-draft commerical ships (F1.2.3). Constructed with reinforced concrete and supported by large sill and mat foundations (S1.5.1.3), steel pipe piles (S1.5.1.3.1), and steel-fabricated gates (S1.5.2.1). They ensure structural stability. Bed protection blankets (S1.5.1.4) on both sides to keep the scour whole at safe distance from the barrier foundation and aids to navigation (e.g., timber guide walls) facilitate safe vessel passage (F1.2.3).

The proposed design for the HSC (i.e., large passing) includes a horizontally rotating Floating Sector Gate (S1.5.2.1). Consisting of a pair of gates positioned on artificial islands (S1.5.1.1). The layout features one-way navigation lanes (F1.2.3), each 200 m (i.e., 650 ft.) wide, with a sill elevation of -18 m (i.e., -60.0 ft.) (NAVD88). This design was chosen to optimize inlet conveyance (F1.3), maintain channel stability, and align with prior study recommendations (e.g., GCCPRD). It supports the port's objective of accommodating future vessels with larger drafts (F1.2.2).

The conceptual design assumes that lateral loads are transferred to the ball joints (S1.5.2.3). These are anchored to a large sill and mat foundation (S1.5.1.3), supported by steel pipe piles (S1.5.1.3.1). To prevent erosion, bed protection blankets (S1.5.2.1) will be installed on both sides of the structure and around the artificial islands. The gates are housed in dry docks (S1.5.1.2) within man-made islands. This way minimizing corrosion and debris accumulation while facilitating routine maintenance (F1.6). During operations the dry dock is flooded, allowing the gates to float into position. Water is then pumped (S1.5.3) into the gates to submerge them into the closed position. Once the flood event subsides, the gates are pumped out, floated back to the dry dock, and secured. Thereby reducing the risk of vessel impacts while in storage (F1.2).

The two gates enhances system resilience. Allowing continued navigation if one Floating Sector Gate fails. However, the artificial island form a bottleneck for vessels (Interview F). Maintenance dewatering bulkheads (F1.6) enable dry servicing (F1.6.5.2) and improve inspection visibility (F1.6.5.6). The design draws from proven structures like the Harvey Canal Sector Gate, St. Petersburg Barrier (Figure 4.8b), and Maeslant Barrier.

4.5.2. From Function to Form

The SBS translates the system functions defined in the FBS into the corresponding physical components of the system, as represented within the SBS itself. This process results in a unique system structure that reflects location specific boundary conditions, and socio-economic demands. By decomposing the system into a hierarchical breakdown of physical components the SBS establishes a clear link between each function and its corresponding subsystem. This structured methodology ensures traceability from the functional requirements to the physical barrier elements.

The SBS serves as a tool for the preliminary evaluation of the Floating Sector Gates feasibility of options for flexibility in design and maintainability. By analyzing the structural breakdown, a qualitative maintenance assessment can be performed. Considering design factors such as interchangeability and accessibility. This analysis also helps define an appropriate maintenance strategy, determining "how" maintenance should be conducted. This will be further explored in Subsection 4.6.2. As of now (2025), the O&M Organization for the Floating Sector Gates remain undecided and are currently under the purview of the GCPD (Interview E), a status reflected in the SBS.

4.6. Managing Storm Surge Barrier Upkeep

This section presents a qualitative maintenance policy and maintainability assessment of the Floating Sector Gates, as highlighted in the FBS (refer to Section 4.4). Focusing on the supportive functions of the FBS, this analysis evaluates maintenance needs within the SBS (Section 4.6.1), and assessing maintenance policy and system maintainability (Section 4.6.2) while excluding cost. For an overview of other sections of the Bolivar Roads Gate System, refer to Appendix D.5.2. In Phase 3, after selecting a specific components for a conceptual flexible design, the maintenance policy will be integrated within the Asset Management Strategy for the designated component (refer to Section 6.5).

4.6.1. Understanding the Maintenance Demands

The three primary component types: fixed-, movable parts, and electrical installations, deteriorate differently. Thereby necessitating different maintenance approaches. For instance, concrete (i.e., 100 years), steel components (i.e., 20-50 years) age at different rates. To explore future maintenance needs for the SSB, this study draws on literature regarding the maintenance history, expertise, and management framework of SSBs in the Netherlands, the *Objectbeheerregime Stormvloedkeringen 2023* (Rijkswaterstaat, 2019), summarized in Figure 4.9.

Fixed parts, like the concrete dry docks are vulnerable to sulfate attack, alkali-aggregate reactions, and reinforcement corrosion from carbonation (Rijkswaterstaat, 2019). Reinforcement corrosion is the primary risk, requiring repairs every 25 to 35 years applying cathodic protection, with component replacement after 100 years (Rijkswaterstaat, 2019). Movable parts, like coated gates for corrosion protection, requiring touch-up and conservation measures. Inspections every 10-15 years, full reapplication every 20–40 years, and replacement after 50-100 years (Rijkswaterstaat, 2019).

The drive mechanism, subject to wear and fatigue, requires, depending on factory requirements and percentage of damaged surface, refurbishment every 15–20 years, and full replacement after 20-50 years (Rijkswaterstaat, 2019). Electrical systems require replacement every 8-15 years due to wear, while hardware and software updates are needed every year to keep pace with technological advancements (Rijkswaterstaat, 2019). The SSB "furnishing" (e.g., stairs, railings, doors, shutters) needs, depending on factory requirements and percentage of damaged surface, conservation measures every 20 years, with replacement after 100 year. Major maintenance of buildings and grounds is every 15 years, with replacement after 100 years.

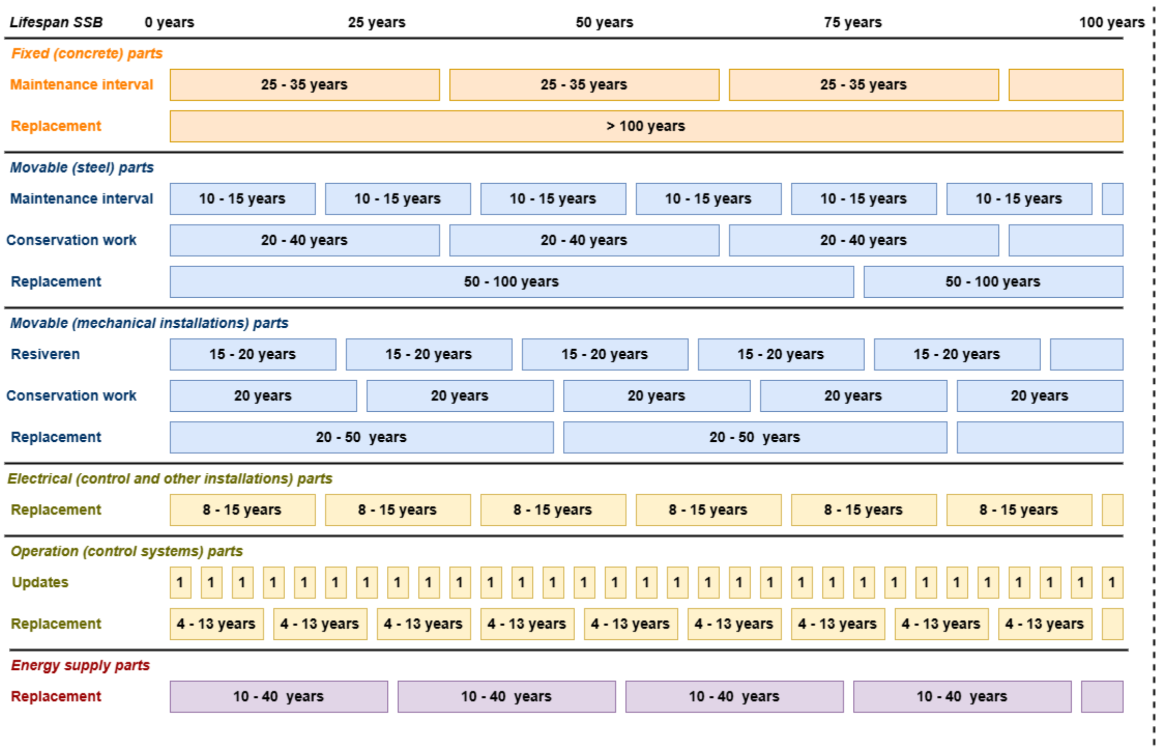


Figure 4.9: Generalized measures and maintenance intervals of SSBs, based on Rijkswaterstaat (2019).

4.6.2. A Preventive Maintenance Strategy is Needed for Flood Protection

Following the maintenance demands of SSB components, maintaining a SSB requires a strategy that balances reliability, cost-efficiency, and risk mitigation. The Literature Review (refer to Chapter 2), discuss various approaches, including failure-, load-, time-, and state-based maintenance. Each with benefits and drawbacks. Given the extreme conditions and operational demands of SSBs, this study argues that a state-based approach is the most effective, the rational below.

The choice of maintenance policy is driven by two factors: failure consequences and deterioration predictability (Schiereck and Verhagen, 2019). If failure poses large economic, social, or environmental risks, a proactive or state-based approach is deemed essential. Next, when deterioration is unpredictable, state-based maintenance is preferred. If wear is predictable time- or failure-based strategies are suitable. For SSBs, the consequence of failure is exceedingly high. Hence, millions of people may be affected by flooding, and industrial activities rely on the barrier's continual operation. Thus, a proactive or state-based maintenance approach is necessary for SSBs.

Monitoring wear and degradation in SSBs is straightforward in stable weather conditions. Structural decline can be measured consistently. However, SSBs operate in volatile environments, making SSBs frequently exposed to extreme weather, deterioration unpredictable, and SSBs must remain on constant "stand-by" during the storm- or hurricane season. This limits the windows for maintenance, leading to the necessity of a proactive or state-based maintenance approach.

Hurricane-Ready Maintenance: Ensuring Reliability at Bolivar Roads
The Bolivar Roads Barrier, will operate in a hurricane-prone environment, subject to extreme weather conditions (refer to Section 4.2). Hurricane-induced forces accelerate wear and introduce unpredictable stress mechanisms (refer to Section 4.2.1). Unlike navigation locks, which may retain functional after impact, failure of a SSB compromises the entire system's flood protection capabilities. Given the critical need for continuous operability, a state-based maintenance approach is the most suited. The state-based approach maintains the barrier's optimal condition by triggering maintenance at predefined degradation limits for each component (see Figure 4.10), as defined in Section 4.6.1. A state-based strategy ensures reliability through regular inspection (i.e., frequency 1x per 2-3 months), condition inspection (i.e., 1x per 2 year), measures inspection (i.e., approx. 2-3 years before scheduled maintenance measure), and conservation inspection (i.e., 1x per 5 year) (Rijkswaterstaat, 2019).

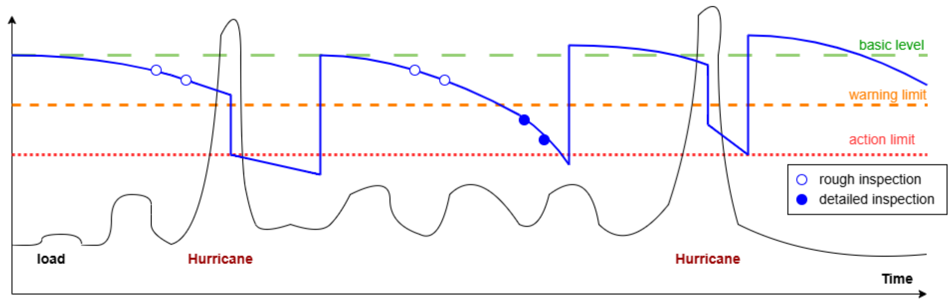


Figure 4.10: State-based maintenance policy (Schiereck and Verhagen, 2019, adjusted by S.D. van der Geer)

As shown in Figure 4.10, the state-based approach uses regular inspections and condition thresholds to trigger preventive maintenance. Visual and sensor-based monitoring tracks wear, with warning and action limits enabling timely interventions (Rijkswaterstaat, 2019). This approach balances reliability and cost by focusing preventive efforts on critical components. For example, ball-joints require continuous monitoring due to their high consequences of failure.

High-Criticality Components: What Strategy Is Required to Ensure Continuous Protection?
High-priority components like movable mechanical installations require stringent condition monitoring. In contrast, less critical elements may warrant a different approach. For example, minor structural components or non-essential supports, where failure does not compromise overall system integrity, could follow an opportunistic maintenance strategy (i.e., whenever a convenient opportunity arises). This approach balances reliability with cost efficiency, allocating resources based on each component's role and failure impact. In practice, each component's risk profile, established by its deterioration, guides the choice of maintenance method, resulting in a element specific approach:

1. *State-Based Maintenance for High-Criticality Items:* fixed-, movable steel, mechanical-, and electrical parts must be maintained via regular inspections and action thresholds;
2. *Corrective-Based or Opportunistic Maintenance for Lower-Criticality Items:* components such as shutters with lower failure impacts could be serviced whenever a convenient opportunity arises;
3. *Failure-Based Maintenance:* components that require immediate emergency repairs upon failure during operation (i.e., storm conditions) to prevent system malfunction.

Figure 4.11 illustrates the state-based maintenance framework. This framework combines preventive, corrective, and failure-based interventions. Preventive maintenance serves as the primary approach. For SSBs, this relies on real-time condition data (i.e, "talking assets"). When structural deterioration indices reach predefined warning thresholds of high-critical fixed-, movable-, or electrical parts (e.g., deep-draft gates, control systems) maintenance is scheduled to ensure operational readiness.

Hence, maintenance interval, conservation work, resiveren, and updates in Figure 4.9. Corrective maintenance adds to this strategy, addressing emerging maintenance opportunities of non-critical parts (e.g., shutters). In emergency situations such as damage from a ship collision, failure-based interventions become necessary to restore functionality as swiftly as possible.

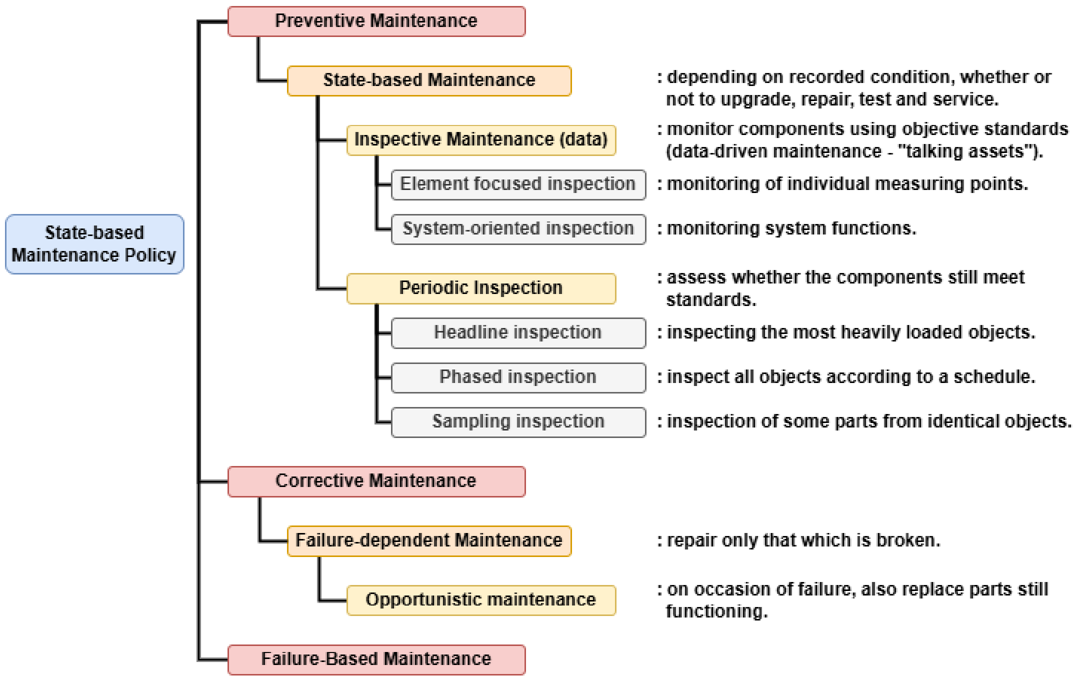


Figure 4.11: State-based maintenance policy SSB (Vereeke, 2003, adjusted by S.D. van der Geer)

Applying this framework to the Floating Sector Gates would involves implementing an AM-team. In Phase 3, the maintenance strategy will be implemented in the Asset Management Strategy.

4.7. Summary and Conclusions

This chapter set a baseline for further study, defining the system's technical, environmental, and social dimensions. Using a Functional Breakdown Structure (FBS), functions were identified and linked to components in a System Breakdown Structure (SBS), a stakeholder review mapped relevant interests.

Phase 1 addressed the question: *[SQ2] How can operational and maintenance requirements be efficiently integrated into barrier design and planning to ensure continuity and stability over the next 150 years?* storm surge barrier (SSB)s have long lifespans, operate rarely, yet must remain highly reliable. This makes it challenging to define a maintenance strategy early in the design process, as future system drivers are uncertain and each design introduces different maintenance demands. In response to this dilemma, this chapter findings argues that SSBs must be deliberately designed with maintenance intervals for fixed, movable, and electrical components in mind. State-based maintenance policy is essential due to the high failure impact and uncertain degradation of components. This includes preventive, corrective, and failure-based maintenance. Fixed components, such as concrete dry docks, are prone to reinforcement corrosion and require repairs every 25-35 years and replacement after 100 years. Movable parts, like coated gates, should be inspected every 10-15 years, recoated every 20–40 years, and replaced after 50-100 years. Drive mechanisms need refurbishment every 15-20 years and replacement after 20-50 years. Electrical systems require replacement every 8-15 years, with software and hardware updated annually. Inspections guide these maintenance actions: periodic (every 2–3 months), condition-based (every 2 years), pre-measure (2-3 years before scheduled work), and conservation (every 5 years). Corrective or opportunistic maintenance applies to lower-critical components and can be performed whenever convenient. Failure-based maintenance remains necessary for emergency repairs during storm conditions to prevent functional failure. To conclude, these results call for a maintainability mode in the design and planning of SSBs, prioritizing stability, and predictability.

5

Phase 2: The Shape of Uncertainty

The goal of Phase 2 is to inventory and evaluate system drivers affecting storm surge barrier (SSB)s performance, and in particular the Floating Sector Gates at Bolivar Roads (i.e., dictated to CE + CME). Building on Phase 1, the primary aim is to determine which physical and socio-economic drivers most critically shape gate functionality. A dilemma in this phase, and in SSB design in general, is the volatile behavior of system drivers can be partially known in advance. Different design configurations expose different vulnerabilities, thus uncertainties. Instead of seeking to eliminate all uncertainty, this chapter aims to identify which uncertainties may arise and how adaptable design options can address them. This provides a foundation to examine options for flexibility in design. By examining factors like climate dynamics, this chapter seeks to support the answer of sub-questions (SQ's) 1 to 4, particularly SQ1.

This chapter starts with the methodology used in Phase 2 (Section 5.1), highlighting how qualitative heuristics (i.e., historical data, expert judgment) helped identify high-impact uncertainties. Section 5.2 outlines operational, structural, and hydraulic failure modes for storm surge barrier (SSB)s. Sections 5.3 and 5.4 analyze physical and socio-economic drivers, ranging from hurricane intensity to economic growth, and their impacts on the functional performance of the Floating Sector Gates at Bolivar Roads. Lastly, Section 5.5 uses a scenario-based approach to identify dominant "trend-breakers."

5.1. Research Methodology

Phase 2 assessed system drivers affecting the long-term performance of the SSB, focusing on the Floating Sector Gates at Bolivar Roads. Using the framework of Vader et al. (2023) and insights from Mooyaart et al. (2025), Phase 2 activities included (I) data collection, (II) examination principale failure modes SSBs, (III) inventory physical system drivers, (IV) inventory socio-economic system drivers, (V) identify trend-breakers via Delta-Scenarios, and (VI) determine the governing system driver. Prioritizing these system drivers will guide options for flexibility in design in Phase 3. The trade-off approach, inspired by the Dutch Delta Scenarios (van der Brugge and de Winter, 2024), ensured practicality. Methodological details are in Appendix E.1, below a short briefing.

5.1.1. Data Collection Method

Phase 2 utilized public archival data together with stakeholder interview insights to identify system drivers and contextual factors that might challenge the barrier's functionality. These integrated findings, together with the baseline design (i.e., Phase 1) were subsequently incorporated into the conceptual Delta-Scenarios for the Houston-Galveston Bay Region, refer to Figure 5.1.

Existing Data

Using variables from the Theoretical Framework (refer to Chapter 3), in this phase, environmental studies, economic trends, technical- and consultancy reports, and grey literature (e.g., newspaper articles) were primary sources of information. Appendix E.1.2 provides an overview. Much of this archival data was collected because it relate directly to ongoing conceptual design efforts for the Floating Sector Gates at Bolivar Roads (anno 2025).

Semi-structured Interviews
Semi-structured interviews, together conducted with Phase 1 and 3, also informed Phase 2, particularly when clarifying tacit stakeholder knowledge about vulnerabilities impacting SSBs. But above all the system driver dynamics in the Houston-Galveston Bay Region. Through thematic analysis of these interviews (i.e., identify common themes), and with the archival evidence, Phase 2 ensured that the identification of significant drivers was grounded in both practical experience and scientific data. Refer to Appendix G for the interview transcripts and elaboration on the thematic analysis.

5.1.2. Applied Method
The analysis focused on estimating possible outcome distributions affecting SSB performance based on heuristics, rather than predict exact scenarios. Using the qualitative assessment framework of Vader et al. (2023), system drivers were (**I**) identified and evaluated based on (**II**) historical patterns and (**III**) projected trends from existing studies. Their qualitative trend magnitude was assessed for potential impact on functional performance using the failure pathways of Mooyaart et al. (2025), which classify failure modes as operational-, structural failure, or hydraulic overload. Drivers expected to trigger significant failure mode(s) were selected for further analysis (i.e., shown with '+' in Figure 5.3), ensuring focus on those most likely to affect the functional performance of the SSB.

To explore how these selected drivers could evolve under interruptions of the smooth continuation of recent trends, (IV) the Dutch Delta Scenarios by van der Brugge and de Winter (2024) were adapted to develop four qualitative futures for the Houston–Galveston Bay Region. These scenarios were used to discuss the shortlisted drivers in consultation with experts and stakeholders via interviews, to assess their potential functional impact in more extreme trajectories. Based on these expert judgments, two drivers were ultimately identified as having the most substantial influence on the barrier's performance (i.e., shown with '++' in Figure 5.3). This scenario-based approach leaded to identification of the dominant drivers and yielded a firts understanding of how the SSB needs to adapt (see Figure 5.1).

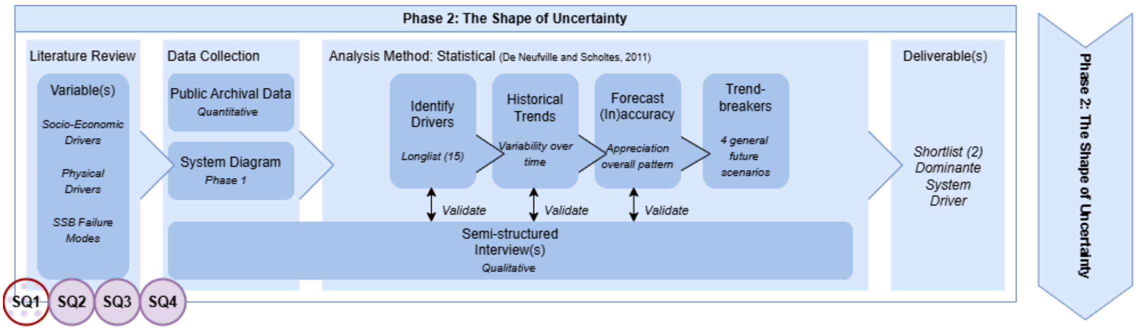


Figure 5.1: Research methodology Phase 2: The Shape of Uncertainty.

5.2. Failure Pathways
To examine how system drivers affect the performance of SSBs, this analysis applies the failure categorization framework of Mooyaart et al. (2025). To remind, an SSB's objective is to prevent extreme water levels in the inner basin from exceeding critical thresholds (refer to Section 4.4.1). Hence, its effectiveness is therefore determined by how often it can avert threshold exceedance under evolving external conditions. Using this framework helps to structure how different system drivers such as mechanical wear and human decision-making, map onto three failure mechanisms (see Figure 5.2):

- *Operational Failure:* occurs when the barrier is opened or closed incorrectly due to malfunctioning equipment, or human-factor issues. Late or misjudged closures can leave the basin too full before an extreme event, increasing the likelihood of critical water level exceedances;
- *Structural Failure:* involves the barrier's physical inability to withstand loads such as high flow velocities, or waves. This can lead to partial or complete collapse, compromising the entire protective function. For multi-gate barriers, the collapse of one gate can cause failures elsewhere;
- *Hydraulic Overload:* even with correct operation, extreme water levels may still surpass defense thresholds, especially if river discharge, or wind setup interact to raise water behind it.

Categorizing the impacts on the functional performance of system drivers by these failure mechanisms helps to understand how these impacts lead to possible failure. This way informing decisions on the integration of Operations & Maintenance (O&M) into the barrier design and planning process. This approach highlights trade-offs in managing SSB systems. For example, advanced forecasting mitigates operational failures but not necessarily structural overload risks. Fortifying barriers enhances robustness without necessarily addressing operational vulnerabilities.

Balancing resources across these risks is a strategic challenge regarding O&M, which will be further highlighted in the Asset Management (AM) Strategy (refer to Section 6.5). The following sections applies this framework to systematically categorize stressors and prioritize Phase 3 interventions.

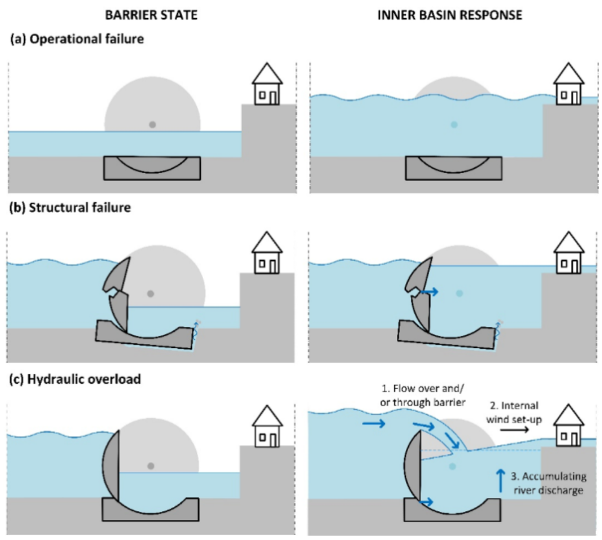


Figure 5.2: Failure modes SSBs (Mooyaart et al., 2025).

5.3. The Power of Physical Drivers

This section introduces the mutually interdependent physical system drivers that potentially influence the functionality of SSBs, as illustrated in Figure 5.3. To recall, each physical driver was (**I**) identified, (**II**) analyzed on its historical and (**III**) projected magnitude of change, using published studies, to examining the possible impact of a qualitative trend strength. The analysis begins by identifying the affected functions, as defined in the FBS (refer to Section 4.4). These are driven primarily by climate related factors (Section 5.3.1). Subsequently, it investigates the hydrodynamic conditions that further shape SSB functionality (Section 5.3.3). The potential impact of each trend on functional performance was assessed via the failure pathways of Mooyaart et al. (2025) (refer to Section 5.2). Only physical system drivers whose trend magnitude indicated a high likelihood of triggering these failure modes were retained for subsequent scenario exploration, as marked with '+' in Figure 5.3.

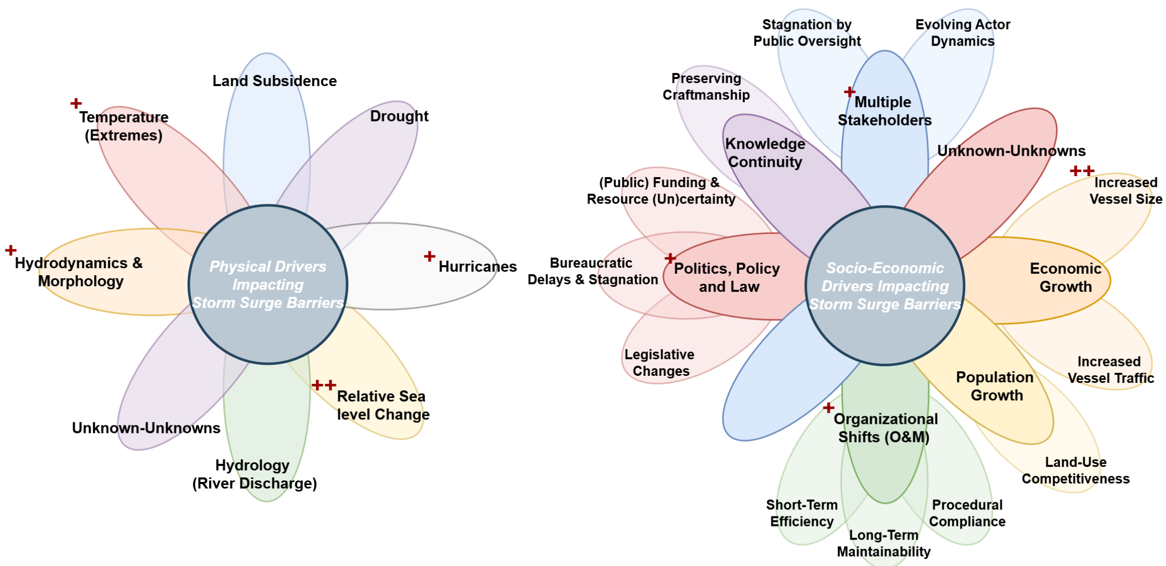


Figure 5.3: Overview diagram of system drivers impacting SSBs.

5.3.1. Climate Stressors in the Houston-Galveston Bay Region

Local climate changes, driven by global variations, can exhibit significant regional differences. As highlighted in Section 1.1.1, low-lying coastal deltas such as the Houston-Galveston Bay Region, are particularly susceptible to these changes. This analysis focuses on key local climate drivers including temperature, precipitation, drought, and wind. But excluding CO_2 concentration, as it is deemed irrelevant to functional requirements (Bakker et al., 2023). Trends and their potential impacts on the Floating Sector Gate at Bolivar Roads will be evaluated to identify drivers requiring further investigation.

Temperature Extremes

Global temperature variations produce region specific climatic effects impacting SSBs differently. Equatorial located SSBs face more warm days annually, while those in the northern hemisphere encounter more frequent cold days (NOAA, 2023). These temperature fluctuations indirectly affect a SSB's primary function, Flood Protection (F1.1), by influencing key support functions. Particularly Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6). The rational below (see Figure 5.4).

In the Texas Gulf area, where summers are typically warm and humid (refer to Section 4.2), rising temperatures, especially extreme heat waves (Grundstein and Dowd, 2011), pose notable risks to both the structural and operational functionality of the SSB. Although research findings on mean temperature trends in this region are mixed, with some indicating a slight cooling (Wang and Zhang, 2008) trend and others showing a warming trend (Grundstein and Dowd, 2011), the consensus is that future climate scenarios project a significant temperature increase of 3°C to 5°C by mid- to late century (Liu et al., 2012; Liu et al., 2013; refer to Appendix E.2). This will be alongside more frequent extreme heat events in summer (Kunkel et al., 2010). Extreme heat, coinciding with the Atlantic Hurricane Season (i.e., June 1–November 30), drives storm surges as hurricanes gain energy from ocean heat and high humidity, with evaporation occurring above 26°C (NASA, 2021). Hurricanes be further discussed below as separate driver.

Temperature variations impact two support functions of an SSB: Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6), both vital for Flood Protection (F1.1). Prolonged high temperatures accelerate material degradation, aging, and thermal expansion of steel gates. This increases structural failure risks. As stated in Interview B: *"climate change effects beyond sea level rise (e.g., temperature, drought) have minimal impact on the barrier's core function."* Interviewees emphasized that while the structural purpose of blocking storm surge may remain technically unaffected, the operational and maintenance demands under rising temperatures such as accelerated corrosion and biofouling, are expected to increase. Warranting further investigation into the effects of frequent high-temperature events in subsequent Section 5.5.

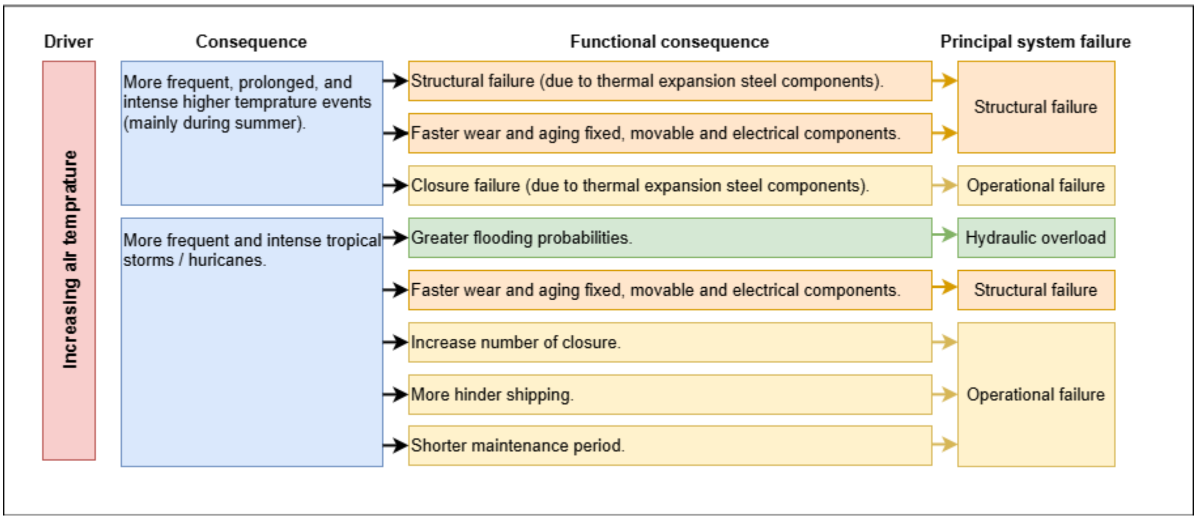


Figure 5.4: Functional consequences physical driver: air temperature.

Precipitation Patterns
Global precipitation patterns, driven by solar energy, resulting in region specific climatic effects (Zhou, 2025) can moderately influence an SSB functionality. In wetter, tropical zones, SSBs experience more frequent rainfall events, while arid and temperate regions face more seasonal precipitation (NOAA, 2023). These variations primarily affect the SSB's core functions of Flood Protection (F1.1) and Water Exchange (F1.3), as well as the supporting function Maintaining Structural Integrity (F1.6).

In the Houston-Galveston Bay Region, historical data indicate a trend of increased fall storm precipitation and winter storm intensity along the coast (Palecki et al., 2005), even as inland areas experience weaker storms or declining rainfall (Wang et al., 2009; McRoberts and Nielsen-Gammon, 2011). Projections to mid-century suggest a continued rise in summer and spring precipitation (Liu et al., 2013; refer to Appendix E.2), with fewer high-precipitation days (i.e., >10 mm) but potentially stronger peak events (Tebaldi et al., 2006; Wang and Zhang, 2008). Although some studies show only moderate or uncertain changes in annual precipitation totals, there is consensus on increasing storm intensity by century's end (anno 2025). This can temporarily raise water levels in combination with wind set-up and atmospheric pressure deficits (Bosboom and Stive, 2023).

In the context of the Floating Sector Gates at Bolivar Roads, higher-intensity rainfall events drive up risk by increasing freshwater inflow (e.g., from the Trinity and San Jacinto Rivers). Elevating hydraulic loads if the SSB is closed (Mooyaart et al., 2023). Though protective coatings and concrete design measures minimize the corrosion risks from heavier rainfall, more extreme precipitation days may still pose challenges for structural longevity and operational reliability. As emphasized by Interview B, the barrier: *"cannot address all hurricane-related risks,"* and is primarily intended to mitigate coastal surge flooding, not rain-induced inundation. One interviewee illustrate this with Hurricane Harvey (2007) which: *"produced catastrophic flooding due to excessive rainfall, not storm surge."* Thus, while precipitation contributes to overall flood risk, it remains a secondary concern in terms of design priority. Due to uncertainty and disagreements among future precipitation projections, precipitation will not be considered in further research.

Drought-Induced Vulnerabilities
Following the interrelated findings on temperature and precipitation, global drought conditions produce region specific climatic effects, impacting SSBs in varying ways. In arid or semi-arid areas, prolonged dry periods lead to soil dehydration, shrinkage, and cracking in adjacent SSB structures, like levees or dikes (van Baars et al., 2009). Exemplified by the Maeslant Barrier (Schelland and Smaling, 2022). These effects primarily threaten Flood Protection (F1.1) by weakening support structures and underscoring the importance of Maintaining Structural Integrity (F1.6). The rationale below.

In the Texas Gulf region, drought trends are less extensively documented than precipitation or temperature changes. Following these interrelated drivers, Liu et al. (2013) project that future increases in temperature and evaporation will outpace any gains in rainfall. This creates a net rise in drought severity and frequency. While such conditions may compromise levees or dikes by worsen soil instability and subsidence, the structural performance of Floating Sector Gates at Bolivar Roads appears minimally affected, as no such structures are in direct contact with the planned SSB (refer to Section 4.5). Interviewees acknowledged broader climate impacts such as drought extremes on infrastructure but they consistently emphasized that such drivers exert minimal influence on the core functionality of the SSB itself. Consequently, the risk of failure of the gates due to drought is deemed negligible. Drought is excluded in further research.

Hurricane-Driven Stress
The pressure differences in the Earth's atmosphere, which are in turn due to air temperature differences, creates global wind variations, placing SSBs in coastal zones at particular risk. Strong onshore winds can generate substantial wave action, raising wave run-up and overtopping risks (Bosboom and Stive, 2023; van Baars et al., 2009) that threaten the primary function of Flood Protection (F1.1), with waves induce vibrations, potentially fatiguing gate structures (Tieleman, 2022). Thereby influencing support functions, especially Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6). The rational below (see Figure 5.5).

In the Houston-Galveston Bay Region, hurricanes and tropical storms are frequent between June and November, reaching a peak in August and September (USACE, 2021d; Keim et al., 2007). Historical records indicate an average of one hurricane landfall every 6-8 years, with extreme winds exceeding 240 km/h and heavy rainfall. For example, Hurricane Claudette stalled over southeast Texas in 1979, setting a U.S. record with 1067 mm of rain in 24 hours at Alvin (USACE, 2021d; refer to Appendix E.2). Although the overall storm frequency may remain steady in future models project an increase in wind speed (Knutson et al., 2020), the intensity of hurricanes (i.e., Category 4 and 5) (Colbert, 2022), and in associated extreme rainfall, as noted earlier.

Interviews with experts emphasize that in the Gulf region: *"each hurricane has unique characteristics, including intensity, trajectory, and duration"* (Interview A), introducing new uncertainties for the barrier's structural and operational performance. There is a consensus across the interviewees that hurricanes present multiple threats including reverse-head affect on the gates (Metselaar, 2024), and indirect impacts like power outages. To illustrate, wind-induced storm surges intensify hydraulic loads, increasing the possibility of overtopping or closure failure. Although documented cases of SSB performance during hurricanes are limited, the Lake Borgne Sector Gate's success during Hurricane Ida in 2021 illustrates that well designed barriers can mitigate flooding due to hurricanes (Reynier and Gregg, 2024). Given the potential severity of hurricane impacts, further investigation is conducted in subsequent Section 5.5.

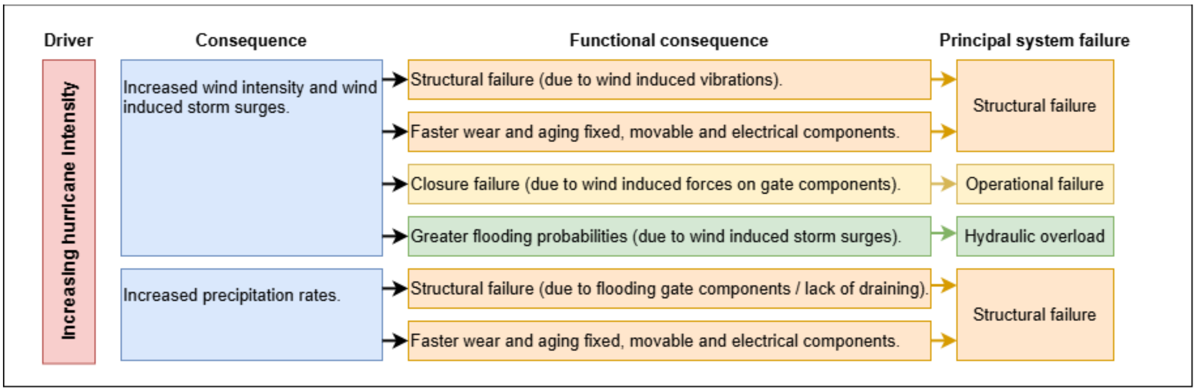


Figure 5.5: Functional consequences physical driver: hurricane.

5.3.2. Sinking Grounds: The Threat of Land Subsidence

In many coastal regions, land subsidence results from factors such as soil compaction, groundwater extraction, and drought. Potentially undermining the stability of hydraulic structures, like levees and dikes (van Baars et al., 2009). For instance, in Thailand and New Orleans, the transitions between hard structures and earthen dikes proved to be vulnerable weak links, often serving as the starting points for erosion (Jonkman and Schweckendiek, 2015). This effect can indirectly compromise a SSB primary function, Flood Protection (F1.1), by changing the levee alignment and stressing support functions. Particularly Maintaining Structural Integrity (F1.6). The rational below.

As noted in Section 4.2, the foundation soils at Bolivar Roads comprise unconsolidated sands and clays (Petitt and Winslow, 1957), with steel piles cut off at $-16\,\mathrm{m}$ (i.e., $-52\,\mathrm{ft.}$) to support the Floating Sector Gates, hence anticipated conceptual design. The subsurface uncertainty risk is classified as medium (USACE, 2021d), as no major seismic hazards have been reported.

Moreover, the progression of subsidence in this area remains minor under current groundwater and oil extraction practices (USACE, 2021d), though future changes in policies, such as intensified drilling policy by the Trump Administration (The Economist, 2024), could induce uneven settlement. Moreover, interviewee A stressed: *"while sea level rise follows a predictable trajectory based on climate models, land subsidence is more variable and site-specific"*. This would mainly affect adjacent flood defenses rather than the gate itself, as the pile-founded design (USACE, 2021d) mitigates settlement. While watchfulness in monitoring settlement is warranted, land subsidence is excluded in further research.

5.3.3. Shifting Currents and Changing Shores

This section examines the evolving hydrodynamic and morphological conditions at Bolivar Roads, emphasizing how the narrowing of the flow profile disrupts the existing morphological equilibrium. It also explores the implications of Relative Sea Level Change (RSLC) and hydrological changes.

Turbulent Waters: Shifting Hydrodynamics and Morphology

Shifts in flow regimes and sediment transport can alter coastal morphology, affecting SSBs in multiple ways. For instance, altered cross-sectional flow and intensified velocities around barriers can lead to scour, sediment deficits, and modified flow patterns (Bosboom and Stive, 2023; Schiereck and Verhagen, 2019). These changes primarily impact two core functions: Flood Protection (F1.1) and Water Exchange (F1.3), by undermining bed stability and altering tidal exchange. Maintaining Structural Integrity (F1.6) is also affected, as greater turbulence and scour pit formation can impose higher stresses on gate foundations (Schiereck and Verhagen, 2019). The rational below (see Figure 5.6).

At Bolivar Roads, modeling indicated that future narrowing of the tidal inlet will disrupt the bay's morphological equilibrium (Ruijs, 2011; refer to Appendix E.2). This constricted flow profile intensifies downstream velocities, generating a tidal jet that promotes scour pit formation (Bosboom and Stive, 2023; refer to Appendix E.2). The resulting increase in flow velocity further fragments the tidal regime, potentially worsen sediment deficits and shifting sediment flow dominance either landward or seaward (de Jong et al., 2012). Interviewees expressed concern that the SSB could disturb the local hydrodynamic equilibrium, potentially triggering morphological responses, and disturbing the Houston Shipping Channel (HSC). Specifically, Interviewee D noted parallels to the Eastern Scheldt Barrier where altered tidal dynamics following construction led to scour formation.

These hydrodynamic changes may also pose significant challenges on maritime traffic, as highlighted by interviewee F. Asymmetrical gate designs can generate uneven shearing forces on large vessels such as tankers, compromising maneuverability and heightening collision risks (Burkley et al., 2022). These findings underscore the importance of further investigation in subsequent Section 5.5.

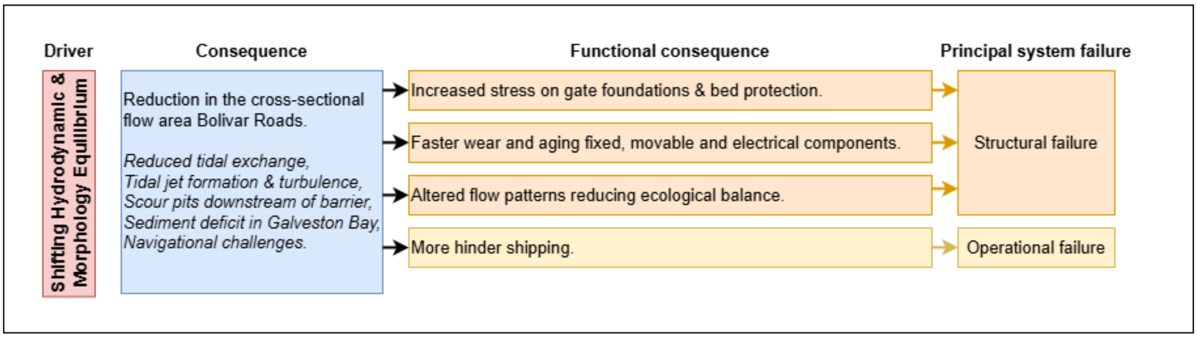


Figure 5.6: Functional consequences physical driver: shifting hydrodynamics and morphology.

Rising Water Levels: The Impact of Relative Sea Level Change (RSLC)

Shifts in sea levels, together with local land subsidence, produce region specific impacts on SSBs. In particular, higher mean water levels increase flood hazards and alter coastal processes (Bosboom and Stive, 2023). For example, rising sea levels heighten tidal flooding and coastal erosion (Bosboom and Stive, 2023). This way placing greater stress on coastal structures and their foundations affecting two core functions: Flood Protection (F1.1) and Water Exchange (F1.3), as well as the supporting function of Maintaining Structural Integrity (F1.6) (refer to Figure 5.7).

In the Houston-Galveston Bay Region measurements by NOAA and USACE indicate a RSLC of approximately $+6.4$ mm/year at Galveston Pier 21 (USACE, 2021d; refer to Appendix E.2). While much variability stems from local settlement and sediment compaction, future projections diverge. USACE 2013 and NOAA 2017 model scenarios (i.e., low, intermediate, and high) predict 0.6 m to 2.4 m of RSLC by 2100 (refer to Appendix E.2), reflecting various assumptions about climate acceleration. While changes have been gradual, these projections highlight great uncertainty.

For the Floating Sector Gates at Bolivar Roads, rising RSLC may leads to increased gate loads, prolonged storm durations, and more frequent closures (Hamerslag and Bakker, 2023; Trace-Kleeberg et al., 2023). These intensified operational demands elevate the risk of structural failure, while simultaneously reducing shipping windows (Hamerslag and Bakker, 2023) through the HSC. Also interviewees emphasized that RSLC is one of the most critical uncertainties, potentially requiring: *"higher barriers, stronger foundations, and more adaptable gates to handle extreme water levels"* (Interview B). As noted in Interview C, if sea level rise exceeds projections, the barrier may require significant modifications, directly affecting sill elevation and foundation stability. Critical components including mechanical and electrical systems, experience accelerated wear and shortened maintenance intervals (Trace-Kleeberg et al., 2023). Given the significant uncertainty surrounding regional RSLC, continued exploration is conducted in subsequent Section 5.5.

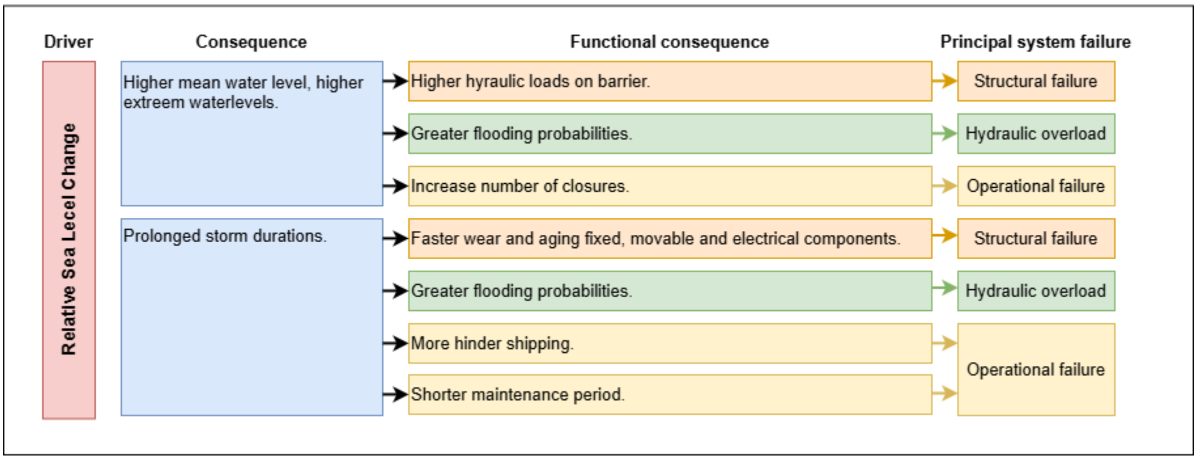


Figure 5.7: Functional consequences physical driver: relative sea level change.

Hydrology in Motion: River Discharge and Coastal Dynamics

River discharge can influence SSB's primary functions, Flood Protection (F1.1) and Water Exchange (F1.3), by altering water levels, flow velocities, and sediment transport (Jonkman et al., 2017). Increases in discharge may cause localized scouring and erosion. These decreases can lead to sediment deposition that changes channel morphology. Either way, these phenomena can casually affect the supportive function of Maintaining Structural Integrity (F1.6).

In the Houston-Galveston Bay Region approximately 12.3 million cubic meters of freshwater enter the estuary annually, primarily from the Trinity (54%) and San Jacinto (28%) rivers (USACE, 2021d). Studies suggest a modest upward trend in mean river flow (Mauget, 2004; Kalra et al., 2008; Xu et al., 2013) although future projections (2071–2100) point to a possible runoff decline of 10–100 mm per year (Hagemann et al., 2013; Döll and Zhang, 2010). During SSB closures, high river inflows can raise water levels in Galveston Bay, potentially increasing hydraulic loads (Mooyaart et al., 2025). Nonetheless, the bay's large surface area provides ample storage (USACE, 2021d), limiting the stress on the Floating Sector Gates. Therefore, river discharge factors are deemed negligible for future research.

5.3.4. Unknown-Unknown Physical Drivers

Certain unforeseeable events, commonly described as "Black Swans" (Taleb, 2007), can significantly impact SSBs but are rarely captured in conventional risk models. Examples such as the 2010 Deepwater Horizon incident (BP, 2010), tunneling in the adjacent Maeslant Barrier dikes due to animal activity, or the nesting of protected bird species on the Maeslant Barrier itself (Schelland and Smaling, 2022), illustrate how unexpected events can pose systemic risks. This includes sudden threats to structural components and operations. This unpredictability influences both the primary- and supportive functions. For the Floating Sector Gates at Bolivar Roads such high-impact events emphasize the need for robust and adaptable designs that incorporate system redundancies. While specific scenarios are difficult to anticipate, integrating flexible O&M regimes and including 'lessons learned' from existing barriers helps mitigate potential catastrophic outcomes. Acknowledged in subsequent Section 5.5.

5.3.5. Conclusion on the Impact of Physical Drivers

Multiple physical drivers, ranging from rising air temperatures to shifting coastal morphology, affect SSB performance in the Houston-Galveston Bay Region. Based on historical trends, future projections, and their assessed impact on functional performance via failure pathways, four physical drivers stand out as most dominant: Temperature, Hydrodynamics and Morphology, RSLC, and Hurricanes (see Figure 5.12 and refer to Appendix E.2). These were consistently highlighted in prior studies, and marked with '+' in Figure 5.3. Other drivers such as precipitation, land subsidence, drought, and changes in inland hydrology, showed lower magnitude trends or limited impact on functional performance, therefore deprioritized. Low-probability, high-impact "Black Swan" events were acknowledged but excluded from further analysis due to their unpredictability. The four selected physical drivers will guide future scenario development (refer to Section 5.5).

5.4. Socio-Economic Forces Shaping Barrier Performance

This section examines socio-economic drivers that influence the performance of the Floating Sector Gates following the same reasoning as for physical drivers. Each driver was identified and assessed based on historical patterns and projected trends from existing studies. Their qualitative change magnitude was evaluated for potential impact on system functionality, using the failure pathways defined by Mooyaart et al. (2025) (refer to Section 5.2). Drivers likely to affect functional performance were retained for further analysis (i.e., marked with '+' in Figure 5.3). The analysis begins with population growth (Section 5.4.1) and economic development (Section 5.4.2), followed by institutional dynamics (Section 5.4.3), policy and law (Section 5.4.4), stakeholder engagement (Section 5.4.5), knowledge continuity (Section 5.4.6), and emerging unkmown-unknowns (Section 5.4.7).

5.4.1. Population Growth and Flood Risk

Population increases can indirectly affect an SSB's primary function, Flood Protection (F1.1), by driving higher flood-risk awareness and potentially stricter design standards (Du et al., 2020). For instance, in the Houston-Galveston Bay Region, where the population surged from 4.7 million in 2010 to 5.6 million in 2020, and is projected to reach 7.8 million by 2045 (USACE, 2021e). This growing urban footprint intensifies land-use pressures, particularly in low-lying, flood-prone zones (Brekelmans et al., 2012).

Because the planned Floating Sector Gates lie on artificial islands at Bolivar Roads (refer to Section 4.5) direct competition with residential development is minimal. The barrier's design threshold involves closure for storm events with a 1-in-50-year recurrence (USACE, 2021a). This is unexpected, as a barrier, combined with a robust dune system, would typically be expected to significantly reduce storm surge and damage from more frequent hurricanes, particularly those with return periods ranging from 5 to 50 years (Merrell et al., 2021) (e.g., Maeslant Barrier's which closes for 5 to 10 year events (Trace-Kleeberg et al., 2023), and the Eastern Scheldt barrier on an annual basis). From a trade-off perspective, tightening closure criteria could provide even greater safety protection to a growing population but at the cost of more frequent gate operations. Given that development pressures do not directly intersect with the gate's physical footprint and the gate possible adjustment of closure levels or frequencies, population growth is deemed a negligible driver for future research.

5.4.2. Economic Growth: Fueling Maritime Challenges

Regional economic growth can indirectly impact an SSB's primary function, Flood Protection (F1.1), along with its support functions. This effect is evident at the Maeslant Barrier, which is closely located to the Port of Rotterdam, where surrounding projects like 'Maasvlakte 2' and the 'Zand Motor' altered the local water system, influencing barrier performance (van den Dungen et al., 2016). Rising industrial output and urbanization typically lead to increased maritime traffic (van den Dungen et al., 2016) elevating the frequency and scale of shipping operations and, consequently, complicating the O&M of SSBs. The rationale is outlined below (refer to Figure 5.8).

In the Houston-Galveston Bay Region, economic activity is in this research defined primarily through shipping in the HSC which handles over 8,000 deep-draft vessels annually (USACE, 2021e) and has grown alongside a jump in regional employment from 2.3 million to 2.9 million between 2010 and 2020 (USACE, 2021e).

Interviewee F noted that while the overall number of vessels has stayed relatively stable over the past decade, there has been a marked increase in vessel size. Interviewee A: *"The Gulf region is experiencing increasing maritime trade, with ever-larger vessels requiring deeper and wider shipping channel."* Several interviewees emphasized that larger ships increase navigational complexity and raise compatibility concerns with fixed (flood defense) infrastructure.

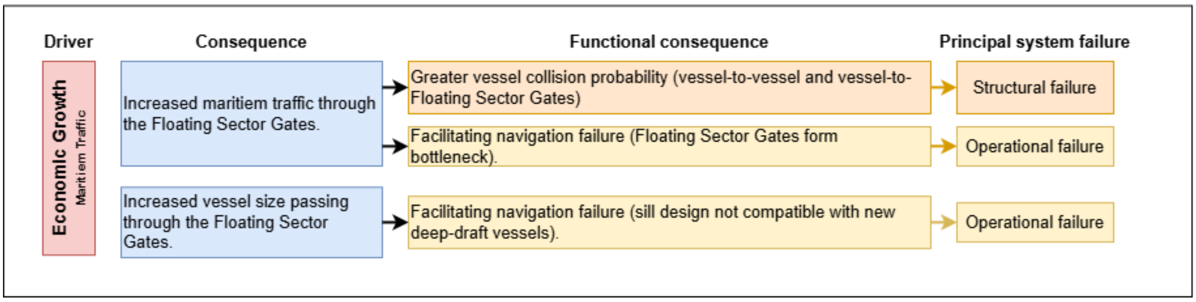


Figure 5.8: Functional consequences socio-economic driver: economic growth.

Global trends toward larger vessels (Tran and Haasis, 2015; Dempsey et al., 2021; refer to Appendix E.3) further elevate navigational demands. Port of Houston expansion projects like Project 11, aim to deepen and widen the HSC (Port Houston, 2024) to accommodate post-Panamax vessels (Jonkman, van Ledden, et al., 2013), which is driven by economies of scale that increased container ship capacity (Meersman et al., 2014) by 1,500% since the late 1960s (Yang, 2019). Potentially conflicting with gate design parameters. Interviewee F notes that: *"a narrow passage through the barrier increases the risk of collisions,"* reinforcing the need to future proof gate geometry against increasing vessel dimensions and maneuverability limitations.

Texas industries fuel an uptick in crude oil tanker traffic (i.e., main business Port of Houston) (Vestereng, 2024), heightening design compatibility demands (Burkley et al., 2022). Emphasized by interviewee A: *"ports along The Gulf coast are in constant competition for deeper channels to accommodate the latest generation of cargo and oil tankers."* In this study, maritime traffic interaction with the SSB is defined by vessel draft, posing the most prominent future design challenges.

Following this, more frequent gate closures to manage flood threats could disrupt vessel schedules, incurring higher trade costs (Sánchez et al., 2003; Kaneria et al., 2019). Over the long term, misalignment between gate design and evolving vessel sizes could lead to operational failures (e.g., an incompatible sill depth), which is heavily emphasized by the interviewees. To accommodate these growth dynamics, future research will focus on this trend in subsequent Section 5.5.

5.4.3. Institutional Dynamics: Navigating Organizational Change

Over the long service life of an SSB changing regulations, restructure agencies, and evolving strategic aims introduce organizational uncertainties (van den Dungen et al., 2016). Even when a barrier such as the Floating Sector Gates is rarely used, it exists within multi-interest organizations that may undervalue its upkeep, exposing vulnerabilities in Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6). These supportive functions indirectly influence the barrier's primary tasks, particularly Flood Protection (F1.1). The rational below (refer to Figure 5.9).

Interviewees underscore that organizational capacity and long-term funding are major uncertainties in the O&M of the Floating Sector Gates. Interview E noted that: *"GCPD may need time and resources to develop robust maintenance routines, specialized staff, and reliable response systems,"* raising concerns about their readiness post-handover. Interview C emphasized U.S.: *"weak infrastructure maintenance culture,"* where maintenance often receives attention only after failure.

In theory, different "Institutional Logics": Asset Management (AM) Logic (i.e., focusing on long-term maintainability), Project Logic (i.e., emphasizing short-term efficiency), and State Logic (i.e., favoring procedural compliance), can diverge organizational goals and approaches, refer to Appendix A.2 for an elaboration on Institutional Logics Theory. Evidence from the Netherlands reveals that shifting to risk-based AM redefined maintenance priorities for the Maeslant Barrier (i.e., Asset Management Logic) (van den Bogaard and van Akkeren, 2011), whereas the fast track design-build model for the Lake Borgne Surge Barrier in the U.S. accelerated construction post-Katrina (i.e., Project Logic) (Interview C; Huntsman, 2012) but compromised future maintainability (Schwartz and Schleifstein, 2018).

To effectively navigate these conflicting "Logics," organizations overseeing SSBs, including the GCPD responsible for the Floating Sector Gates' O&M, must embrace innovative solutions such as digital twins (Ponsioen, 2023), remote sensing, and predictive analytics (e.g., "talking assets"). This adaptability is particularly important given that electrical and software systems typically undergo significant updates every eight years (Rijkswaterstaat, 2019). According to interviewee B, software reliability has proven to be a critical vulnerability, as evidenced by challenges encountered during the Maeslant Barrier's closure operations (Schelland and Smaling, 2022). These advancements underscore a trade-off: while prioritizing maintainability may extend initial construction timelines, it ultimately minimizes operational disruptions, and reduces life-cycle costs (van den Dungen et al., 2016).

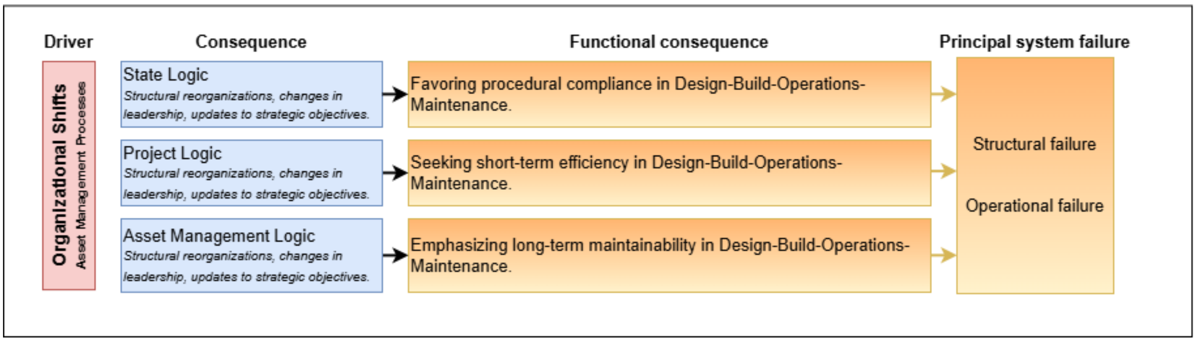


Figure 5.9: Functional consequences socio-economic driver: organizational shits and processes.

Organizational shifts significantly shape SSB resilience by influencing how design, operations, and maintenance decisions are made and funded. Given these long-term implications, this socio-economic driver can lead to operational or structural failures if not carefully managed. Acknowledging and planning for evolving agency priorities thus becomes an important component in ensuring SSB performance and is considered in further research (refer to Section 5.5).

5.4.4. Politics, Policy & Law: The Power of Policy

Shifting regulations, extended political debates, and evolving public investments can deeply affect SSB design, operations, and maintenance (van den Dungen et al., 2016). These factors often impose rigid new requirements, sometimes mid-project, as illustrated by the Maeslant Barrier's costly hinge-paint retrofit following an environmental law change (van den Dungen et al., 2016), or the legislative changes regarding health and safety (i.e., ARBOwet) during maintenance works (Schelland and Smaling, 2022). While these influences primarily target the supportive functions of Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6), their secondary effects ripple through Flood Protection (F1.1) and other SSB functions. The rational below (refer to Figure 5.10).

Several interviewees emphasized that slow political processes delay approvals and construction timelines for the Bolivar Roads project. According to Interviewee E, even with the urgent need for coastal protection, complex public funding mechanisms such as reliance on state-level decisions and voter referendums, contribute to bottlenecks. As emphasized by interviewee E, the GCPD, responsible for the future O&M of the barrier, depends heavily on non-federal resources. This introduces funding instability, especially as shifts in state budget priorities could compromise long-term barrier performance.

Interview insights also revealed that industry influence can significantly (de-)accelerate project phases. For instance, the: *"rapid approval of Project 11"* (Interview F) of the HSC was driven by a strategic coalition between the oil, gas, and shipping industries, illustrating how political and economic alignment can bypass standard bureaucratic delays.

In practice, large-scale SSBs demand extensive public funding to meet evolving safety standards (DeSoto-Duncan et al., 2011; Aerts et al., 2013). With project budgets ranging from $940 million (i.e., Maeslant Barrier, 1997) to $7.7 billion (i.e., St. Petersburg Barrier, 2011) (Mendelsohn et al., 2022), public check, policy stagnation, and political debate can stretch lead times and delay completion (Kharoubi et al., 2024). Conversely, urgent political mandates such as post-Katrina rebuilding, can speed up construction (e.g., Lake Borgne Barrier) but risk heightened O&M complexities.

Within this arena, conflicting "Institutional Logics" steer decision-making: State Logic (i.e., emphasizes procedural compliance, can elongate timelines amid bureaucracy and public oversight), Project Logic (i.e., focuses on near-term build efficiencies, can sometimes compromise long-term maintainability), and Asset Management Logic (i.e., targets life-cycle performance, may slow initial construction but can reduce overall costs and failures). Refer to Appendix A.2 for an elaboration on Institutional Logic Theory. In the Houston-Galveston Bay Region, these same drivers influence the Floating Sector Gates through regulations, budget allocations, and public acceptability. Thus, is determined in further research (refer to Section 5.5).

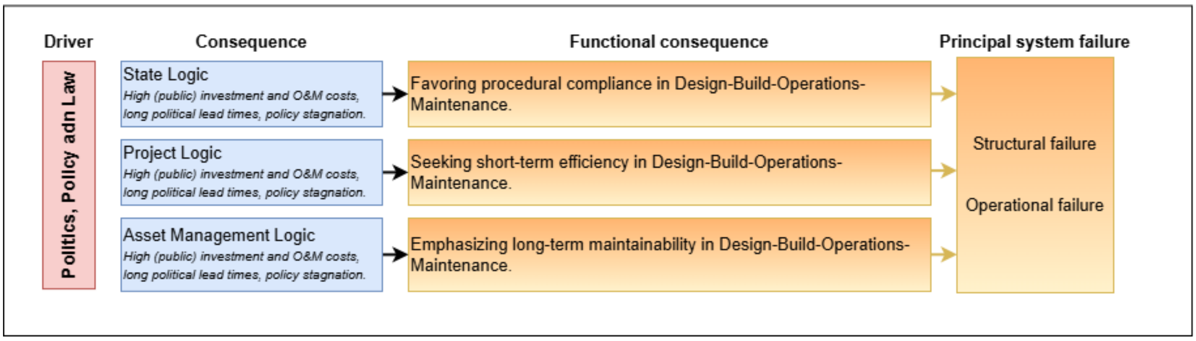


Figure 5.10: Functional consequences socio-economic driver: politics, policy and law.

5.4.5. Bridging Interests: Multiple Stakeholders

Large-scale SSB projects span diverse interests, from port authorities and local governments to NGOs, all of whom can influence both core and supportive functions. Indeed, the Maeslant Barrier experience, where initial opposition from the Port of Rotterdam later shifted to collaboration, demonstrates how economic and ecological concerns can converge (van den Dungen et al., 2016). Such evolving stakeholder dynamics can directly affect the basic functions, while also indirectly shaping Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6). The rational below (refer to Figure 5.11).

In the Houston-Galveston Bay Region, multiple stakeholders include industries reliant on the Houston Shipping Channel, local communities concerned with flood safety, and environmental groups advocating for habitat preservation (refer to Section 4.3). Interviewee D specifically emphasized that ecological concerns could influence public perception and stakeholder support, making proactive engagement essential. Interview D pointed out the legal risks from environmental groups, noting that: *"minor stakeholders can challenge large-scale infrastructure projects,"* potentially delaying implementation. Stakeholder priorities can change over time due to unexpected developments, political pressure, or shifts in public opinion (Meijerink, 2005; refer to Section 4.3.2).

Consequently, the design, construction, and O&M of the Floating Sector Gates must adapt competing demands: economic development, ecological stewardship, and stringent flood protection, throughout the gate's lifespan. Failing to engage actors early can result in costly redesigns or delayed projects, as seen with the Eastern Scheldt Barrier where a total closure was met with much public opposition. (van der Ham et al., 2018; Taebi et al., 2020).

Hence, proactive stakeholder management becomes a strategic lever: it can mitigate future conflicts, enhance social acceptance, and encourages adaptive decision-making (de Bruijn and ten Heuvelhof, 2008). This research therefore includes this system driver in further research (refer to Section 5.5).

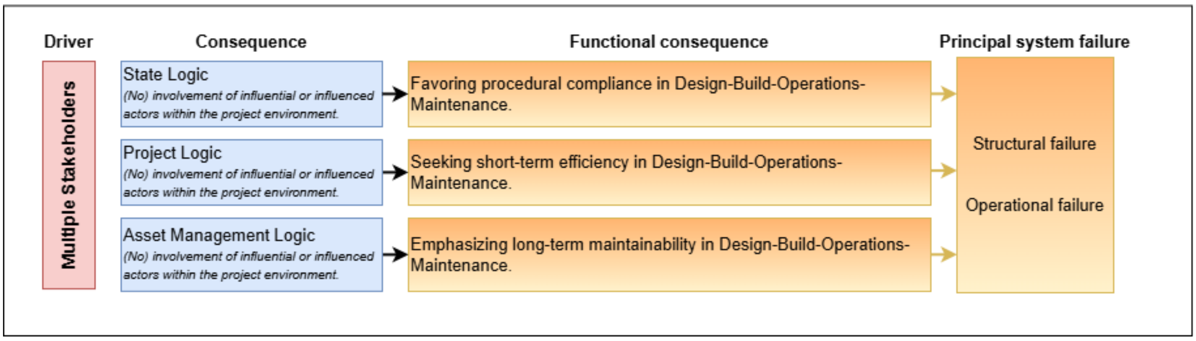


Figure 5.11: Functional consequences socio-economic driver: multiple- stakeholders.

5.4.6. Preserving Expertise: Knowledge Continuity & Craftsmanship

The long lifespan of a SSB requires a continuous transfer of specialized technical know-how, yet infrequent operational use, the uniqueness, and long lifespan of each barrier can lead to a decreasing pool of experienced personnel (van den Dungen et al., 2016). While the basic functions may not seem directly affected, this driver significantly influences the functions of Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6), thereby shaping overall system reliability.

In the Netherlands, rapid knowledge gains followed the 1953 flood disaster, yet long pauses in major SSB construction caused competencies to decay (Walraven et al., 2022). Much of this knowledge is tacit, rooted in hands-on experience rather than formal documentation, making it susceptible to loss through generational turnover (Kamps, van den Boomen, et al., 2024). The Maeslant Barrier exemplifies this challenge: while design calculations remained accessible, reconstructing the original assumptions required extensive effort due to absent or eroded tacit knowledge (Kamps, van den Bogaard, et al., 2024). Increasing reliance on external specialists can fill short-term skill gaps but may also introduce vulnerabilities if outsourced partners restructure or exit the market (Kamps, van den Bogaard, et al., 2024). Thus, maintaining in-house familiarity with core SSB systems mitigates potential disruptions, and ensures continuity in maintenance routines.

Interviewee B emphasized that the long-term functionality of SSB depends on preserving specialized, often tacit, technical knowledge across generations. In particular, organizational restructuring at Rijkswaterstaat (RWS) was cited as warning example, where the fragmentation of responsibilities and shifting mandates led to the gradual erosion of in-house expertise. Interviewee B remarked that: *"Rijkswaterstaat's restructuring led to a loss of specialized knowledge, impacting maintenance quality and decision-making."* Interviewee B noted that the growing reliance on third-party contractors, while offering short-term flexibility, introduced long-term vulnerabilities, especially when vendor lock-in limits internal knowledge retention. These trends mirror concerns raised in the Dutch context, where long pauses in major infrastructure projects resulted in the degradation of craftsmanship and made it difficult to interpret original design assumptions years later.

Collectively, these findings underline the strategic importance of institutional mechanisms that actively support knowledge retention such as dedicated training programs, long-term staffing strategies, and internal documentation practices. Maintaining in-house expertise is not only an operational preference but a safeguard against the cumulative risks posed by knowledge weakening over the service life of complex, infrequently used SSBs. Although the importance of knowledge continuity is undisputed, it manifests as part of "Organizational Shifts and Processes." Therefore, existing research forms a sufficient foundation, and this study does not treat "Knowledge & Craftsmanship" as a standalone driver. Nevertheless, the lesson is clear: advance sustained expertise over the SSB's life-cycle is integral to mitigating long-term operational and structural risks, further stipulated in Section 6.5.

5.4.7. Unknown-Unknown Socio-Economic Drivers

Certain low-probability but high-impact “Black Swan” events (Taleb, 2007) such as sudden funding cuts, policy reversals, or global financial shocks, can profoundly reshape an SSB’s operating context. For example, national infrastructure cuts in the Netherlands led to the removal of certain Maeslant Barrier gate components, which currently increases maintenance costs (Schelland and Smaling, 2022). Although these disruptions are rarely captured in conventional risk models, they can swiftly alter the economic and political landscape, affecting both the basic and supportive functions. For instance, the 2008 global financial crisis (The Economist, 2017), demonstrated how infrastructural investment can be cut down almost overnight, potentially leading to construction delays, or maintenance backlogs.

The Houston-Galveston Bay Region is equally susceptible to these socio-economic unknown-unknowns. Funding shortfalls, accelerated population shifts, or supply-chain disruptions can compromise the Floating Sector Gates’ performance by delaying essential upgrades or reducing skilled labor availability (Kharoubi et al., 2024; Alcaraz and Zeadally, 2015). Thus, planning for such uncertainties involves adopting flexible design and robust O&M strategies to buffer against abrupt economic downturns or geopolitical upheavals. Future work in Section 6.5 will further explore how O&M regimes can maintain gate resilience when confronted with unforeseen social, or financial shocks.

5.4.8. Conclusion on the Impact of Socio-Economic Drivers

A range of socio-economic drivers affect the functional performance of the Floating Sector Gates in the Houston–Galveston Bay Region. Based on historical trends, projected developments, and their assessed impact via failure pathways, four drivers stand out as most influential: Economic Growth (i.e., increased vessel draft), Organizational Shifts, Politics, Policy & Law, and the Role of Multiple Stakeholders (see Figure 5.12 and refer to Appendix E.3). These were repeatedly emphasized in literature and are marked with ‘+’ in Figure 5.3. Other drivers, such as population growth and knowledge continuity, were found to have limited direct impact on functional performance and were deprioritized. The four selected socio-economic drivers will inform the scenario development in Section 5.5.

5.5. Identifying Trend-Breakers

This section build on the shortlisted system drivers identified in Sections 5.3 and 5.4. Chosen for their historical and projected change magnitude and their impact on SSB functionality (see Figure 5.12). To test how these drivers might evolve under disruptive conditions, four qualitative scenarios for the Houston–Galveston Bay Region were developed, adapted from the Dutch Delta Scenarios, covering socio-economic and climate trajectories to 2100. Through expert and stakeholder interviews (Section 5.5.1), drivers were discussed within these scenarios (see column “Expert & Stakeholder Interview Outcome” in Figure 5.12). Two proved most dominant and are marked ‘++’ in Figure 5.3. These “trend-breakers” form the basis for selecting the key driver to guide design options in Phase 3 (Section 5.5.2).

5.5.1. Delta Scenarios: Mapping for Uncertain Tomorrows

The Delta Scenarios, developed by Ministry of Infrastructure and the Environment and Ministry of Economic Affairs (2014), offer insights into future climate and socio-economic conditions in the Netherlands. They highlight challenges related to water availability, flood safety, and spatial planning. By exploring plausible futures, these scenarios aid policymakers in problem analysis, strategy formulation, and evaluating long-term adaptation measures. As emphasized by van der Brugge and de Winter (2024) and illustrated in Figure 5.13, the Delta Scenarios are organized along two primary axes:

Climate change and emissions:
This axis ranges from limited to severe climate change, reflecting greenhouse gas emission pathways from strong mitigation to minimal reduction. Resulting impacts include temperature rise, altered precipitation patterns, and RSLC, directly affecting water management.

Socio-economic development:
This axis reflects population and economic growth rates. High growth drives urbanization, increasing demand for water, infrastructure, and land, while low growth reduces resource pressure but may limit adaptation funding and urgency.

Function		Basic Functions			Supportive Functions		Expert & Stakeholder Interview Outcome
System Driver		Flood Protection (F1.1)	Facilitate Navigation (F1.2)	Water Exchange (F1.3)	Managing Operations (F1.5)	Maintaining Structural Integrity (F1.6)	
Physical	Temprature	*See F1.5 & F1.6*			Closure failure (due to thermal expansion steel components)	Structural failure (due to thermal expansion steel components).	
	Precipitation	*Limited Impact*		*Limited Impact*		*Limited Impact*	
	Drought						
	Hurricanes (wind)	Greater flooding probabilities (due to wind induced storm surges)	*Limited Impact*		Closure failure (due to wind induced vibrations)	Fast wear and aging fixed, movable and electrical components; Structural failure (due to wind induced	*Limited Impact*
	Land subsidence						
	Shifting hydrodynamic and morphological		Altered flows hinder shipping.			Increased stress on gate foundation & bed protection; Faster wear and aging fixed, movable and electrical	*Limited Impact*
	Relative Sea Level Change	Greater flooding probabilities; Higher hydraulic loads on barrier.	Increase number of gate closures.		Increase number of gate closures.	Shorter maintenance period; Faster wear and aging fixed, movable and electrical components.	*High Impact*
	Unknown-Unknowns	*Unknown*	*Unknown*	*Unknown*	*Unknown*	*Unknown*	*Unknown*
Socio-Economic	Population Growth						
	Economic Growth (Vessel Draft)		Gates form bottleneck; Not compatible with drafts			Greater vessel collision probability.	*High Impact*
	Organizational Shifts	*Indirect Impact*	*Indirect Impact*	*Indirect Impact*	State Logic vs. Project Logic vs. Asset Management Logic.	State Logic vs. Project Logic vs. Asset Management Logic.	*Indirect Impact*
	Politics, Policy and Law	*Indirect Impact*	*Indirect Impact*	*Indirect Impact*	State Logic vs. Project Logic vs. Asset Management Logic.	State Logic vs. Project Logic vs. Asset Management Logic.	*Indirect Impact*
	Multiple Stakholders	*Indirect Impact*	*Indirect Impact*	*Indirect Impact*	State Logic vs. Project Logic vs. Asset Management Logic.	State Logic vs. Project Logic vs. Asset Management Logic.	*Indirect Impact*
	Knowledge Continuity						*Indirect Impact*
	Unknown-Unknowns	*Unknown*	*Unknown*	*Unknown*	*Unknown*	*Unknown*	*Unknown*

Legend

Grey	Negligible Impact	Light blue-grey	Unknown Impact
Green	Limited Impact	Light orange	Important / Dominant System Driver
Light blue	Indirect Impact	Orange	Identified Most Important System Driver
Pink	High Impact		

Figure 5.12: Overview consequences system drivers impacting floating sector gates.

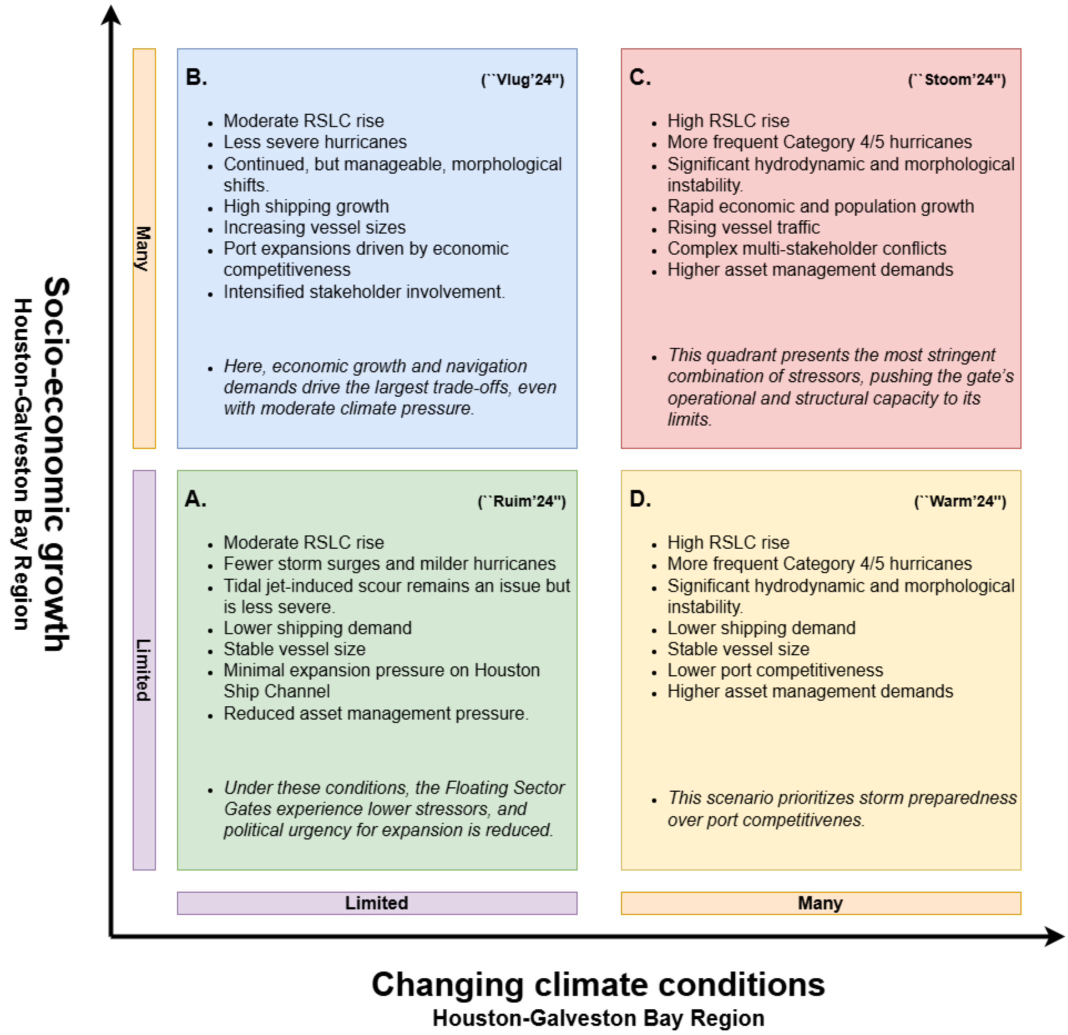


Figure 5.13: The 4 Delta Scenarios for The Houston-Galveston Bay Region.

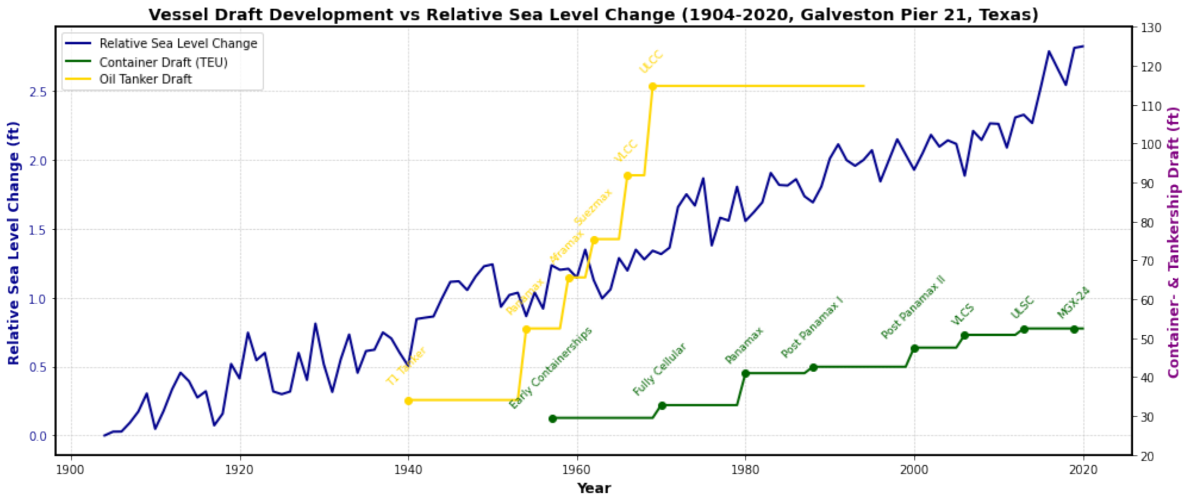


Figure 5.14: International vessel draft development and RSLC (USACE, 2021d; Notteboom et al., 2022; Rodrigue, 2024), adjusted by S.D. van der Geer).

Combining these two axes produces four distinct scenarios (refer to Figure 5.13):

- *Vlug'24 (Fast):* Limited Climate Change / High Socio-Economic Growth;
- *Ruim'24 (Room):* Limited Climate Change / Low Socio-Economic Growth;
- *Stoom'24 (Steam):* Severe Climate Change / High Socio-Economic Growth;
- *Warm'24 (Hot):* Severe Climate Change / Low Socio-Economic Growth.

Each scenario outlines possible trajectories in RSLC, population and economic growth, water availability, and flood safety. By mapping different combinations of these factors, policymakers and engineers can identify the key pressures on water infrastructure, including SSBs, and plan adaptation measures accordingly (van der Brugge and de Winter, 2024).

Adopting a similar two-axis approach for the Houston-Galveston Bay Region (Figure 5.13), a clear trade-off emerges across the quadrants: physical extremes, intensify along the climate axis, while socio-economic pressures, rise along the development axis. Quadrant C presents the most demanding scenario, where severe climate impacts intersect with rapid industrial and maritime growth, necessitating measures to balance economic activity and flood risk resilience. These four qualitative scenarios yields a first conceptual understanding on how the SSB could adapt to diverting futures.

5.5.2. From Sea-Level Rise to Super Ships

Building on the study findings about socio-economic and physical drivers (refer to Sections 5.3.5 and 5.4.8), this section presents an trade-off to identify which system driver most critically influences the Floating Sector Gates' long-term functional performance.

Dominant Drivers and the Rationale Behind Their Significance

In the socio-economic domain, four drivers stand out: Economic Growth (i.e., Increased Vessel Size), Organizational Shifts and Processes, Politics, Policy & Law, Multiple Stakeholders. Meanwhile, among physical drivers, Temperature, Shifting Hydrodynamics & Morphology, Relative Sea Level Change (RSLC), Hurricanes have the highest impact. Although these eight drivers collectively shape functional performance (see Figure 5.12), certain ones exert more direct, high-stakes pressure on design and operations. This can be constituted by the four Delta Scenarios (see Figure 5.13), outlined below.

First to mention: a probabilistic design approach, often applied to hydraulic structures, emphasizes the "upper tails" of probability distributions, which are rare but high-impact events (Jonkman, Steenbergen, et al., 2015). Similarly, Taleb (2007) stresses preparing for extremes rather than average conditions. Among the Delta Scenarios (see Section 5.5.1), Quadrant C ("Stoom'24") best aligns with this principle, combining rapid socio-economic expansion with severe climate stressors: RSLC (USACE, 2021d), frequent Category 4–5 hurricanes (Colbert, 2022), accelerated port expansions (Port Houston, 2024), larger vessels (Dempsey et al., 2021; Tran and Haasis, 2015), and complex stakeholder interactions (den Heijer, Rijke, et al., 2023). Designing for Quadrant C also ensures resilience under milder scenarios (A, B, D), highlighting which drivers demand flexibility in design.

Although various drivers impact the SSB, the projected changes in Quadrant C underscore RSLC and Economic Growth (i.e., Increased Vessel Draft) as the most direct critical stressors in the Bay Region. Hence, which were most emphasized by the interviewees. RSLC is forecasted to rise by 2–2.4 m (i.e., 6.5–8 ft.) (USACE, 2021d), increasing hydraulic loads and operational demands. Meanwhile, container vessels have quadrupled in size over the past 25 years (Dempsey et al., 2021, see Figure 5.14) and are expected to grow further (Tran and Haasis, 2015), driven by expanding trade agreements (Meersman et al., 2014). Over its lifespan, the SSB faces increasing operational challenges from RSLC, as rising hydraulic loads may exceed elevation or closure capacity (Hamerslag and Bakker, 2023), complicating maintenance (Trace-Kleeberg et al., 2023). While retrofitting is feasible, it is costly and complex. Simultaneously, rapid Economic Growth in maritime trade, risks surpassing design limits (Dempsey et al., 2021) such as draft clearance. Beyond port competitiveness, larger ships navigating narrower channels heighten structural risks. The analysis shows that RSLC and Economic Growth, specifically larger vessel drafts, are the two governing drivers for Bolivar Roads. The rationale for selecting Economic Growth as the primary driver for Phase 3 options for flexibility in design exploration is outlined below.

Prioritizing Economic Growth - Increased Vessel Draft
Although both RSLC and Economic Growth (i.e., Increased Vessel Draft) are significant drivers, this study prioritizes the impact of increasing vessel size, for further analysis. This focus is justified by several factors. First, the time scale of impact differs considerably: rapid port expansions and shifts in global shipping logistics can reshape design requirements within a decades, whereas RSLC typically unfolds over decades (IPCC, 2023), see Figure 5.14. Hence, operational bottlenecks faster emerge if vessel sizes outgrow channel dimensions, undermining port competitiveness (Dempsey et al., 2021), which is particularly important in the region.

Retrofitting SSB components demands mega-project long-lead times (Davies et al., 2009), leaving little room for new design studies. With slow changing RSLC their is “plenty” of time to start a retrofitting design process, whereas with rapid increasing vessel sizes, driven by GDP increase (Meersman et al., 2014), the structure must be able to respond fast. Finally, the body of knowledge surrounding RSLC regarding SSBs is relatively well-developed, with extensive research on its implications (e.g., Trace-Kleeberg et al., 2023; Mooyaart et al., 2023) whereas the impact of maritime growth remains less explored. While RSLC remains a critical long-term concern, in this study it is deprioritized. Consequently, this research emphasizes Increased Vessel Draft as the primary driver requiring options for flexibility in design and complemented AM strategy, which will be investigated in Phase 3.

5.6. Summary and Conclusions

The central dilemma discussed in this chapter is that only a subset of system drivers affecting the functional performance of SSBs can be anticipated. Each design configuration reveals its own vulnerabilities and uncertainties once built. Rather than eliminating uncertainty in the SSB design, this chapter identified the most likely drivers and evaluated their potential impact on SSB functional performance based on heuristics, with a focus on the Floating Sector Gates at Bolivar Roads. This provides guidance for incorporating design and governance flexibility to cope with a range of future conditions.

This completes a first step toward answering SQ1–SQ4, especially *[SQ1] What is the distribution of potential future scenarios for physical and socio-economic system drivers that the Bolivar Roads Gate System in the region may encounter over the next 150 years?* First, physical and socio-economic drivers were inventoried and rated on their historical and projected trend magnitude, based on existing studies. Each was then mapped to potential SSB failure modes: operational, structural, or hydraulic overload. Only drivers whose trend magnitude suggested a high likelihood of triggering these failure modes were retained. This yielded eight dominant drivers: Temperature, Hydrodynamics & Morphology, Relative Sea Level Change (RSLC), Hurricanes, Multiple Stakeholders, Politics, Policy and Law, Organizational Shifts (i.e., Operations & Maintenance (O&M)), and Economic Growth (i.e., Increased Vessel Draft).

Second, the Dutch Delta Scenarios were adapted to four qualitative future scenarios for the Houston–Galveston Bay Region. These scenarios, combined with expert and stakeholder interviews, tested each driver under disruptive trajectories, narrowing the list to two: Relative Sea Level Change (RSLC) and Economic Growth (i.e., manifested as increasing vessel draft). Finally, the two remaining drivers were ranked on (I) expected rate of change and (II) current research coverage. Although RSLC constitutes the foremost long-term threat by raising hydraulic loads and maintenance demands, rapid growth in vessel draft could outpace barrier design limits within a much shorter time frame. Together, these three considerations (i.e., historical-, projected trend magnitude affecting functional performance, expert judgment) justify the selection of Economic Growth (i.e., increased vessel draft) as the governing driver for the Phase 3 exploration of options for flexibility in design.

Phase 2 showed that physical drivers like RSLC are easier to quantify, while socio-economic drivers are more unpredictable. In addition to the proposed maintainability focused mode (refer to Section 4.7), Phase 2 results call for a second mode prioritizing options for flexibility in design in the design and planning process to let SSBs evolve with uncertainty, avoiding design lock-in. This sets the stage for exploring options for flexibility in design in Phase 3.

6

Phase 3: Options for Flexibility in Design

Phase 3 determines where options for flexibility in design can give the greatest value, building on Phase 1 and the governing system drivers identified in Phase 2. Although flexibility can in theory be incorporated into any SSB component, each element is affected differently by the system drivers and entails its own cost of future modification. A trade-off is required: priority is given to components most sensitive to system drivers and costly to retrofit, such as designing an adaptable sill to accommodate future larger ship drafts. The goal of Phase 3 is to develop an adaptive SSB component (i.e., dictated to CE), together with an accompanied Asset Management (AM) strategy (i.e., dictated to CME). Addressing sub-questions 3 and 4, especially SQ3. Section 6.2 presents the Engineering System Matrix (ESM), the cross-domain dependent relationships between the system drivers and SSB components. Section 6.3 integrates cost of changing SSB components with the cross-domain dependent relationships from the ESM. This way deriving a risk susceptibility ranking for the SSB components, resulting in the sill as best options for flexibility in the design. Section 6.4 takes these insights into four alternative spatial-functional adaptable sill concepts, from which two are verified (i.e., basic structural design calculations). Finally, Section 6.5 outlines the Asset Management (AM) strategy for the alternative sill concept.

6.1. Research Methodology and Hydraulic Design Method

Phase 3 identified options for flexibility in design within the Floating Sector Gates at Bolivar Roads. With the governing system drivers identified in Phase 2 this phase focused on the feasibility of designing an adaptable SSB component. Inspired by the flexibility evaluation framework of Hu and Cardin (2015), and the Hydraulic Engineering Design method of Molenaar and Voorendt (2022), the activities included: (I) data collection; (II) map the dependent relationships between system drivers and SSB components via the ESM, (III) calculate the cost of change of each SSB element, (IV) determine the risk-susceptibility per SSB component, and (V) develop spatial-functional flexible option of designated SSB component (i.e., verified with basic structural calculations). Below briefly, detailed in Appendix F.1.

6.1.1. Data Collection Method

Phase 3 built upon the deliverables from Phases 1 and 2 (i.e, System Diagram Houston-Galveston Bay Region, governing system drivers) to identify options for flexibility in the design of the Floating Sector Gates at Bolivar Roads. This phase used expert knowledge (i.e., semi-structured interviews), data on construction costs, archival sources on technical aspects of the Floating Sector Gates (i.e., Coastal Texas Study Report; USACE, 2021a), and technical manuals to develop conceptual designs.

Existing Data

Using variables from the Theoretical Framework (refer to Chapter 3), Phase 3 was mainly informed from Phases 1 and 2 (e.g., Functional Breakdown Structure (FBS)). In particular, the current design for the Floating Sector Gates, as presented by USACE (2021a) in the Coastal Texas Study Report, is taken as a starting point. Technical characteristics and boundary conditions of the Floating Sector Gates were extracted from Appendix D of the Coastal Texas Study Report (USACE, 2021d). Additional data sources included technical manuals (e.g., Rock Manual) (refer to Appendix F.1.2).

Semi-structured Interviews
Semi-structured interviews, initially conducted to inform Phases 1 and 2, also contributed to Phase 3. Through thematic analysis of these interviews (i.e., identify common themes), the subsequent discussed ESM and AM framework were constructed. This process enabled an evaluation of the dependent relationships between the governing system drivers and the SSB components of the Floating Sector Gates. By integrating expert judgment with prior findings (i.e., Phase 1 and 2), Phase 3 ensured a expert-based judgment for evaluating options for flexibility in design. Refer to Appendix G for the interview transcripts and elaboration on the thematic analysis.

6.1.2. Applied Method

Phase 3 followed the sequence shown in Figure 6.2, with each step informing the next.

Engineering System Matrix (ESM)
An ESM was constructed to map the dependent relationships between governing system drivers, and SSB components. Dependent relationships, along with the degree of these relationships (if applicable), were identified based on thematic analysis of interview data. This resulted in an adjacent matrix (i.e., the ESM), which is a quantified view of how system drivers impact the SSB. For instance, the system driver “Increased Vessel Draft” has a dependent relationship with the SSB component ”Sill & Mat Foundation”, with an impact degree of 0.7 on a scale from 0 to 1 (e.g., 1 equals high impact).

Flexible Design Opportunity Identification
The ESM outcomes were further integrated with a cost impact assessment (see Figure 6.1). Solely focusing on the system driver Economic Growth (Increased Vessel Draft), inline with Phase 2 findings. Following the method of Hu and Cardin (2015), the analysis combined the dependent relationships, along with the degree of these relationships, $P_{s_i}\Big|_{\forall u_j \in U}$, with the cost of changing a SSB element, C_i^{norm} (i.e., the construction cost share C_i, of SSB component s_i, relative to the total construction cost of the SSB, C_{total}). To calculate the Risk Susceptibility Index (RSI) for each SSB component:

$$R_{s_i}^{\text{Received}} = P_{s_i}\Big|_{\forall u_j \in U} C_i^{\text{norm}} \tag{6.1}$$

To illustrate, the system driver “Increased Vessel Draft” has a cross-domain dependent relationship with the SSB component “Sill & Mat Foundation” ($u_j \in U$) with an impact degree of 0.7 ($P_{s_i}\Big|_{\forall u_j \in U} = 0.7$). The component “Sill & Mat Foundation” has a normalized cost of change of $C_i^{\text{norm}} = C_i/C_{total} = 5.9\%$. Resulting in $R_{s_i}^{\text{Received}} = 0.041$.

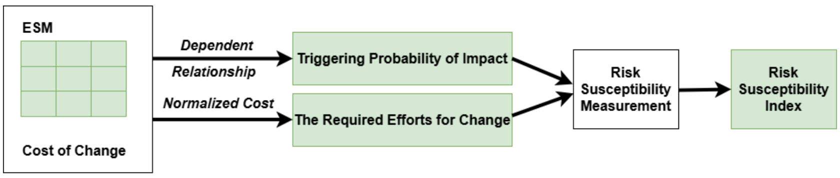


Figure 6.1: Analysis method: flexible design opportunity identification by Hu and Cardin (2015).

The value of this metric indicated which components were both impacted by the system driver, and costly to modify.

The Hydraulic Engineering Design Method
Next, a design exercise was executed to make the SSB component adaptable. The Hydraulic Engineering Design method by Molenaar and Voorendt (2022) was applied and informed via manuals (e.g, PIANC (2015)). This design method includes: (I) problem analysis, (II) define basis of design (i.e., requirements, evaluation criteria, boundary conditions), (III) development of concepts, (IV) verification of concepts, (V) evaluation of alternatives, (VI) integration of subsystems, and (VII) validation of results. This study excluded step (I), already addressed in Phase 1, and steps (V), (VI) and (VII), as it focuses on the development-, evaluation-, and selection of functional-spatial design, and subsequently verif the structural design feasibility of one concept rather than aim for the most acceptable solution.

Developing Asset Management (AM) Strategy
Having a technical design of an adaptable SSB component an AM perspective was incorporated to ensure the adaptive SSB component can also be implemented. The build ahead with Literature Review findings on Operational, Tactical, and Strategic layers of AM (refer to Chapter 2). Thereby, addressing aspects such as operations, funding, and maintenance tasks as outlined in Section 4.6.

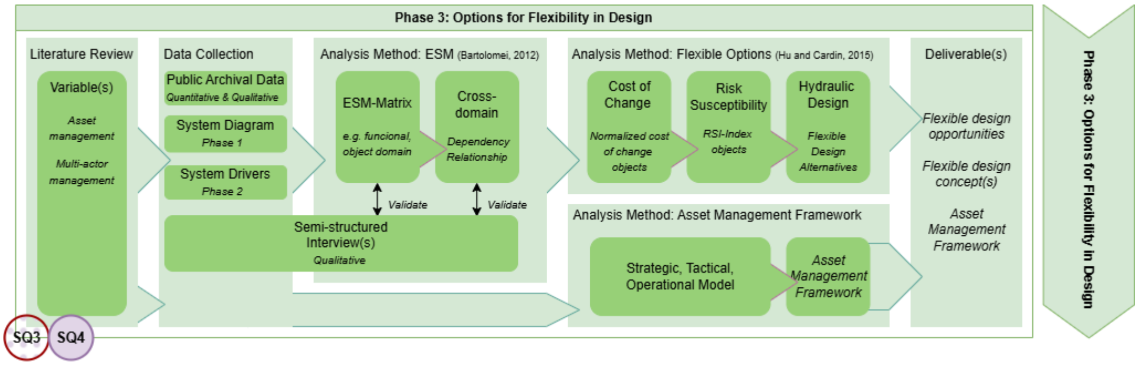


Figure 6.2: Research methodology and hydraulic design method phase 3: options for flexibility in design.

6.2. The ESM: A Blueprint for Flexibility

The Engineering System Matrix (ESM) shows how the system drivers propagate through organizational and physical domains of the Floating Sector Gates (e.g., Functional Breakdown Structure (FBS) and System Breakdown Structure (SBS)). The left column in Table 6.2 illustrates the SSB domains. Figures 6.3 and 6.4 visualize the SSB components (i.e., simplification reference design by USACE (2021a)). The degree of dependent relationships between system drivers and components were assigned through thematic analysis of the interviews (refer to "System Drivers" column in Table 6.2). The stated probabilities translate the qualitative dependency degrees extracted from the interviews (i.e., none, weak, moderate, strong) into a semi-quantitative format (i.e., 0; 0.2; 0.4; 0.7), argumented in text below. This informed the risk-susceptibility analysis in Section 6.3.

6.2.1. Cross-Domain Interactions in the Engineering System Matrix (ESM)

The matrix shows that [S3] Sill & Mat Foundation and [S5] Steel Deep-Draft Gates have high relational dependency under both drivers (i.e., (S1) Economic Growth (Increased Vessel Draft), and (S2) Relative Sea Level Change (RSLC), refer to Section 5.5. This makes them as primary candidates for built-in flexibility (refer to Table 6.2). The strong functional coupling [F2] underline the need to emphasize navigational capacity, relates to interviewees statements that: *"If global shipping trends demand larger vessels, the Houston shipping Channel must be modified to accommodate them"* (Interview F).

Governing System Driver (S1): Economic Growth - *"Ever-larger vessels"*
Interviewees stressed that with deeper ship drafts and wider beams the: *"the barrier could become a bottleneck for economic activity, necessitating potential future modifications"* (Interview A). Strong links emerge with (I) navigation functionality [F2] (0.7) and (II) the [S3] Sill & Mat Foundation (0.7), whose geometry dictates under-keel-clearance. Collision risk in the narrow channel gives a moderate influence on the [S5] steel gates (0.2) and on [F4] operational management (0.4).

Governing System Driver (S2): Relative Sea Level Change (RSLC)
Interviewees emphasized that RSLC threaten the core [F1] flood protection function (0.7) and, over time, compromise both the vertical clearance of the [S3] foundation, and the fatigue life of the [S5] steel gates (each 0.4). The RSLC projection, which ranges from 0.6 m (low) to 2.4 m (high) (refer to Section 5.3), differs significantly from the planned dredging depth for the sill elevation, which extends from $-14.3\,\mathrm{m\,NAVD}$ (anno 2025) to $-18.3\,\mathrm{m\,NAVD}$ (i.e., intended design, USACE, 2021d). Interview C summarized the implications: *"the barrier is expected to last at least 100 years, raising concerns about long-term durability, maintenance, and adaptability."* Experts confirmed the operational impact with a matching probability of 0.4 on the O&M Organization.

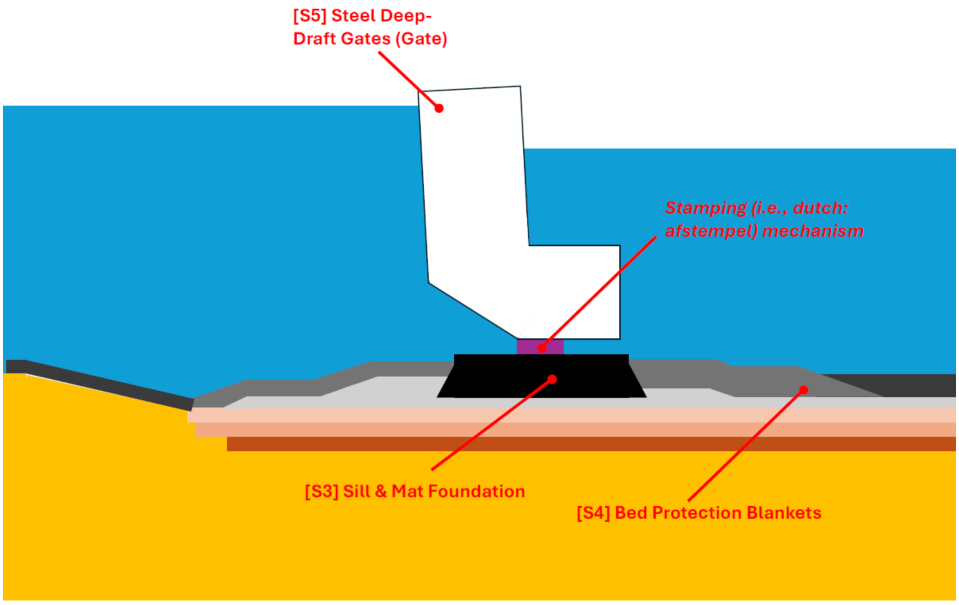


Figure 6.3: Schematic Floating Sector Gates Bolivar Roads - side view (i.e., simplification reference design by USACE (2021a)).

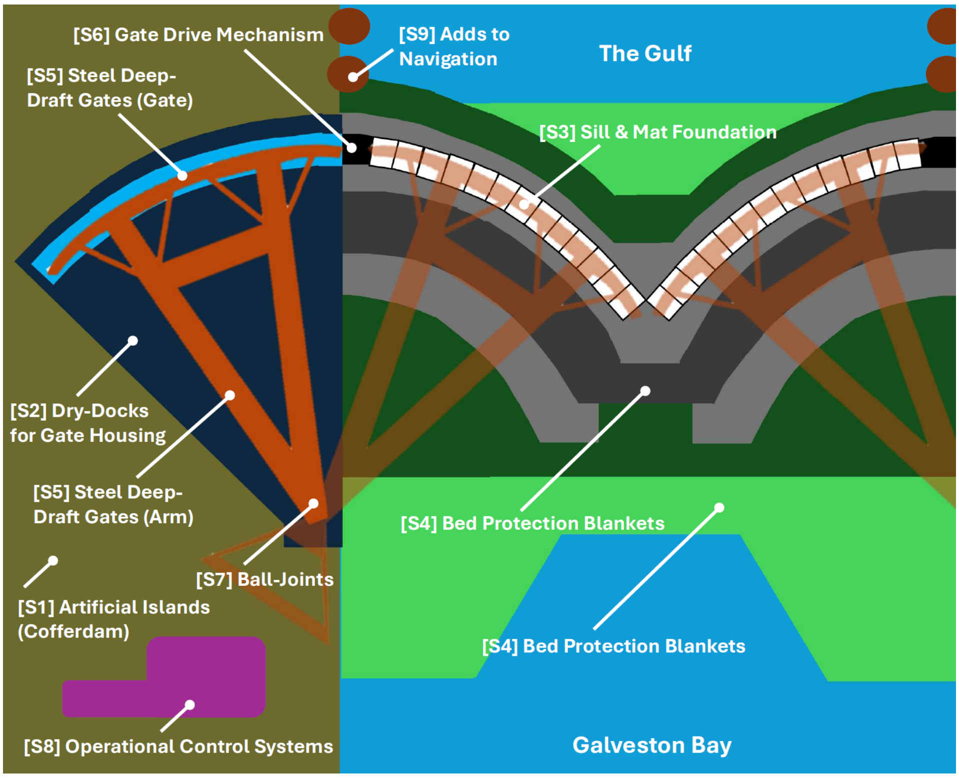


Figure 6.4: Schematic Floating Sector Gates Bolivar Roads - top view (i.e., simplification reference design by USACE (2021a)).

The ESM pinpoints the components where built-in flexibility gives the highest value, most notably the [S3] Sill & Mat Foundation and the [S5] Steel Gates. The stated expert judgments explain these elements stand out. The ESM, guides both the risk-susceptibility calculation and the choice of conceptual design alternatives discussed in the following sections.

6.3. Flexibility by Design: Where It Matters Most

The goal of this step is to pinpoint which SSB components justify built-in flexibility by weighing (I) the cost of future modifications (Section 6.3.1), and (II) their exposure to the dominant system drivers identified in the ESM (Section 6.3.2), focusing only on "Economic Growth" (Increased Vessel Draft).

6.3.1. Normalized Cost of Change

Because component breakdown cost data for Bolivar Roads Gate System at Bolivar Roads are not yet public (anno 2025) the element-by-element distribution of the Maeslant Barrier is adopted as an analogy: *"Staat van Ontleding van de Aangepaste Aanbiedingssom Behorend bij de Aanbieding D.D. 16 oktober 1989 op Basis van Kontrakt DD 001"* (Rijkswaterstaat, 1989). Both projects share comparable sector gate configuration, making Maeslant the closest available precedent. Maeslant's 1989 tender prices were mapped to the Floating Sector Gates object classes (refer to Appendix F.2), which provides cost categories mapped to components of the Floating Sector Gates. Table 6.1 presents the resulting construction cost shares as percentages (%). This indicates that the [S5] Steel Deep-Draft Gates account for the majority of the total expenditure (i.e., construction cost share of 47.8 %).

Following Hu and Cardin (2015), the normalized cost of change is defined as $C_i^{\text{norm}} = C_i / C_{\text{total}}$. Future retro-fit costs are assumed to be $80\,\%$ of the initial outlay when no flexibility is present but only $70\,\%$ if the element was designed to be adaptable. This reduction reflects the improved ease for modifications if flexibility has been embedded from the outset. Implementing flexibility initially increases the up-front cost by 10% of the element's construction cost. So, additional cost during the initial construction phase (+10%) results in cost reduction (-10%) in the later retro-fit construction phase. The column "Norm. CoC" in Table 6.2 summarizes the resulting normalized cost of change.

Object	Description	C_i^{norm}	Object	Description	C_i^{norm}
Fixed					
S1	Artificial Islands	12.02 %	S2	Dry Docks	8.50 %
S3	Sill & Mat Foundation	5.87 %	S4	Bed Protection Blankets	5.87 %
Movable					
S5	Steel Deep-Draft Gates	47.80 %	S6	Gate Drive Mechanism	2.35 %
S7	Ball-Joints (Hinges)	5.87 %			
Electric					
S8	Operational Systems	11.73 %			
Secondary					
S9	Aids to Navigation	–	S10	Anchorage Areas	–

Table 6.1: Construction cost percentage shares based on "Staat van Ontleding" Maeslant Barrier (1989) (Rijkswaterstaat, 1989).

6.3.2. Risk-Susceptibility Index (RSI)

Each element's risk susceptibility $RSI_{s_i} = P_{s_i}\, C_i^{\text{norm}}$ combines the degree of dependent relationship (P_{s_i}), from the ESM with the cost share (C_i^{norm}) as determined in Section 6.3.1. The column "Risk Suscep." in Table 6.2 lists the scoring objects. Although Table 6.2 ranks the [S5] Steel Deep-Draft Gates highest on the RSI scale. That score is driven almost entirely by their sheer capital cost: the gates account for nearly half of the up-front budget. Yet gates are movable components with a planned renewal interval of roughly 50 years (Rijkswaterstaat, 2019). The [S3] Sill & Mat Foundation, cast in concrete and buried below the channel, last the full 100 year design life (Rijkswaterstaat, 2019). Which is practically impossible to alter once in place (refer to Section 4.6; see Figure 6.5).

In this manner, the RSI_{s_i} values cannot be interpreted in isolation. Future enlargement of the [S5] Steel Deep-Draft Gates would not only raise their own CAPEX but also increase the loads transmitted to the [S3] Sill & Mat Foundation. Likewise, a heavier gate elevates loads on the [S6] Gate Drive Mechanism, potentially shortening the 30 year renewal cycle (Rijkswaterstaat, 2019).

ESM		**System Drivers**		**Norm. CoC**	**Risk Suscep.**
		Vessel Draft	**RSLC**	C_i^{norm}	RSI_{s_i}
System Drivers					
S1	Economic Growth (Increase in Vessel Draft)				
S2	Relative Sea Level Change (RSLC)				
O&M Organization					
O&M1	Asset Owner				
O&M2	Asset Manager	0.4	0.4		
O&M3	Service Provider				
Objective					
O1	Block Storm Surge Entry				
Functions					
F1	Flood Protection		0.7		
F2	Facilitate Navigation	0.7			
F3	Water Exchange				
F4	Managing Operations	0.4			
F5	Maintaining Structural Integrity		0.4		
Objects					
Fixed					
S1	Artificial Islands (Cofferdam)	0.7		0.120	0.084
S2	Dry Docks for Gate Housing				
S3	Sill & Mat Foundation	0.7	0.4	0.059	0.041
S4	Bed Protection Blankets	0.4		0.059	0.023
Movable					
S5	Steel Deep-Draft Gates	0.2	0.4	0.478	0.096
S6	Gate Drive Mechanism				
S7	Ball-Joints (Hinges)				
Electric					
S8	Operational Control Systems				
Secondary					
S9	Aids to Navigation				
S10	Anchorage Areas				

Table 6.2: Normalized cost of change and risk-susceptibility for elements impacted by governing system drivers.

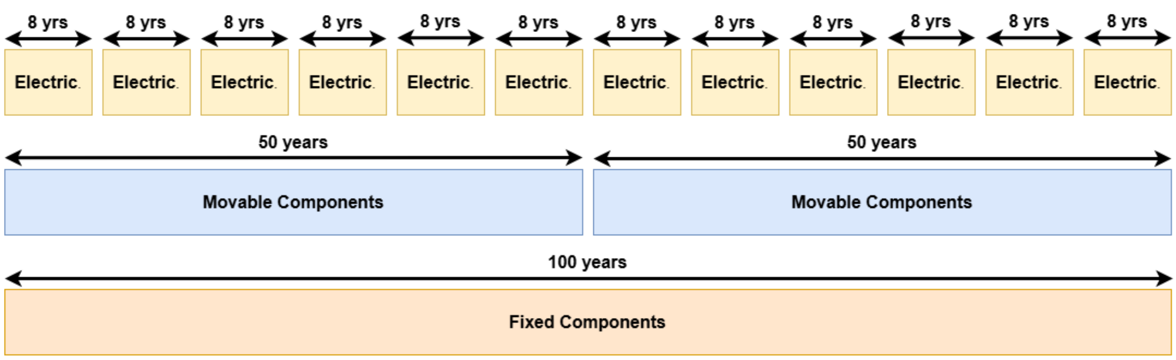


Figure 6.5: Main SSB component replacement cycles (Rijkswaterstaat, 2019).

During closure, the same changing hydraulic conditions that drive future gate development, govern the risk of scour and thus the required thickness of [S4] Bed-Protection Blankets. These cross-couplings reliability consequences onto others, will be further discussed in section 6.4.6. Table 6.2 should be read as the first filter in a broader, system-level trade-off. In other words, a high RSI does not automatically signal the best flexibility target in the case of SSBs. Movable and electrical parts (i.e., renewed at 50- and 8 year cycles respectively; see Figure 6.5) already offer natural “upgrade windows” that accommodate future functional changes, if included in the initial design. However, the fixed foundation is mostly build once. Any unforeseen loading scenario locked into [S3] Sill & Mat Foundation could trigger high retrofit costs.

In the case of SSBs, embedding flexibility into the [S3] Sill & Mat Foundation is a better choice to address future vessel size uncertainties. Interviewees emphasized that, unlike movable parts with “regular” renewal cycles, the foundation is permanent and difficult to modify. Designing [S3] for adaptability from the outset helps reduce long-term costs and avoids disruptive retrofits. Based on this reasoning, the design deviates from the RSI ranking.

6.4. Engineering Design of Adaptable Sill

This section outlines in sequence the steps of the Hydraulic Engineering Design Method: (II) defining the basis of design (i.e., requirements, boundary conditions, evaluation criteria) (Section 6.4.1), (III) development-, evaluation-, and selection of spatial-functional alternatives (Section 6.4.2), and (IV) verification of chosen concept. The sill was identified as the most suitable element for incorporating flexibility. Given that the sill is part of the bottom structure of a SSB, several neighboring components are also considered. First, bottom protection is needed to counteract scour, adding to the stability of the sill. Important in areas where high current velocities around the sill can erode the seabed. A filter layer beneath the sill is necessary to counteract uplift forces.

6.4.1. Defining the Basis of Design

The Floating Sector Gates at Bolivar Roads are still in the pre-design phase, with limited detailed design parameters. Therefore, the structural design parameters of the Maeslant Barrier has been adopted as analogy. This choice was endorsed during the “Gate Redesign Workshop” on 5 March 2025. During the workshop GCPD, USACE, and GLO collectively agreed that a single, large-span design offers greater operational simplicity compared to the initially considered two smaller spans. The Maeslant Barrier serves as a suitable reference for the new proposed Floating Sector Gates configuration. They share several design and operational characteristics. These include a single wide navigational opening and sector gate kinematics (see Figures 6.3 and 6.4 for new design configuration). While there are similarities, several differences between the Maeslant Barrier and the Bolivar Roads Floating Sector Gates should be recognized. These implications will be discussed in Section 6.4.6.

Design Objective

The design objective is to develop an adaptable sill for the Floating Sector Gates at Bolivar Roads that effectively blocks storm surge from the Gulf into Galveston Bay, while allowing, with ease of construction, for incremental in vessel draft over the 100 year operational lifespan of the SSB.

Functional- and Structural Requirements

The main functional requirements are derived from the desired SSB functions as specified in the design objective. The Program of Requirements, consisting of functional- and structural requirements (e.g., constructability, stability) are stated in Appendix F.3.1. An important requirement, which is driven by the dominant system driver Increased Vessel Draft, is to accommodate future vessel draft, and is elaborated below. The current depth of the Houston Shipping Channel (HSC) (i.e., $-47.5\,\mathrm{ft.NAVD}$; $-14.5\,\mathrm{m\,NAVD}$) is limited by the capacity of existing dredging technology. The HSC extends from the Gulf to the Port of Houston (see Figure 4.2). This requires dredging to maintain navigability. Each deepening of the HSC means additional dredging into the Gulf to ensure access, presenting a technical challenge. Current dredging capacity can accommodate channel depths of $-60\,\mathrm{ft.NAVD}$ (i.e., $-18.3\,\mathrm{m\,NAVD}$). Which restricts the maximum vessel draft. This limitation influences current channel design assumptions but may evolve as dredging technology capabilities advance.

To address this, two scenarios are considered. The scenarios are based on projected vessel draft requirements (see Figure 6.6). Alternative 1, the base scenario, adopts a sill elevation of $-18.3\,\mathrm{m\,NAVD}$. Which is the same as the current conceptual design by USACE (2021a). The adaptable sill scenario assumes that future advancements in dredging technology will enable deeper channel depths. Which would allow for a deeper sill elevation of $-83\,\mathrm{ft.\,NAVD}$ (i.e., $-25.3\,\mathrm{m\,NAVD}$), making the channel accessible for fully-laden Suezmax-class tankers. The Suezmax-class was selected as the design vessel due to its alignment with one of the world's busiest shipping routes, the Suez Canal (Feingold and Willige, 2024). This ensures compatibility with a large portion of the global fleet. As many vessels are optimized to this size for passage through the canal. This choice also accommodates New-Panamax vessels, which are generally smaller than Suezmax (see Figure 6.6).

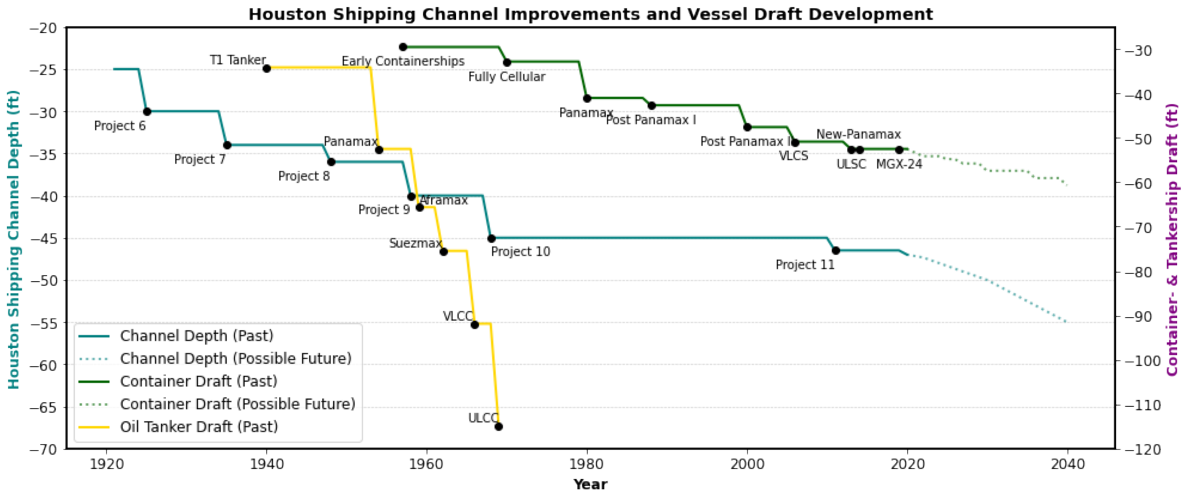


Figure 6.6: Houston Shipping Channel (HSC) improvements and world-wide ship draft developments (Port Houston, 2024; Notteboom et al., 2022; Rodrigue, 2024).

Evaluation Criteria and Boundary Conditions

The evaluation criteria are used to guide the alternative selection of the spatial-functional design alternatives in subsequent Section 6.4.2. As stated in Section 7.1.2, not all alternatives will be verified on its structural design but one concept will be chosen. Alternative selection follows the evaluation criteria as stated in Appendix F.3.1. The natural- (e.g., hydraulic conditions) and artificial boundary conditions (e.g., nautical conditions) are stated in Appendices F.3.3 and F.3.4.

6.4.2. Development of Concepts and Selection of Alternatives

Building on the basis of design, four concepts have been developed as potential solutions (see Figures 6.7 and 6.8). Refer to Table 6.4 for a brief differentiation per concept. A Multi Criteria Analysis (MCA), see brief one in Table 6.3 (refer to Appendix F.3.1), scored each concept against the evaluation criteria.

Main Category	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Ease of Construction	0	1	-1	-1
Duration of Construction Period	1	0	-1	1
Durability	1	1	-1	-1
Maintainability	2	2	-3	-5
Adaptability	-1	1	1	1
Total Scores	3	5	-5	-5

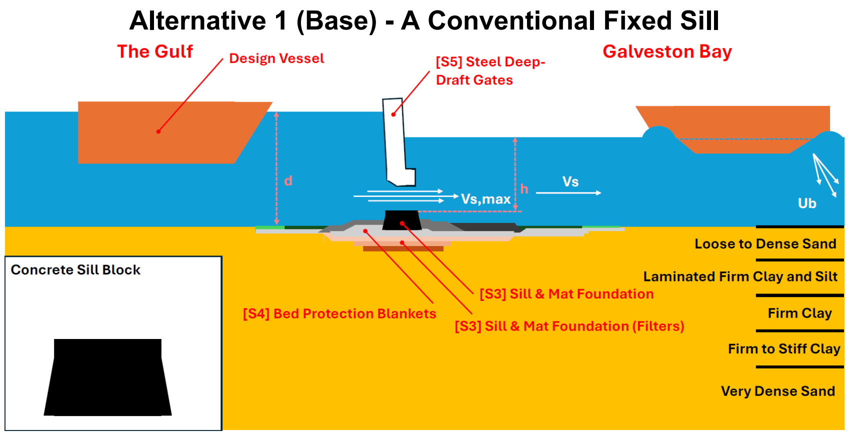
Table 6.3: Multi-criteria analysis of evaluation criteria across design alternatives (refer to Appendix F.3.2).

The LEGO alternative (i.e., Alternative 2) receives the highest score. Its strength lies in its modular design. The caissons simplifies both ease of construction and maintainability. Unlike the other alternatives, the LEGO concept enables adaptability by allowing individual caisson elements to be removed.

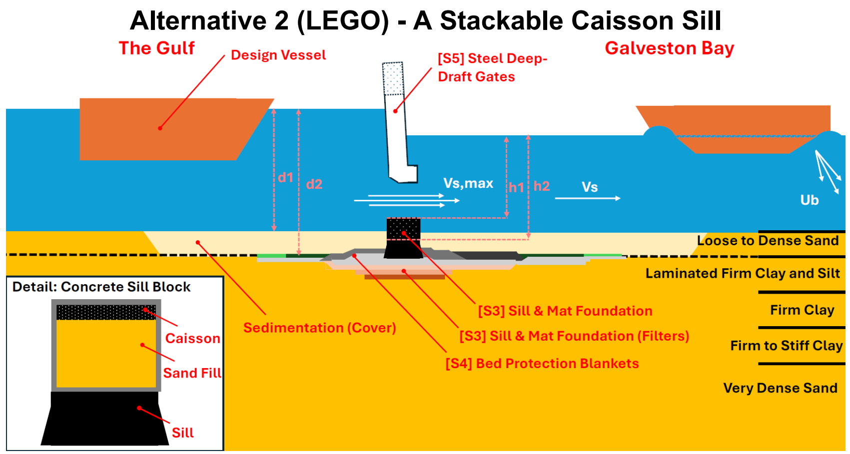
This reduces the need for complex retrofits. This phased approach to adaptability minimizes technical risks. Also, the replaceable blocks offer straightforward replacement, reducing overall downtime. The Layered alternative (i.e., Alternative 3) relies on a layered blockmat with infill system. Which is adaptable but introduces complexity in deepening operations due to the need for large-scale dredging. The Inflatable alternative (i.e., Alternative 4) provides adaptability but has high maintenance demands. Alternative 4 has reliability concerns, due to the challenging deep-sea operating environment. The Base alternative (i.e., Alternative 1) is simple in design but lacks the adaptivity needed for future channel deepening. In summary, the MCA highlights Alternative 2 (LEGO) as the preferred choice. Alternative 1 is retained as the base reference for comparison.

Alternative 1 - Base	**Alternative 2 - LEGO**
This alternative is a concrete sill fixed at $-18.3\mathrm{m}$ NAVD. Its primary advantage is its straightforward design, which is proven at the Maeslant Barrier. The design gives immediate compatibility with MGX-24 design vessel. This fixed sill has only a single construction phase. The sill fixes the system to a static elevation. As a result, all components, including the gate arms, are fixed at one elevation. This makes future modifications challenging and costly. Any significant change such as deeper dredging to accommodate larger vessels, would necessitate substantial reconstruction.	This adaptable sill design uses caissons placed atop permanent sill blocks. This approach allows for future adjustments: as vessel drafts increase more rapidly than anticipated relative to RSLC, the caissons can be removed. Reducing the sill elevation from -18.3 to $-25.3\mathrm{m}$ NAVD. This configuration provides a flexible solution, as the initial caisson elevation satisfies current functional requirements, including MGX-24 design vessel clearance. But also preserving a path for future deepening to accommodate Suezmax drafts. This adaptability results in increased structural complexity. The connections between the caissons and the permanent sill blocks like anchors, introduce additional construction challenges. These challenges may raise maintainability difficulties.
Alternative 3 - Layered	**Alternative 4 - Inflatable**
The Layered concept is a multi-layered sill system. It consists of a permanent lower sill fixed at $-25.3\mathrm{m}$ NAVD. This base layer is overlaid with a temporary fill, for example, composed of lightweight rock or steel slag, and capped with a block-mat (e.g., as seen at Eastern Scheldt Barrier or the Venice Lagoon Barriers). The block-mat sets the current crest elevation at $-18.3\mathrm{m}$ NAVD. When future deepening becomes necessary, the temporary fill can be dredged away. This exposes the lower sill. Thereby, achieving the deeper target elevation. Despite these advantages, the concept introduces several challenges. Its layered design increases construction complexity. For instance, differential settlement at the interface of the layers must be carefully managed despite the layers being largely inaccessible once installed.	This alternative replaces the concrete sill block with a pressurizable tube. Either air- or water-filled, that can be inflated to form the current sill crest at $-18.3\mathrm{m}$ NAVD or deflated to rest nearly flush with the seabed at approximately $-25.3\mathrm{m}$ NAVD. This active system enables switching between standard and “deep-draft” modes. This allows for Suezmax traffic without the need for significant dredging or long retrofit downtime. Minimizing operational disruption. However, this flexibility comes at a cost. The inflatable sill introduces considerable structural complexity and challenging maintenance requirements. The bespoke inflatable tube must be anchored at depths near $-25.3\mathrm{m}$ NAVD, Equipped with redundant inflation lines to handle extreme load cases and fatigue stresses.

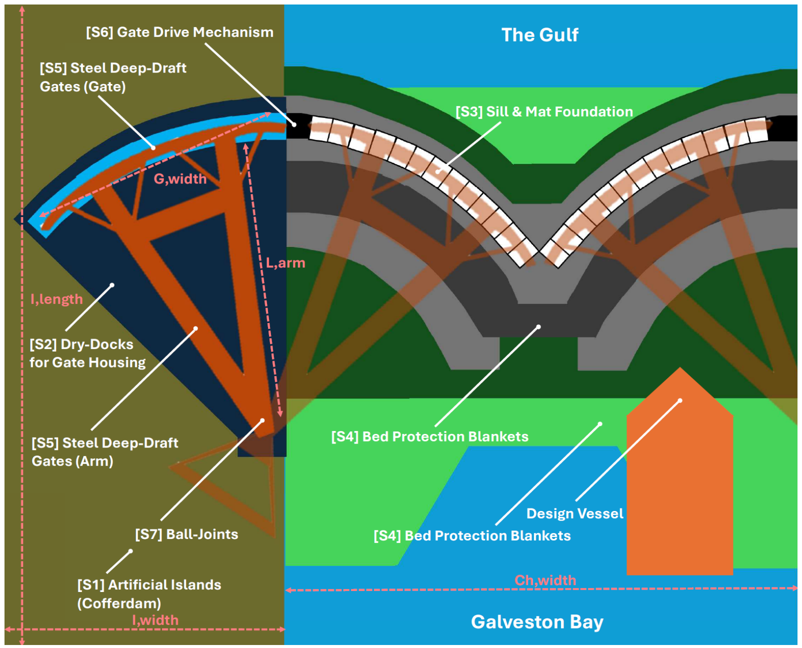
Table 6.4: Overview differentiation of the 4 sill alternatives for Floating Sector Gates at Bolivar Roads.



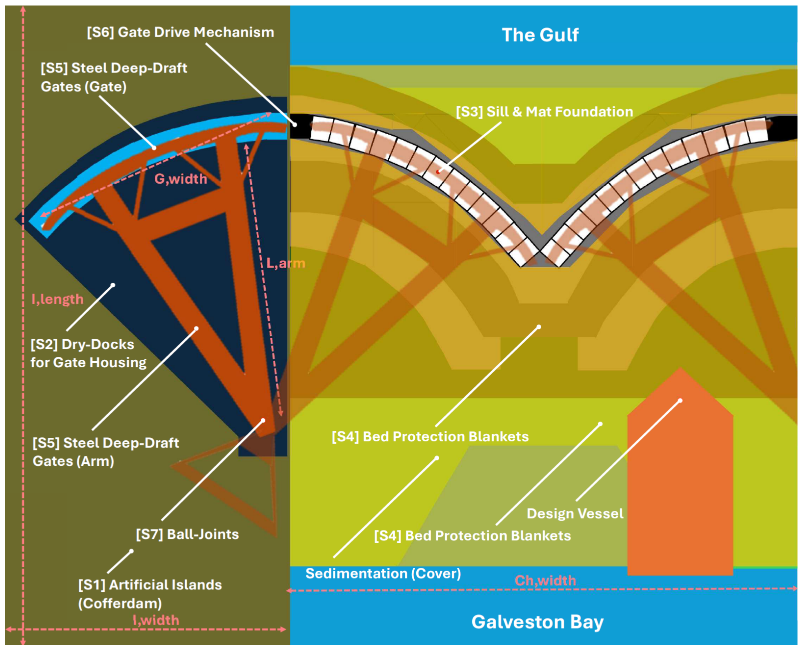
(a) Side view of Alternative 1 (sill elevation at $-18.3\,\mathrm{m}\,\mathrm{NAVD}$).



(c) Side view of Alternative 1 (sill elevation at $-18.3\,\mathrm{m}\,\mathrm{NAVD}$, can be lowered to $-25.3\,\mathrm{m}\,\mathrm{NAVD}$).

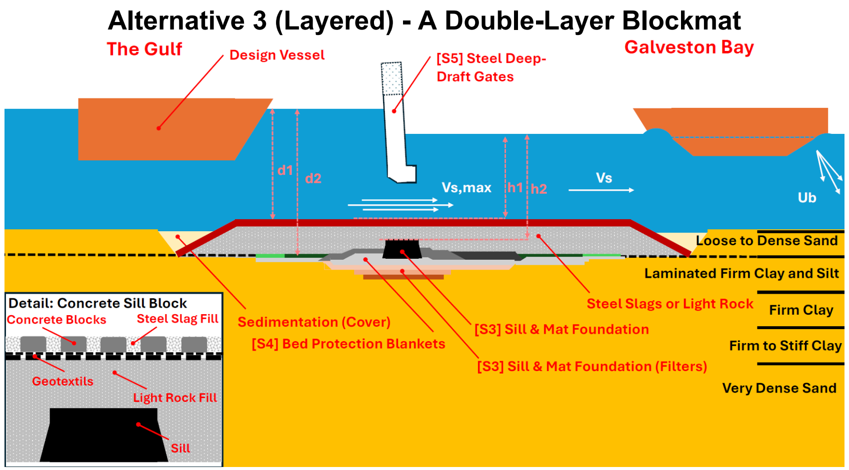


(b) Top view of Alternative 1 (channel width of $360\,\mathrm{m}$).

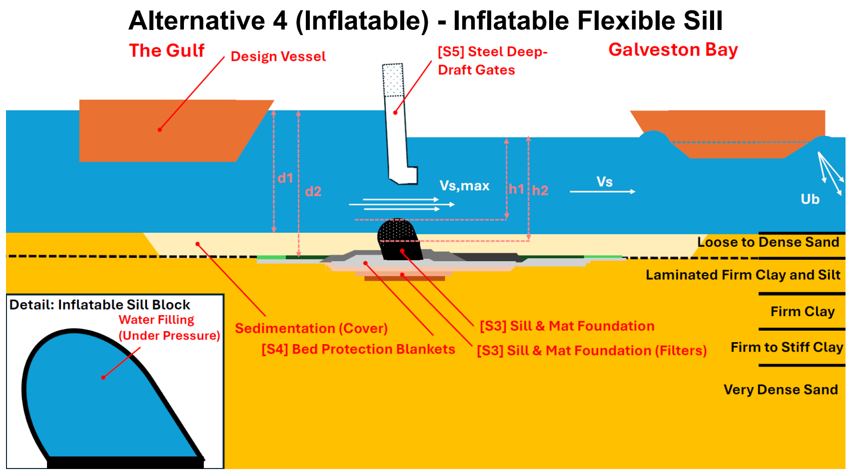


(d) Top view of Alternative 2 (channel width of $360\,\mathrm{m}$).

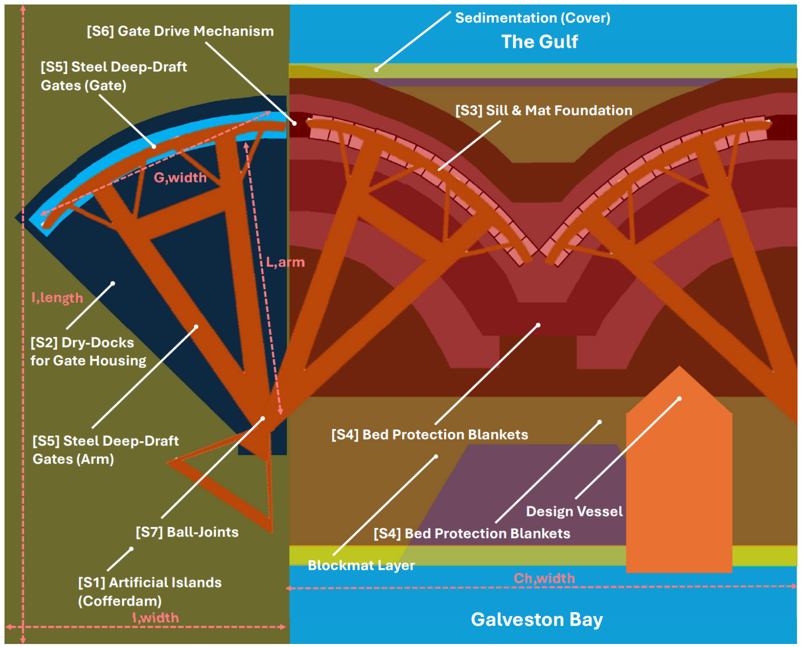
Figure 6.7: Adaptable sill design Alternatives 1 and 2.



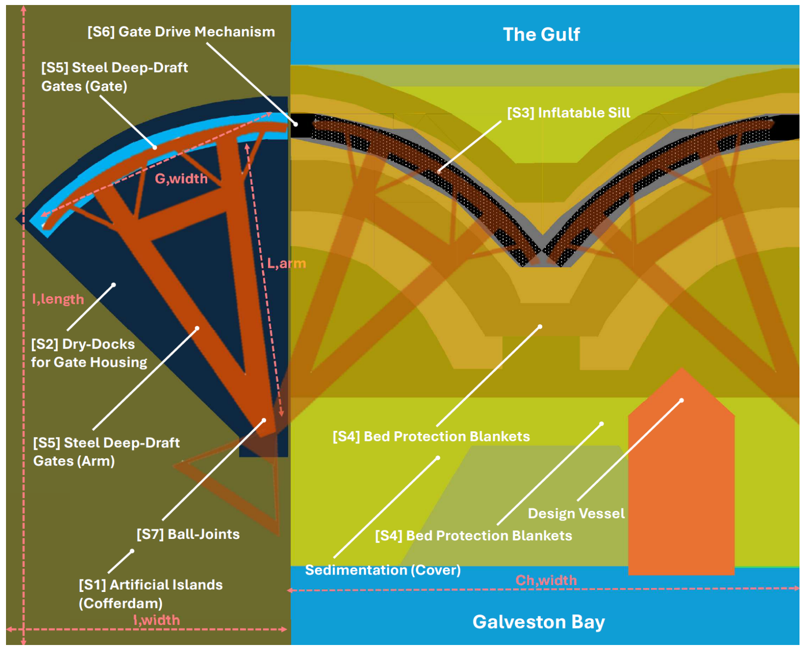
(a) Side View of Alternative 3 (Sill Elevation at $-18.3\,\mathrm{m\,NAVD}$, can be lowered to $-25.3\,\mathrm{m\,NAVD}$).



(c) Side view of Alternative 4 (sill elevation at $-18.3\,\mathrm{m\,NAVD}$, can be lowered to $-25.3\,\mathrm{m\,NAVD}$).



(b) Top view of Alternative 3 (channel width of $360\,\mathrm{m}$).



(d) Top view of Alternative 4 (channel width of $360\,\mathrm{m}$).

Figure 6.8: Adaptable sill design Alternatives 3 and 4.

6.4.3. Structural Design Verification of LEGO Alternative

To verify the structural design parameters of Maeslant Barrier analogy under Bolivar Roads boundary conditions, basic hand calculations were performed using simplified assumptions. While the Coastal Texas Study proposes a pile foundation in favor of sill and gate structure stability, addressing soft subsurface soils (i.e., mainly fine to clayey sands with low shear strength), this analysis assumes a shallow foundation for assessing stability. The Maeslant Barrier site has more stable fine sand and silt, allowing for a non-piled foundation supported by filter layers and bed protection to resist scour and uplift. Given the weak, compressible soils at Bolivar Roads, a similar foundation strategy will be necessary, including bed protection (Section 6.4.4) and filter design (Section 6.4.5).

Overall stability is assessed assuming uniform subsoil with linear-elastic behavior. For pile foundation details, see Appendix D of the Coastal Texas Study Report (USACE, 2021d). Calculations follow Voorendt (2022), with hand calculations elaborated in Appendix F.3.3 (Alternative 1) and Appendix F.3.4 (Alternative 2). Stability requires satisfying three equilibrium conditions under critical loading (see Table 6.5): no horizontal displacement ($\sum H_{\text{total}} = 0$), no uplift ($\sum V_{\text{total}} = 0$), and no rotational failure ($\sum M_{\text{total}} = 0$). Internal erosion effects are excluded here but external erosion is addressed separately.

Load Cases (LC) and Load Combinations (LCC)

Three operational scenarios are considered: (LC01a) fully open with normal tidal flow, (LC01b) in transition during closing with flow beneath the gates, and (LC01c) fully closed under storm surge conditions. These scenarios are illustrated in the provided Figures 6.9 - 6.14. It is assumed that the governing load combination, regarding all failure modes (see Table 6.5), is the fully closed state (LCC03), with a maximum head differential (Gulf > Bay), as this generates the highest loads. The rational below:

- LC01a: fully open with normal tidal flow;
- LC01b: closing with flow beneath the gates;
- LC01c: fully closed (surge conditions);
- LC02a: sill block (elevation $-18.3\,\text{m}\,\text{NAVD}$);
- LC02b: sill block (elevation $-25.3\,\text{m}\,\text{NAVD}$);
- LC03: caisson (elevation $-18.3\,\text{m}\,\text{NAVD}$).

Stage 1 Alt. 2, the sill consists of a sill block and a caisson (LC02b + LC03) with crest at $-18.3\,\text{m}\,\text{NAVD}$, introducing additional sliding and overturning forces, particularly during the fully closed condition (LC01c). At stage 2 the caisson is removed (LC02b), the crest deepens to $-25.3\,\text{m}\,\text{NAVD}$, increasing exposure to uplift and sliding due to the loss of self-weight. Alt. 1 shares the same configuration but remains at $-18.3\,\text{m}\,\text{NAVD}$ (LC02a), resulting in lower hydrostatic forces. In both alternatives, the fully closed storm-surge scenario (LCC03) is the governing load combination for all failure modes due to the maximum water level differential, leading to highest horizontal, and vertical (uplift) forces.

Load Combinations (LCC)	Alternative 1	Alt. 2 (w/ caisson)	Alt. 2 (no caisson)
1. $\Delta h_1 = 0\,\text{m}$; $v_{s1} = 2\,\text{m/s}$	LC01a + LC02a	LC01a + LC02b + LC03	LC01a + LC02b
2. $\Delta h_2 = 9\,\text{m}$; $v_{s,\text{max}} = 13\,\text{m/s}$	LC01b + LC02a	LC01b + LC02b + LC03	LC01b + LC02b
3. $\Delta h_3 = 9\,\text{m}$; $v_{s3} = 0\,\text{m/s}$	LC01c + LC02a	LC01c + LC02b + LC03	LC01c + LC02b
Failure Modes	**LCC03a** (Δh_3)	**LCC03b** (Δh_3)	**LCC03c** (Δh_3)
Horizontal Stability		*Vertical Stability*	
Rotational Stability		*Internal Backward Erosion*	

Table 6.5: Load combinations and considered failure modes for Alternative 1 and Alternative 2 (with and without caisson).

Hand Calculations of Forces - Fully Closed under Storm Surge

This section lists the forces acting on the sill configurations of Alt. 1 and 2 for the governing load combination LCC03 - barrier fully closed under maximum hydraulic head, see Table 6.6 and Figures 6.15 and 6.16. The forces include horizontal and vertical hydrostatic pressures, uplift under the sill, the self-weight of the sill, and caisson, and the downward load of the gate structure. Horizontal pressure H scales with the square of the water depth ($H \propto h^2$), while uplift V is proportional to the whetted area. both therefore increase notably when the sill is placed deeper. Alt. 2 is analyzed in two phases: (LCC03b) directly after construction, caisson in place (see Figure 6.15), and (LCC03c) future case, caisson removed, sill deeper (see Figure 6.16).

Note: For Alt. 2 without caisson, see Figure 6.16, the caisson is removed, leaving the sill at a deeper elevation (i.e., LCC03c). The gate is extended accordingly (see shaded extension in Figure 6.16). Increasing the downward vertical load of the gate. Vertical forces V_2 and V_3 are conservatively neglected due to their minor impact, while V_4 is included, given the gate's deeper submerged position.

Symbol	Force Component	Alt. 1 [kN]	Alt. 2 (w/ caisson) [kN]	Alt. 2 (no caisson) [kN]
H1	Horizontal pressure	18735	29575	29575
H2	Horizontal pressure	4996	15964	15964
H3	Wall area horiz. pressure	3891	14731	4947
H4	Wall area horiz. pressure	2519	10156	3575
V1	Uplift pressure under sill	17157	22436	22436
V4	Downlift above gate slot	–	–	2976
G_{sill}	Self-weight of concrete sill	5625	5625	5625
G_{caiss}	Self-weight of caisson	–	8884	–
V_{gate}	Submerged gate	15663	15663	69817

Table 6.6: Summary of acting forces for Alternatives 1 and 2 during the governing condition (see Figures 6.15 and 6.16).

Table 6.6 highlight differences between the alternatives. In the initial phase of Alt. 2 the caisson adds self-weight ($G_{\text{sill}} + G_{\text{caiss}}$). The normal force increases, friction capacity goes up ($f \cdot \sum V$), and the uplift force V_1 is counter balanced. The caisson wall enlarges the wetted area, so horizontal water pressures $H_3 - H_4$ also rise, producing larger sliding and overturning moments. Once the caisson is removed (Alt. 2 without caisson) the submerged wall area shrinks and H3–H4 drop but the ballast effect disappears (G_{caiss}). The substantial increase in V_{gate} in the second configuration results from the required extension of the gate to accommodate the increased sill elevation ($-25.3\,\mathrm{m\,NAVD}$). In the soft, compressible subsoil of Bolivar Roads this can lead to unacceptable settlements. The proposed pile foundation under the gate is unavoidable. Table 6.6 is leveraged in the subsequent sliding, overturning, and uplift verifications for both alternatives.

Failure Mode Check - Horizontal Stability

Horizontal stability prevents sliding failure by ensuring the sill can resist lateral forces from water pressure, waves, and currents. Under storm-surge closure, these forces reach their maximum (LCC03). Sliding is checked with $\sum H < f \cdot \sum V$, where f is the friction coefficient. For shallow foundations, this resistance comes mainly from soil-structure friction. Sliding is prevented when the total horizontal force $\sum H$ remains below the available frictional resistance, given by $f \cdot \sum V$. Because hydrostatic pressure grows with h^2 while frictional resistance scales vertical load V, deeper and larger submerged faces quickly dominate the sliding balance.

For Alt. 1, a friction coefficient of $f = 0.4$ is used, based on foundation soils classified as clean fine to clayey medium sand, in line with USACE Technical Letters (Voorendt, 2022). For Alt. 2, a higher coefficient of $f = 0.45$ is adopted to reflect the deeper embedment and the presence of laminated firm clay. This composite value accounts for varying subsoil layers with friction values between 0.2 and 0.6. Table 6.7 presents the results for both alternatives.

Description	Alternative 1	Alt. 2 (w/ caisson)	Alt. 2 (no caisson)
$\sum H$ [kN]	1373	4575	1373
$\sum V$ [kN]	4132	-7736	-55983
f [-]	0.4	0.45	0.45
$f \cdot \sum V$ [kN]	1653	3481	25192
Result	$1373 < 1653$ *Satisfied*	$4575 > 3481$ *Not Satisfied*	$1373 < 25192$ *Satisfied*

Table 6.7: Horizontal stability check summary for Alternative 1 and Alternative 2 (with and without caisson).

Alternative 2 - with Caisson
Sill elevation at $-18.3\,\mathrm{m\,NAVD}$

Alternative 2 - without Caisson
Sill elevation at $-25.3\,\mathrm{m\,NAVD}$

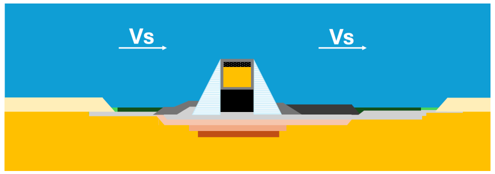


Figure 6.9: LC01a (Open); $\Delta h_1 = 0\,\mathrm{m}$; $v_{s1} = 2\,\mathrm{m/s}$

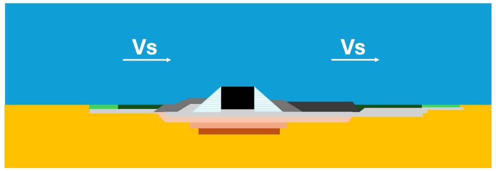


Figure 6.12: LC01a (Open); $\Delta h_1 = 0\,\mathrm{m}$; $v_{s1} = 2\,\mathrm{m/s}$

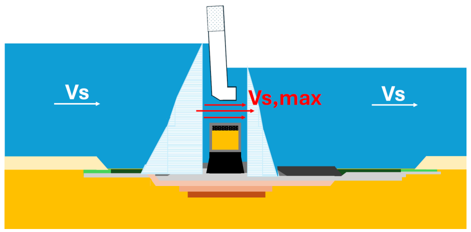


Figure 6.10: LC01b (Closing); $\Delta h_2 = 9\,\mathrm{m}$; $v_{s,\text{max}} = 13\,\mathrm{m/s}$

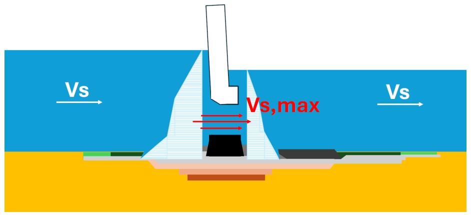


Figure 6.13: LC01b (Closing); $\Delta h_2 = 9\,\mathrm{m}$; $v_{s,\text{max}} = 13\,\mathrm{m/s}$

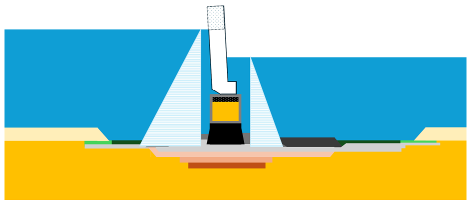


Figure 6.11: LC01c (Closed); $\Delta h_3 = 9\,\mathrm{m}$; $v_{s3} = 0\,\mathrm{m/s}$

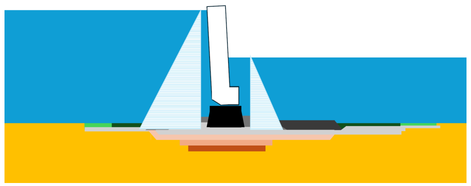


Figure 6.14: LC01c (Closed); $\Delta h_3 = 9\,\mathrm{m}$; $v_{s3} = 0\,\mathrm{m/s}$

Alternative 2 (with & without Caisson) - Forces

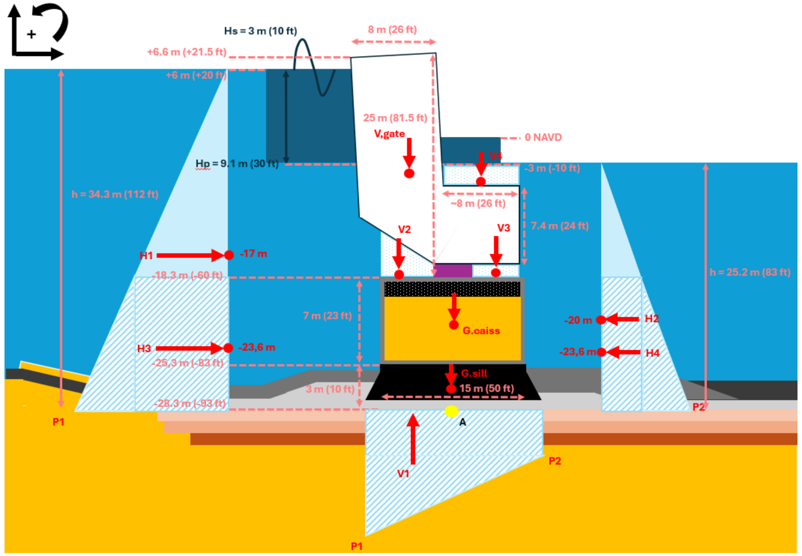


Figure 6.15: LCC03b - Alternative 2 - with Caisson.

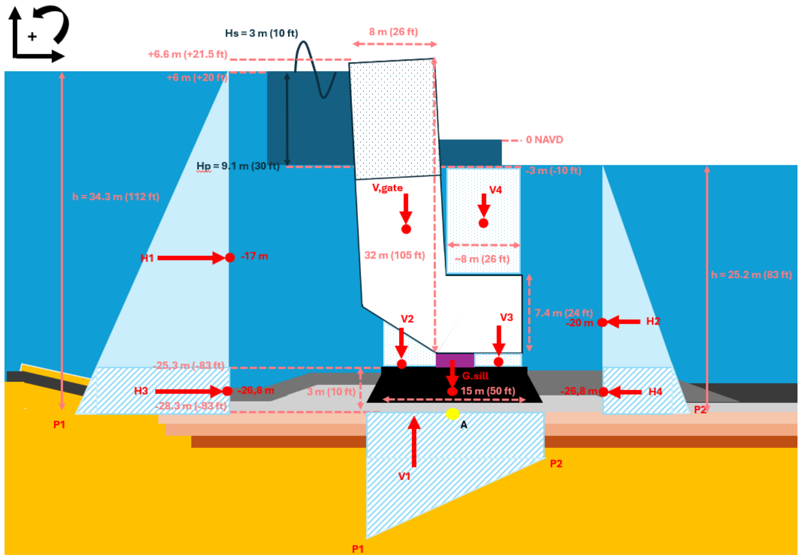


Figure 6.16: LCC03c - Alternative 2 - without Caisson (vertical extension of gate).

Piping Cascading Events - Part I

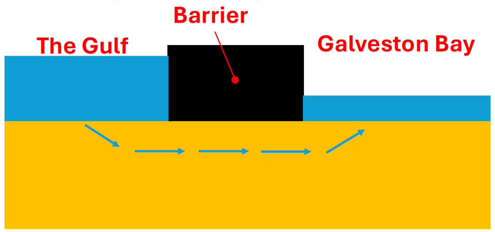


Figure 6.17: I. Prolonged hydraulic gradient.

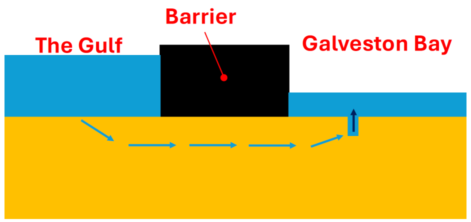


Figure 6.18: II. Development of seepage.

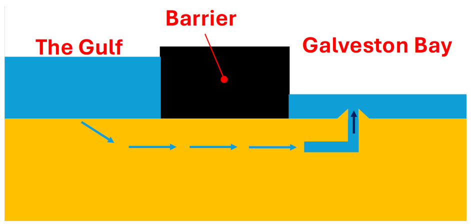


Figure 6.19: III. Formation of sand boils.

Piping Cascading Events - Part II

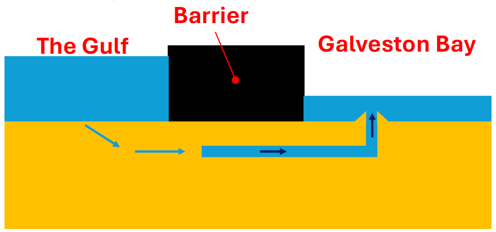


Figure 6.20: IV. Formation erosion channels.

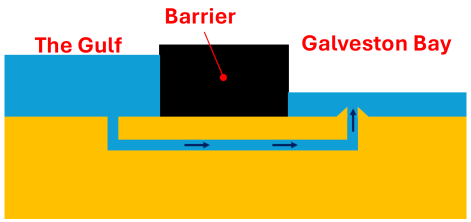


Figure 6.21: V. Settlements and internal erosion.

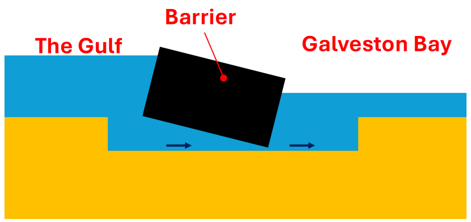


Figure 6.22: VI. Failure of the SSB (sill).

Bed Protection - Current-, Wave- and Ship-Induced Loads

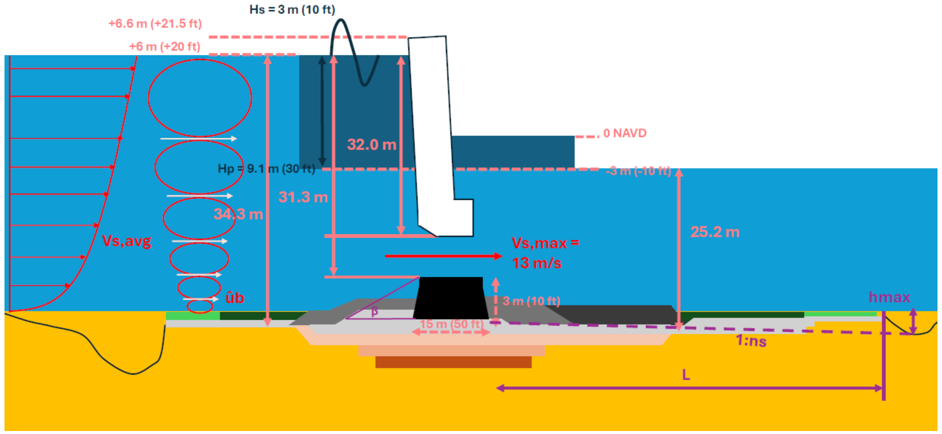


Figure 6.23: Alternative 2 (without Caisson) - bed protection stability under current- and wave load.

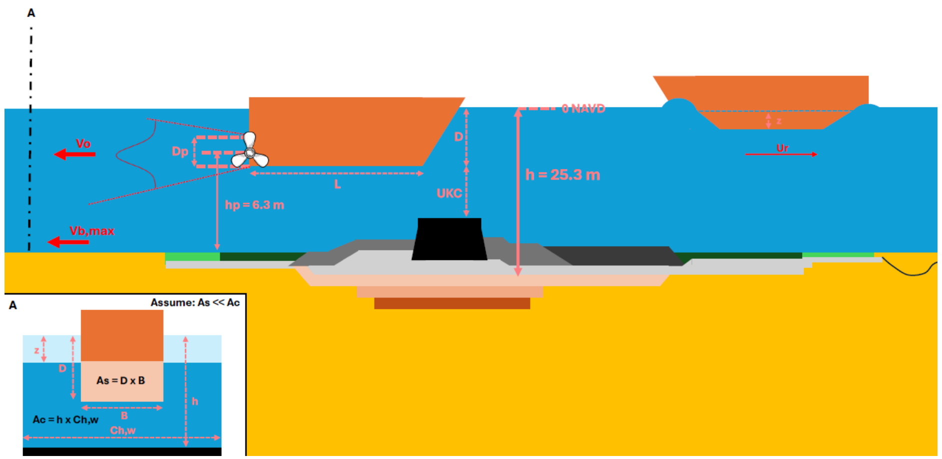


Figure 6.24: Alternative 2 (without Caisson) - bed Protection stability under ship-induced load.

Table 6.7 indicate that only Alt. 2 with caisson does not satisfy. In Alt. 2 with caisson adds weight but it also adds a wall submerged face. That larger face increases the hydrostatic loads $H_3 - H_4$ by roughly a factor of three, whereas the added self-weight appears as negative in $\sum V$, buoyancy (i.e., uplift) subtracts from the net downward load. Net effect: $f \cdot \sum V$ grows only modestly while $\sum H$ triples, so sliding safety is lost. In Alt. 2 removing the caisson eliminates the extra face, cutting $H_3 - H_4$ back to Alt. 1 levels. The extended gate V_{gate}, restoring a large negative $\sum V$, friction capacity $f \cdot \sum V$ now exceeds $\sum H$. The caisson shifts the design from weight- to pressure-controlled. Hence, the added surface area overtake the ballast benefit. A smaller caisson reduces the submerged area and thus $\sum H$, though at the cost of draft clearance. Alternatively, increasing friction through interface roughening or adding shear keys (refer to Section 6.4.6) can enhance resistance without enlarging the wetted surface. Overall, downsizing or removing the caisson improves horizontal stability.

Failure Mode Check - Rotational Stability

In addition to sliding, the structure must resist rotational failure. For shallow foundations, only compressive contact stresses are allowed, as soil cannot carry tension. Stability is ensured when the resultant vertical load lies within the middle third of the base, the “core”, ($\pm\frac{1}{6}b$). This implies that the overturning moment must be balanced by a sufficient counter-moment from self-weight, see Table 6.8.

Description	Alternative 1	Alt. 2 (w/ caisson)	Alt. 2 (no caisson)
$\sum M$ [kNm]	9871	-19878	128674
$\sum V$ [kN]	4132	-7736	-55983
$e_R = \frac{\sum M}{\sum V}$ [m]	2.4	2.6	2.3
$\frac{1}{6}b$ [m]	2.5	2.5	2.5
Result	$2.4 < 2.5$ *Satisfied*	$2.6 > 2.5$ *Not Satisfied*	$2.3 < 2.5$ *Satisfied*

Table 6.8: Rotational stability check summary for Alternative 1 and Alternative 2 (with and without caisson).

Table 6.8 shows Alt. 2 with caisson fails. The caisson increases the submerged face, hence moment from $H_3 - H_4$ in $\sum M$ therefore rises. The resulting eccentricity e_R shifts beyond the core, introducing tensile stresses and overturning risk. The ballast benefit of the caisson acts on the center A, the $H_3 - H_4$ arm acts outside, its moment dominates. Lowering the caisson cut the submerged face and thus the moment from $H_3 - H_4$, bringing e_R back inside the “core”. In Alt. 2 without caisson, the large water-pressure moment reduces. The extended gate V_{gate} adds downward weight eccentric from the center A, producing a stabilizing moment. e_R now lies within $\pm\frac{1}{6}b$, though bearing stresses rise and must be checked (refer to Vertical Stability). Thus, rotational stability depends on balancing the caisson’s water-pressure moment with self-weight, improved by lowering the caisson or repositioning V_{gate}.

Failure Mode Check - Vertical Stability

Vertical stability ensures the soil can carry the applied loads without exceeding its bearing capacity. For shallow foundations this is checked by comparing the maximum allied stress, $\sigma_{k,\text{max}}$, with the allowable bearing capacity, p'_{max}, hence $\sigma_{k,\text{max}} < p'_{\text{max}}$. The maximum vertical stress on the subsoil is computed as a combination of average pressure and stress increase due to eccentric moments, see Table 6.9.

Description	Alternative 1	Alt. 2 (w/ caisson)	Alt. 2 (no caisson)
$\sum M$ [kNm]	9871	-19878	128674
$\sum V$ [kN]	4132	-7736	-55983
$\sigma_{k,\text{max}}$ [kN/m^2]	108	206	57
p'_{max} [kN/m^2]	96	80	80
Result	108 > 96 *Not Satisfied*	206 > 80 *Not Satisfied*	57 < 80 *Satisfied*

Table 6.9: Vertical stability check summary for Alternative 1 and Alternative 2 (with and without caisson).

Physically, uplift reduces the effective vertical load, while an eccentric moment increases stress at one edge of the sill, the two effects combine in $\sigma_{k,\max}$. The values in Table 6.9 show contrasting soil responses. For Alt. 1 $\sigma_{k,\max}$ exceeds $p'_{\max}$ because uplift dominates the relatively light sill. For Alt. 2 with caisson, the caisson adds weight, but the larger submerged face increases the water-pressure moment ($H_3 - H_4$), resulting in $\sigma_{k,\max}$ rising three times $p'_{\max}$. Although the caisson's self-weight is centered, the larger submerged face shifts the resultant toward the edge, creating tension and overstress. For Alt. 2 without caisson, removing the caisson reduces the water-pressure induced moment ($H_3 - H_4$). The eccentric stamping, heavier, extended V_{gate} adds a large (positive) moment, and increases downward load, $\sigma_{k,\max}$ falls below $p'_{\max}$. The combination of large (positive) V_{gate} moment and lower water-pressure induced moments ($H_3 - H_4$) gives a favorable stress distribution.

For Alt. 1 and Alt. 2 with caisson, the bearing stress exceeds soil capacity under shallow-foundation assumptions, expected due to weak subsoil. Uplift and water-pressure moments (H_3-H_4) increase edge stresses beyond what the subsoil can sustain. As the conceptual design includes a pile foundation (Appendix D Coastal Texas Study; USACE, 2021d), no redesign is proposed. Final stability will depend on pile design, which is beyond this study's scope.

Failure Mode Check - Internal Backward Erosion

Piping is a form of internal erosion caused by water seepage beneath the SSB due to prolonged hydraulic gradient across the SSB (i.e., Gulf - Bay). Soil particles are displaced, forming channels that can lead to failure of stability. Critical for fixed structures like the sill, where settling subsoil may lead to uncontrolled seepage. The risk is assessed using the Lane method (i.e., $L \geq \gamma \cdot C_L \cdot \Delta H$), which differentiates between vertical and horizontal seepage paths due to their varying resistance to erosion.

For both Alt. 1 (i.e., $C_L = 8.5$ Lane's coefficient for loose sand, silt, and clay), and Alt. 2 (i.e., $C_L = 1.8$ Lane's coefficient for the deeper foundation firmer clay conditions), the piping criterion is not satisfied (refer to Appendices F.3.3 and F.3.4). This outcome is expected due to the soft subsoil conditions at Bolivar Roads. Despite this, the actual risk of piping is considered low, as bed protection, and filter layers will be set in place around the sill. Internal backward erosion typically requires sustained head differences over several days. Since the barrier is only closed during short duration storm events (12-hours to several days) the time needed for piping to develop is unlikely. To better understand the cascading sequence of conditions necessary for failure, a event diagram was developed (see Figure 6.25 and visualizations in Figures 6.17 - 6.22). It highlights the dependency on soil composition, and the development of sand boils leading to destabilization.

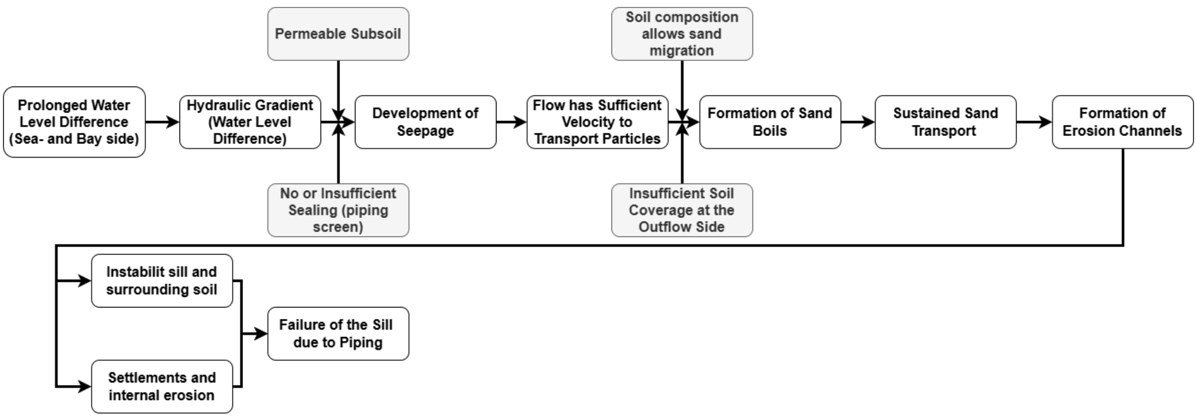


Figure 6.25: Event diagram showing required cascading effects for piping-induced sill failure.

While the risk is not deemed critical, due to the bed protection and filter layers underlying the bed protection, which manage exit gradients, the following countermeasures can be considered in combination with extending the bed protection length and filter layer measures to reduce susceptibility to piping: (I) install a piping screen to block seepage paths; (II) introduce a clay core to limit permeability; (III) apply sandbags at seepage points as an emergency solution.

6.4.4. Design Verification of Bed Protection Around the Adaptable Sill

The SSB changes local flow patterns and velocities. This increases the risk of scour near the structure. If unprotected, scour can lead to settlement, and thus stability failure. To maintain stability, a bed protection system is essential, as continuous sediment supply to the bottom is often not feasible. While not aiming to prevent scour entirely, the bed protection controls its extent. Ensuring that scour holes form safely away from the structure, reducing the risk of undermining.

Various types of bed protections can be used in hydraulic engineering including: loose rock, fascine mattresses, and composite mattresses are the most common (Schiereck and Verhagen, 2019). A bottom protection made of loose rock is relatively straightforward to construct. Typically, one or two layers are sufficient to prevent the loss of underlying bottom material. Rock or gravel is readily available, making this approach practical and cost-effective. When an active parallel filter gradient is present, such as at the Maeslant Barrier and Bolivar Roads, a filter layer is required between the top layer and the base soil to prevent fine material from being washed away. In such cases, a material with a broad gradation, like slag, is preferred to ensure proper filtering and stability (Schiereck and Verhagen, 2019).

Fascine mattresses are bound willow faggots covered with a layer of stones. Providing a durable protection system. If kept submerged, these mattresses can last over a century. A minimum coverage of stones is necessary to ensure the mattress sinks and remains in place. However, willow twigs alone are too porous to function effectively as a filter, limiting their applicability (Schiereck and Verhagen, 2019). For situations where stringent filter requirements must be met, composite mattresses are often used. These combine concrete blocks with geotextiles, offering structural integrity and filtration. An example is the Eastern Scheldt Barrier, where such mattresses have been implemented.

Based on the above for the Bolivar Roads, a loose rock protection system with filter layers has been selected. This is due to its simplicity and ease of construction and maintainability. It uses widely available materials and proven methods. Filter layers beneath the rock prevent hydraulic pressure buildup and will be addressed in Subsection 6.4.5. Additionally, Alternative 2's design allows future removal of caissons. The bed protection must remain effective both during the initial phase (i.e., with caisson) and in second phase (i.e., without caisson), when the sill is more exposed to hydraulic forces. Please refer to Appendix F.3.3 (i.e., Alternative 1) and Appendix F.3.4 (i.e., Alternative 2) for an elaborated of hand calculations on the bed protection around the sill.

Load Cases (LC) and Load Combinations (LCC)

To state the governing load combination (refer to Table 6.10), three operational scenarios were analyzed to identify the most critical load condition for bedrock stability. These include: (LC01a) barrier fully open with normal flow (see Figure 6.9 and 6.12); (LC01b) delayed closure under increased head difference (see Figure 6.10 and 6.13); and (LC01c) barrier reopening. For Alternatives 1 and 2, LC01b - delayed closure of the barrier, is identified as the governing load case. In this case, the maximum water level difference between the Gulf and Bay results in the highest flow velocity beneath the gate. This is described by Torricelli's law: $v = \sqrt{2 \cdot g \cdot \Delta h}$, where v is flow velocity, g is gravitational acceleration, and Δh is hydraulic head. Using Torricelli's law, the resulting flow velocity at the sill elevation is estimated to be $v_{s,\text{max}} = 13\,\text{m/s}$, leading to the highest current induced load on the bedrock. Wave reflection against the gate may temporarily increase the hydraulic head and flow velocity, assessing this effect for the Floating Sector Gates is recommended but beyond this study's scope

Load Combinations	Alternative 1	Alt. 2 (w/ caisson)	Alt. 2 (no caisson)
1. $\Delta h_1 = 0\,\text{m}$; $v_{s1} = 2\,\text{m/s}$	LC01a + LC03	LC01a	LC01a + LC03
2. $\Delta h_2 = 9\,\text{m}$; $v_{s,\text{max}} = 13\,\text{m/s}$	LC01b + LC02	LC01b + LC02	LC01b + LC02
3. $\Delta h_3 < \Delta h_2$; $v_{s3} < v_{s,\text{max}}$	LC01c	LC01c	LC01c
Stability Check	**LCC02a** (Δh_2)	**LCC02b** (Δh_2)	**LCC02b** (Δh_2)
Current Attack (LC01)	*Wave Load (LC02)*	*Ship Load (LC03)*	

Table 6.10: Load combinations and considered stability checks for Alternative 1 and Alternative 2 (with and without caisson).

For Alt. 2, the bed protection must perform in both the initial phase (see Figure 6.10) and the second phase (see Figure 6.13). The second phase is identified as the governing case due to increased exposure to current (LC01), wave (LC02), and ship-induced (LC03) loads, see Table 6.10:

- In the initial phase, a sediment layer covers the bed protection, shielding it from direct flow (LC01a), and ship-induced loads, hence no LC03 (see Figures 6.7c and 6.7d). When closing this layer can erode away (LC01b), which is not deemed as a problem, as below this layer the bed protection is in place. In the future, with full channel dredging, this layer is likely to be eroded, leaving the protection fully exposed under normal conditions (LC01a).
- With the caisson in place, ships sail higher above the bed, reducing the impact of propeller wash. Without the caisson, vessels pass closer to the bed, increasing near-bed velocities (LC03).
- During closure, the caisson acts as a flow buffer. Once removed, the gate operates lower in the water column. This exposes the bed protection to more intense flow, similar to Alternative 1.

These conditions make Alt. 2 without caisson more critical. Load Combination LCC02b (see Figure 6.13), hence current-attack (LC01) with wave load (LC02), results in the highest loading. The following sections evaluate which of the three loading conditions: current (LC01), wave (LC02), or ship-induced loads (LC03), governs the bed protection stability design. Specifically, the assessment identifies which load case results in the largest required rock size to ensure bed stability.

Bed Protection Stability Check - Current Attack (LC01)
The required rock size for bed protection is estimated with the empirical Pilarczyk (1998) formula, widely used for current-driven stability checks (i.e, LC01). The formulas, parameters, and assumptions necessary for this assessment are extracted from Chapter 5 of the Rock Manual (CIRIA et al., 2007). Table 6.11 summaries the calculated sizes near the sill, detailed calculations are provided in Appendix F.3.3 (i.e., Alternative 1) and Appendix F.3.4 (i.e., Alternative 2).

Location	Parameter	Alternative 1	Alternative 2
Upstream of the Sill	$D_{50,\text{up}}$ [m]	1,07	0,95
	$d_{n50,\text{up}}$ [m]	0,90	0,80
	Grading Class	HMA 1000–3000	HMA 1000–3000
Downstream of the Sill	$D_{50,\text{down}}$ [m]	1,29	1,15
	$d_{n50,\text{down}}$ [m]	1,09	0,97
	Grading Class	HMA 3000–6000	HMA 3000–6000

Table 6.11: Summary of grading for bed protection around the sill for Alternatives 1 and 2 under current-attack (Schiereck and Verhagen, 2019).

The rock sizes differ only marginally between alternatives because the greater flow depth in Alt. 2 reduces bed shear. Upstream flow velocity v_s and shear stress τ scale approximately with $\sqrt{g \cdot h}$. As Alt. 2 has a deeper sill elevation, the computed depth-averaged flow velocity (U) is slightly lower, resulting in a smaller D_{50}. Both alternatives exhibit a larger grading downstream of the sill than upstream. Passing the sill the flow accelerates and a hydraulic jump forms, raising turbulence and shear stresses. This jump produces eddies that increase be shear, resulting the downstream grading being a class higher (i.e, HMA 3000-6000) to resist scour. This explains why Alt. 2 may leverage smaller stones and still statisfy the current-attack stability.

Bed Protection Stability Check - Wave Load (LC02)
A wave-loading stability check was performed to size the bed protection upstream of the sill under storm-wave conditions (LC02), and to compare it with current- and ship-induced loads. Unlike steady currents, waves impose oscillatory horizontal shear through bottom-orbital velocity $\dot{u}_b$, which flattens near the bed and varies harmonically with amplitude $\hat{u}$ (Holthuijsen, 2007). At the bottom, vertical velocities are zero by definition (Holthuijsen, 2007). If unprotected, the horizontal motion can erode the subsoil. Downstream effects are neglected, assuming wave energy is dissipated by the barrier. Stability check follows Schiereck and Verhagen (2019). For non-breaking waves, the Rance–Warren (1996) formula, based on a modified Shields approach and Sleath's (1978) experiments, is used.

In shallow water ($kh \ll 1$; i.e., $kh < \pi/10$ or $h/L > 1/20$), the horizontal orbital velocity simplifies to $\hat{u}_b \approx \sqrt{gh}\frac{H}{2h}$, greater depth reduces bed shear and allows smaller stone sizes. Table 6.12 lists the resulting rock sizes, , detailed calculations are provided in Appendix F.3.3 (i.e., Alternative 1) and Appendix F.3.4 (i.e., Alternative 2).

Parameter	Alternative 1	Alternative 2
d_{n50} [m]	0.10	0.06
D_{50} [m]	0.12	0.08
Grading Class	LMA 40–200	CP45/180

Table 6.12: Summary of grading for bed protection around the sill for Alternatives 1 and 2 under wave loading (Schiereck and Verhagen, 2019).

For Alt. 2 without caisson requires smaller stones because the sill is $7\,\mathrm{m}$ deeper, the increased depth decreases $\hat{u}$, lowering the orbital motion at the bed ($\dot{u}_b$), and allowing a lighter grading (i.e, CP45/180), compared with Alt. 1 (i.e, LMA 40-200). In Alt. 1 the shallower depth keeps waves affected by the bottom, so higher shear demands larger rock sizes.

Bed Protection Stability Check - Ship Load (LC03)
In addition to storm loads, the bed protection must withstand scour from vessel traffic over or near the sill (Figure 6.24), especially during routine navigation through the HSC (i.e., LC03). This load case is compared with current- and wave-induced stability. The primary mechanism is propeller wash, high-velocity jets near the bed, while effects from primary- and secondary waves or return currents are considered negligible. All design assumptions and formulas follow PIANC Guidelines (PIANC, 2015).

The governing case for ship-induced loading occurs in the future configuration of Alt. 2 (without caisson), which allows deeper-draft vessels like a Suezmax tanker. Compared to the MGX-24 container ship in Alt. 1, the Suezmax has a deeper draft (23 m vs. 16 m), wider beam (45 m vs. 32.3 m), and shorter length (285 m vs. 400 m), possibly resulting in stronger near-bed wash due to reduced propeller clearance h_p, see Figure 6.24. Although the propeller of the Suezmax sits closer to the bed (i.e., smaller h_p) its lower engine power P and propeller diameter D_p results in a weaker jet, therefore net bed shear is lower than in Alt. 1.

The “Dutch Method”, derived from Izbash’s formulation, is applied here to determine the required rock size D_{50} by relating the bed shear to the velocity near the bed. The resulting grading is provided in Table 6.13. For a detailed discussion on the bed protection under ship-induced loading, please refer to Appendix F.3.3 (Alternative 1) and Appendix F.3.4 (Alternative 2).

Parameter	Alternative 1	Alternative 2
$D_{50,\mathrm{up}}$ [m]	0.56	0.42
$d_{n50,\mathrm{up}}$ [m]	0.47	0.35
$D_{50,\mathrm{down}}$ [m]	0.56	0.42
$d_{n50,\mathrm{down}}$ [m]	0.47	0.35
Grading Class	HMA 300–1000	LMA 60–300

Table 6.13: Summary of grading for bed protection around the sill for Alternatives 1 and 2 under ship loading (Schiereck and Verhagen, 2019).

Both alternatives need relatively large rock size because Under-Keel-Clearance is small, allowing propeller jets to reach the bed. The difference between the two ship types is clearly reflected in the results. The MGX-24 container vessel in Alt. 1 is equipped with twin 29.7 MW engines and larger propellers, producing a higher efflux velocity and resulting bottom velocity. The Suezmax tanker in Alt. 2 has a lower installed power (i.e., 17.1 MW), and smaller propellers, reducing jet velocity, so lighter rock size suffices.

Bed Protection Length Check
The stability determinations show that current-induced loads are the governing factor for sizing the rock in the bed protection. Turbulent flow near the edge of the protection zone can create scour holes in the sandy bed, particularly when sediment transport over the bed rock layer is limited (see Figure 6.23). To avoid undermining the sill, the expected scour depth must be assessed, and the armour layer length sized accordingly. The potential scour depth (i.e., h_{max}) can be estimated using the simplified method based on clear-water conditions and the velocity for sediment motion initiation, as given by Voorendt (2022). For a more detailed discussion on the scour depth (i.e., elaboration of calculations) refer to Appendix F.3.3 (i.e., Alternative 1) and Appendix F.3.4 (i.e., Alternative 2).

The bed protection must extend far enough to contain the full development of a potential scour hole caused by current-induced flow. If too short, the scour hole may reach beneath the sill, risking instability. To avoid this, the required length L is calculated based on the maximum scour depth h_{max} and the assumed slope $1 : n_s$ of the failure plane (i.e., $L \geq \gamma \cdot n_s \cdot h_{\max}$; see Figure 6.23).

The required bed protection length for Alt. 1 is calculated as $L = 248\,\text{m}$. Theoretically this is sufficient to ensure that the failure plane remains outside the sill's base. This length assumes a relatively loose bed material, which reflected by a slope parameter of $n_s = 15$. For denser or more cohesive soils, a steeper slope (e.g., $n_s = 6$) could reduce the required length. For Alt. 2, application of the same method results in a large scour depths. Given the greater water depth ($h_0 = 25.3\,\text{m}$) in this scenario, the calculated maximum scour depth is $h_{\max} = 19.73\,\text{m}$. This is rarely observed in the field. This overestimation arises because the underlying empirical scour formulas are calibrated for shallow depths. Thus these become unreliable in deep water. Parameters such as the Shields stress, no longer accurately capture the sediment transport dynamics under these conditions.

It is chosen to retain the $248\,\text{m}$ protection length from Alt. 1 also for the adaptable sill in Alt. 2. This approach acknowledges the limitations of the formula and avoids potentially over-engineering. For more precise estimates, future design phases may consider advanced scour assessments. These includes computational fluid dynamics (CFD) simulations or physical scale modeling.

6.4.5. Design Verification of Geometrically Open Filters under the Sill

Filter layers prevent internal erosion (i.e., piping) but allows controlled water flow to reduce pore pressure. As stated earlier, for the sill at the Floating Sector Gates, a geometrically open granular filter is selected. This is due to its robustness and maintainability under site conditions. This type of filter uses coarser material relative to the base layer, allowing limited grain movement without causing erosion, as long as the hydraulic gradient remains below a critical threshold (Schiereck and Verhagen, 2019).

When particles shift, no significant erosion occurs. The filter ensures stability for both parallel and perpendicular flow (see Figure 6.26), enabling efficient designs with coarser materials and fewer layers. Geometrically closed filters, which prevent any grain movement by tightly restricting pore size, can result in unnecessarily thick constructions (Schiereck and Verhagen, 2019). Closed-filters do not explicitly account for hydraulic loads and rely only on grain-size ratios to block movement. They offer theoretical robustness but may lead to over-dimensioning, reduced permeability, or both.

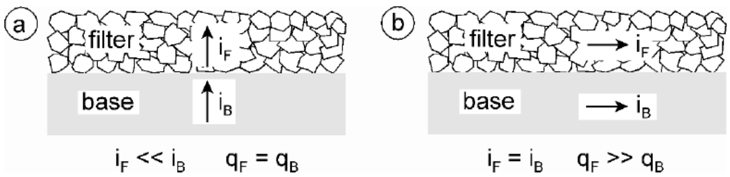


Figure 6.26: Perpendicular and parallel flow in granular filter (Schiereck and Verhagen, 2019).

From a practical, operational, and life-cycle perspective, the choice of a geometrically open granular filter presents several advantages. According to Deltares (2015):

- *Robustness and resilience:* these filters offer high permeability, reducing the likelihood of pore pressure buildup under loading;
- *Proven durability:* unlike geotextiles, granular filters are insensitive to mechanical damage during construction or over the structure's lifetime. With correct grading, they can remain effective well beyond 50 years;
- *Ease of inspection and repair:* granular materials are easier to monitor and maintain after construction, especially in submerged or buried applications;
- *No degradation:* granular filters are immune to biological or chemical decay, and they present no uncertainties regarding material aging or creep common concerns with synthetic geotextiles.

Based on the hydraulic loading and the expected base material at Bolivar Roads (i.e., silty to medium sand) the filter must be appropriately sized. Well-graded crushed stone or coarse gravel is recommended, with typical gradings ranging from 2/6 mm to 20/40 mm or 22/32 mm, depending on the required function (Deltares, 2015). To ensure coverage and internal stability, the minimum thickness should be at least three grain layers, about 5 to 10 cm (Schiereck and Verhagen, 2019). For practical underwater construction, a filter thickness of 0.5 m is adopted (Deltares, 2015). Please refer to Appendix F.3.3 (Alternative 1) and Appendix F.3.5 (Alternative 2) for an elaborated discussion on the determination of the filter layers under the sill. Below briefly.

Filter Layer Design Check – Interface Top Layer and Subsoil
This section assesses whether a filter layer is needed between the top layer and the existing non-cohesive subsoil, a first step in designing a geometrically open granular filter system. For Alternative 1, two independent methods are used to determine the necessity of a filter layer.

Critical Gradient Method (CUR, 1993)
This method compares the actual hydraulic gradient i_{act} at the interface with a critical threshold value i_{cr} that marks the onset of instability of the base material. When $i_{\text{act}} > i_{\text{cr}}$, transport of base material particles may occur, indicating the necessity for a filter layer. The critical gradient is derived from empirical design charts (refer to Appendix F.3.3), which relate the ratio $n_f \cdot D_{15t}/D_{85b}$ to i_{cr}, where:

- n_f = porosity;
- D_{15t} = sieve size for which 15% of the top layer is finer;
- D_{85b} = sieve size for which 85% of the base layer is finer.

The actual gradient i_{act} is derived from flow resistance and turbulence considerations (refer to Appendix F.3.3). Results in: $i_{\text{cr}} = 0.020$ and $i_{\text{act}} = 0.033$. $i_{\text{act}} = 0.033 > i_{\text{cr}} = 0.020$. The hydraulic conditions at the interface exceed the stability threshold for the base material, and a filter layer is necessary to prevent transport of the subsoil. The subsequent sections will design this filter layer in accordance with geometrically open filter principles.

Bakker-Konter Method (CIRIA et al., 2007)
To assess the need for a filter layer between the top layer and the non-cohesive subsoil, the Bakker-Konter method can also be applied. This method provides a simplified criterion for geometrically open filters in bed protection. Assuming the highest hydraulic load acts on the top layer. The filter must therefore prevent erosion of the underlying subsoil. As defined by Bakker-Konter (1994), the actual ratio $\frac{D_{15f}}{D_{50b}}$, must be less than or equal to a theoretical threshold defined by:

$$\frac{D_{15f}}{D_{50b}} \leq \frac{15.3 \cdot R}{C_0 \cdot D_{50t}} \tag{6.2}$$

where:

- D_{15f}, 15th percentile grain diameter of the filter layer [m];
- D_{50b}, 50th percentile grain diameter of the base material (subsoil) [m];
- D_{50t}, 50th percentile grain diameter of the top layer [m];
- R, hydraulic radius, taken equal to the flow depth h in this case [m];
- C_0, correction factor, typically 30 for conservative design assumptions [-].

Substituting the given parameters of Alt. 1 in Equation 6.2. Results in the maximum allowable ratio $\frac{D_{15f}}{D_{50b}}$ « the actual ratio $\frac{D_{15f}}{D_{50b}}$. Thus, additional filter layers are required between the top layer and the subsoil to avoid material erosion or piping from the base layer. Both methods (i.e., Critical Gradient and Bakker-Konter) require extra filter layers between the top layer and the subsoil to ensure popper protection. In the subsequent paragraph, these layer will be determined via the Bakker-Konter Method.

Filter Layer Design – A Multi-Layered Filter System
In this section, the filter layer system is developed using the Bakker-Konter criterion. The goal is to ensure that each interface between two adjacent layers (i.e., between top layer, filter layers, and subsoil) meets the stability conditions required to prevent failing of finer materials into coarser ones. In a multi-layered system, the application of Equation 6.2 follows specific indexing conventions:

- t, refers to the top layer;
- f, to the filter layer being evaluated;
- b, to the underlying layer, which may be another filter or the base (i.e., subsoil).

For example, when evaluating the interface between the top layer and the first filter layer, D_{50t} refers to the top layer, D_{15f} to the first filter layer, and D_{50b} to the same first filter layer. When assessing the filter layer against the base soil, D_{15f} still refers to the filter, but D_{50b} now corresponds to the subsoil (see Figure 6.27). The design procedure consists of the following steps:

1. A candidate filter layer is proposed with known grain size characteristics (i.e., grading);
2. The filter layer is checked using the Bakker-Konter formula against the adjacent upper layer (i.e., typically coarser) and lower layer (i.e., typically finer);
3. If either of these checks does not meet the stability criterion, an extra intermediate filter layer must be inserted;
4. This process is repeated iteratively until all interfaces comply with the stability condition in Equation 6.2.

The filter system is considered sufficient once every transition between layers meets the requirement (i.e., the actual value of $\frac{D_{15f}}{D_{50b}}$ is lower than or equal to the theoretical threshold for both the upper and lower interface). This process leads to a step-wise refinement of the gradation to ensure a stable, permeable, and constructible filter structure. Appendix F.3.3 present the step-by-step construction and verification of the filter layers for Alt. 1. Figure 6.27 gives an example of the considered interfaces, and the final filter configuration as determined for Alt. 1.

For Alt. 2 (with and without caisson), the filter system is reassessed considering larger hydraulic radius, from $R = 17\,\mathrm{m}$ to $R = 22\,\mathrm{m}$. Despite this change, current-induced loading remains the governing factor for top layer sizing, requiring the same HMA 3000–6000 class as in Alt. 1. The subsoil is assumed unchanged (i.e., fine silty sand or clayey fines). Although a larger hydraulic radius could affect the critical gradient and filter requirements, re-evaluation confirms the filter design from Alt. 1 remains sufficient. The Bakker-Konter check, applied with the updated R value, show the filter still meets stability and permeability criteria. Since the subsoil and bed rock grading are unchanged, and no significant shifts in hydraulic conditions occur, the existing multi-layer geometrically open filter system remains valid for Alt. 2 configuration.

6.4.6. Final Design Configuration - Alternative 2

The final design for the adaptable sill in Alternative 2 is presented in Figures 6.29 and 6.30. For a comparison with Alternative 1, refer to Appendix F.3.3. In the initial configuration, where the caissons are in place, a sediment cover naturally forms over the bed protection. This sediment layer provides an additional buffer against hydraulic forces. It can be eroded due to propeller wash or flow contraction when the barrier closes. Despite this, the presence of bed protection ensures that erosion is not considered a significant concern at this stage.

The caisson modules can be anchored to the sill blocks using “shear keys”. These shear keys can be integrated into the caisson base and the sill, providing horizontal stability and shear resistance.

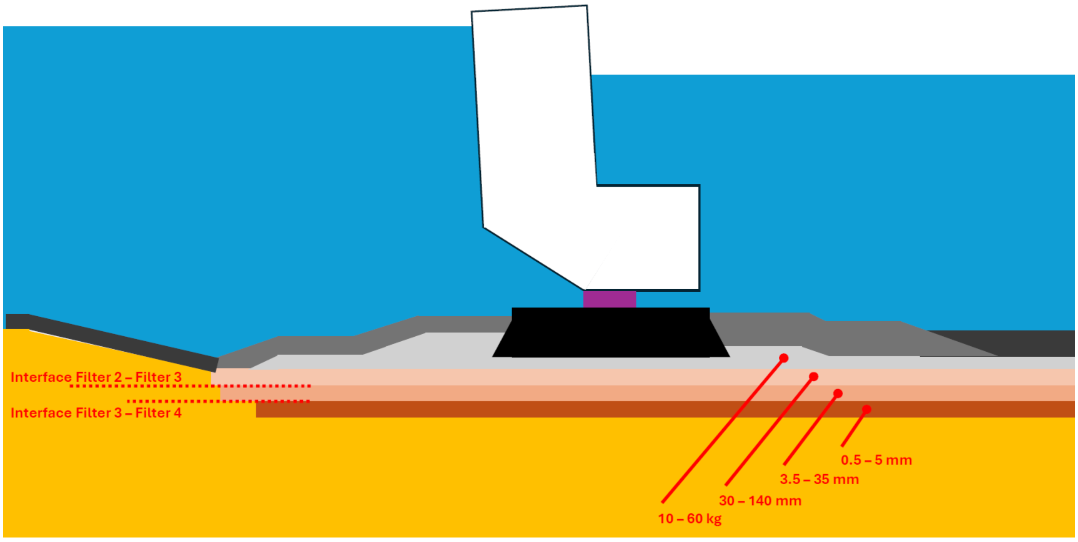
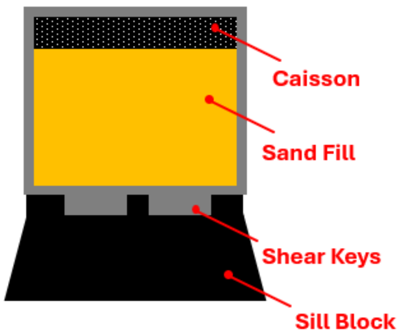


Figure 6.27: Alternative 1 and 2 - schematic of filter layer construction.

Locking the caissons in place with these “shear keys” prevents misalignment and distribute forces evenly across the structure (Voorendt et al., 2020). This approach allows for future removal, as the shear keys can be vertically disengaged if necessary (see Figure 6.28). In the second configuration, once the caisson are removed to accommodate deeper-draft vessels, the bed protection remains governed primarily by current-induced loading, both upstream and downstream of the sill. Specifically, 3–6 ton bed rock is specified downstream of the sill. The transition from heavier rock classes (up to 6 tons) to progressively lighter grading (1–3 tons, 300–1000 kg, 60–300 kg, and 10–60 kg) follows the bed protection configuration used at the Maeslant Barrier project (i.e., as explicit determination is outside the scope of this study) reflecting the gradual reduction in turbulence.



(a) Schematic of shear key attachment caisson - sill block.

(b) Shear key connection Volkerak caisson (Klein, 1969).

Figure 6.28: Shear key anchoring of caisson in hydraulic engineering applications.

The Maeslant Barrier vs. Bolivar Roads Specific Concerns
The design parameters of the Maeslant Barrier have been adopted as the primary reference for the Bolivar Roads Floating Sector Gate. This approach was chosen because the current conceptual design parameters provided in Appendix D of the Coastal Texas Study Report (USACE, 2021d) were insufficient for a comprehensive analysis (refer to Section 6.1). Taking these design assumptions for the final design is neither feasible nor advisable. The Gulf has unique environmental and geotechnical challenges.

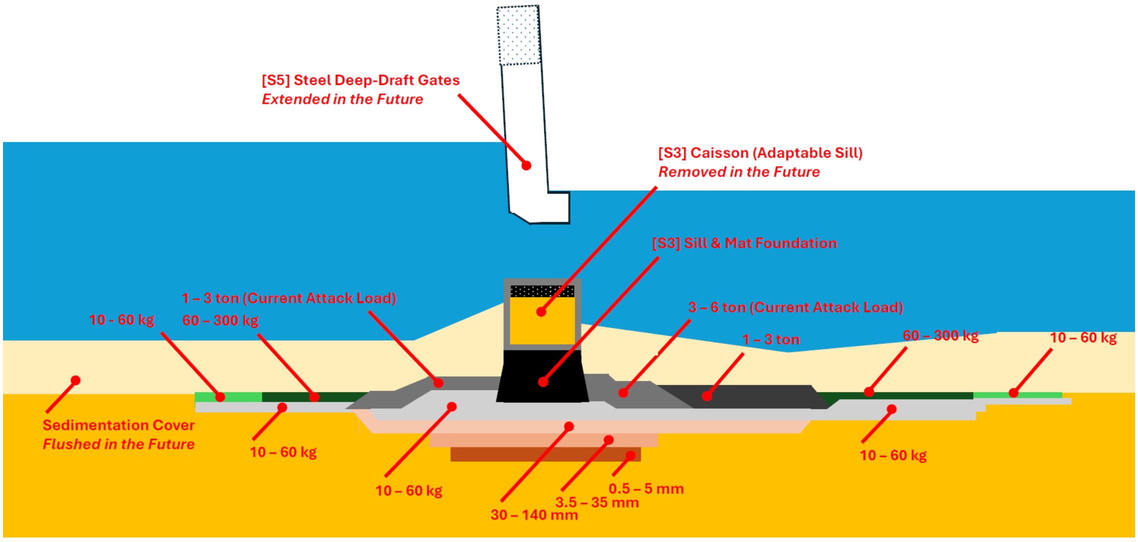


Figure 6.29: Schematic of final design Alternative 2 – side view.

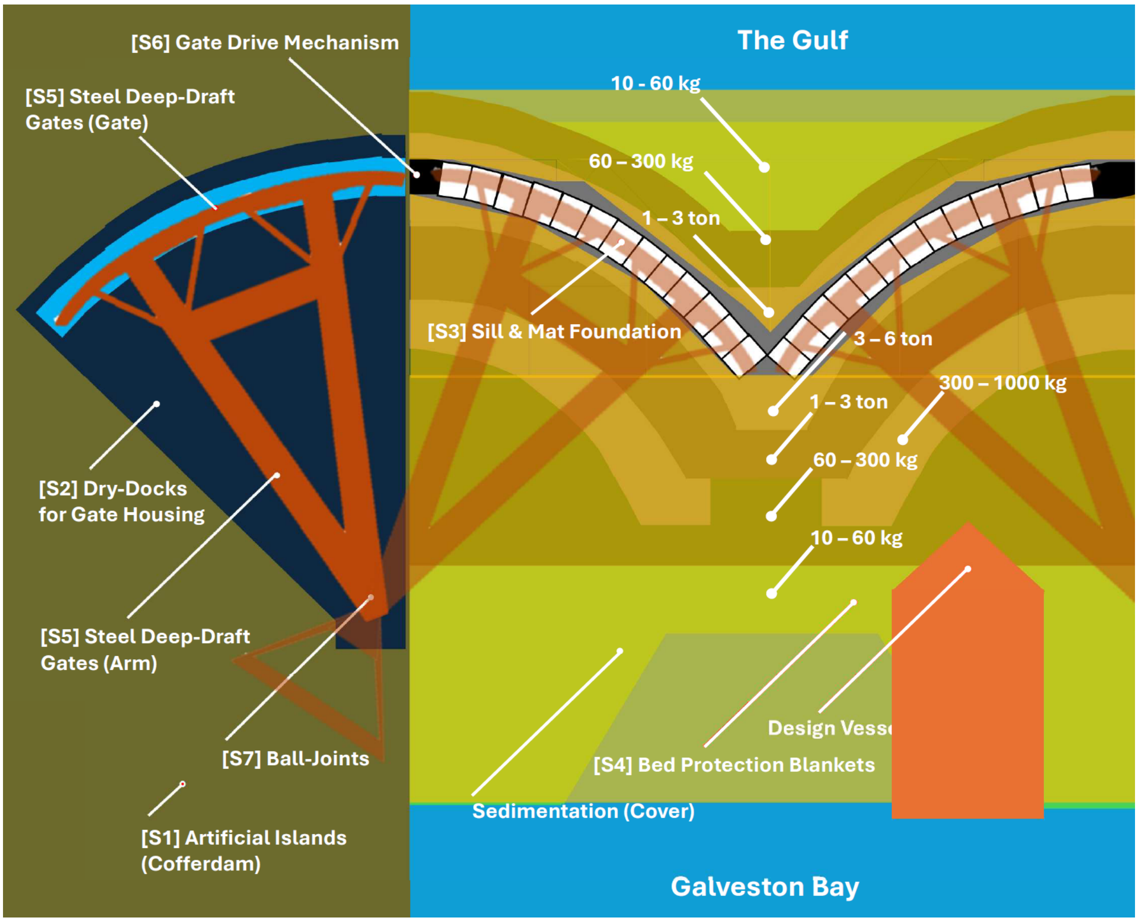


Figure 6.30: Schematic of final design Alternative 2 – top view.

The Maeslant Barrier is designed to close against storm surges from the North Sea, wind speeds can reach up to 100 km/h (60 mph) and storm durations typically range from 12 to 48 hours. The surge propagate as one-way waves through the confined “Nieuwe Waterweg” canal, creating a predominantly unidirectional head differential. The Bolivar Roads SSB faces more severe environmental conditions, yet with shorter duration. It must withstand the forces of Category 5 hurricanes, which can produce wind speeds of up to 260 km/h (160 mph) and generate multidirectional surge patterns.

Hurricanes can affect the SSB for 12 hours to several days, with the most intense wind and rainfall from the eye-wall typically lasting 12–18 hours (Biswas and Keneally, 2022). This introduces fluctuating positive and negative head differentials, creating a more complex loading environment (Metselaar, 2024). Unlike the Maeslant Barrier, which faces primarily unidirectional loads, the Bolivar Roads structure must withstand variable forces and longer disruptions to maritime traffic (refer to Section 5.4.2).

The geotechnicals of the two structures vary due to the differing subsoil conditions at each site. The Maeslant Barrier is build on relatively dense, compact sand. This provides a stable base. The Bolivar Roads site has much softer, unconsolidated, clay-rich layers (refer to Section 5.3.2). This weaker, more compressible soils is prone to consolidation. This necessitates a pile-supported sill to provide stability (refer to Appendix D of the Coastal Texas Study Report; USACE, 2021d). These piles are needed to limit differential settlement, which can lead to misalignment of the sill. Resulting in increased stresses on the ball-joints, and potential damage to the surrounding bed protection over time. The requirement for a pile-supported foundation at Bolivar Roads introduces additional structural complexity and higher initial construction costs.

Finally, a difference between the two sites lies in their respective hydrodynamic and morphological environments. The Maeslant Barrier is located within a straight, regulated, and dredged canal, providing a relatively stable environment. Bolivar Roads serves as the primary tidal inlet for Galveston Bay, a dynamic system characterized by active sediment flushing, and shifting bathymetry (refer to Section 5.3.3). The HSC intersects with the Bolivar Roads estuarine opening (see Figure 4.2), is constantly dredged. The reshaping of the bed alters local flow patterns, increasing the risk of foundation undermining. Given these challenging conditions, the foundation at Bolivar Roads will likely require a more extensive bed protection system to counteract the scouring. For example, the the block-mats, filled with sand and gravel, placed at the Eastern Scheldt- and Venice Lagoon Barrier.

In conclusion, while the design parameters of the Maeslant Barrier provide a valuable baseline for the preliminary assessment of the Bolivar Roads Floating Sector Gates, reconsiderations are necessary to account for the more extreme environmental forces and site-specific challenges present in the Gulf.

Implications of the Adaptable Sill
Integrating the adaptable sill into the Floating Sector Gate introduces a cascade of design changes. While the primary intention is to provide long-term flexibility, this decision alters the design of multiple related components, which should manifest flexibility. The modification to the sill can trigger a series of downstream adjustments, affecting the following main elements: [S5] Steel Deep-Draft Gates (Gate) - [S5] Steel Deep-Draft Gates (Arms) - [S7] Ball-Joints (Foundation) (see Figure 6.30). Refer to Figure 6.31 for the cascading diagram, the rational below.

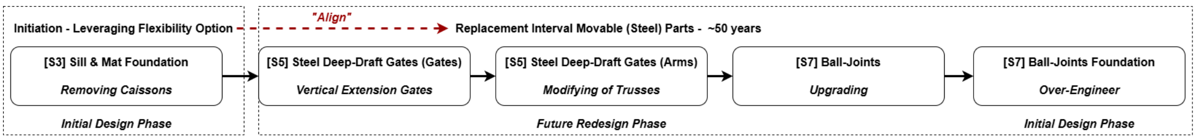


Figure 6.31: Cascading Diagram of Implications Adaptable Sill Design.

As the sill is lowered to accommodate deeper vessel drafts, the vertical extension of the [S5] Steel Deep-Draft Gates (Gates) is needed to maintain sufficient height against storm surges. This leads to higher dead weights and greater hydrodynamic forces. These forces must be effectively transmitted through the [S5] Steel Deep-Draft Gates (Arms), which connect to the [S7] Ball-Joints. The deeper, more massive [S5] Steel Deep-Draft Gates (Gates) impose additional demands on the [S5] Steel Deep-Draft Gates (Arms), requiring them to be both stronger and more precisely engineered to handle the increased vertical height, larger submersion angles, and greater dead loads. This places greater strain on the [S7] Ball-Joints, which provide the rotational freedom and force absorption of the gate arms. Consequently, the [S7] Ball-Joint Foundations must also be reinforced to support these loads. The foundation components, particularly the ball-joint bases, are subjected to higher stresses, potentially requiring reinforcement to prevent excessive wear, or differential settlement.

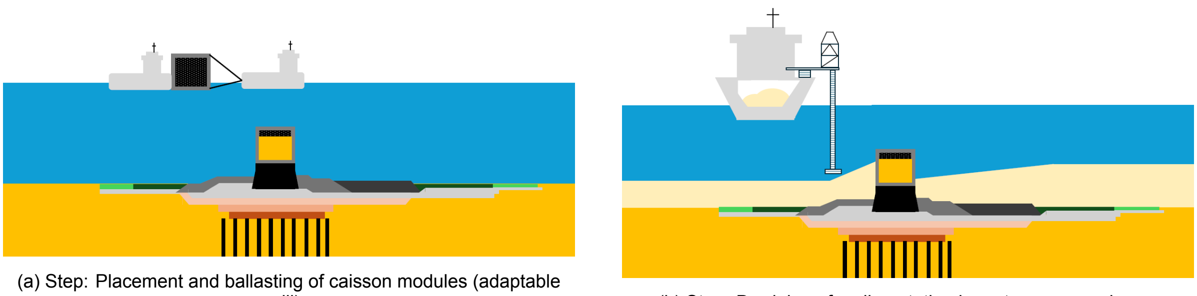
The proposed changes are feasible within the project life-cycle, as the [S5] Steel Deep-Draft Gates (Gate & Arm) have a typical lifespan of 50 years (refer to Section 4.6), shorter than the 100 year design life of fixed structures like the [S3] Sill & Mat Foundation and [S7] Ball-Joints Foundation. This shorter replacement cycle presents an opportunity to implement the flexibility option when the [S5] Steel Deep-Draft Gates (Gate & Arm) reach the end of their service life, aligning upgrades with replacement intervals (see Section 4.6 and Subsection 6.3.2).

When the [S5] Steel Deep-Draft Gates (Gate & Arm) needs to be replaced, this interval provides an opportunity to migrate the physical components to the new configuration. This means extending the [S5] Steel Deep-Draft Gates (Gate) to the required vertical height. Modifying the [S5] Steel Deep-Draft Gates (Arm) trusses for the increased draft and angle of submergence. But also upgrading the [S7] Ball-Joints to withstand the anticipated higher forces and angle of submergence. The [S7] Ball-Joints Foundation, being a fixed structure with a 100 year design life, presents a constraint. It is not easily replaced. To avoid costly retrofitting, the [S7] Ball-Joints Foundation needs to be over-engineered from the outset to accommodate both the initial and future configurations. It is recommended to incorporate options for flexibility into the fixed [S3] Sill & Mat Foundation through an adaptable sill design, over-dimension the [S7] Ball-Joint Foundation from the outset to accommodate future retrofits, and defer modification to the [S5] Steel Deep-Draft (Gate & Arm) and [S7] Ball-Joints until their replacement cycle.

The adaptable sill increases system flexibility but also has broader implications for system operations, maintenance, asset management, and upfront investment risks. These trade-offs must be weighed against potential long-term savings, as further discussed in Section 6.5.

6.4.7. The Construction and Use Sequence of the Adaptable Sill

The caisson-based sill has a proven construction method (Voorendt et al., 2020), supporting a phased approach. Its modularity allows for construction using standard marine equipment. The concept is executed in two phases (refer to Appendix F.3.5 for a detailed step-by-step overview). In the Initial Construction Phase, prefabricated caisson modules filled with sand are placed on the sill and filter system (see Figure 6.32a). Once submerged and integrated with the bed protection, the sill becomes fully functional and inherently adaptable from the outset. In the Future Construction Phase, the system's built-in flexibility is activated. First, the sedimentation cover is dredged or flushed (see Figure 6.32b). Then, the caissons are emptied, floated, and removed to restore full channel depth, allowing adaptation to deeper-draft vessels.



(a) Step: Placement and ballasting of caisson modules (adaptable sill).

(b) Step: Dredging of sedimentation layer to expose caisson.

Figure 6.32: Construction sequence for Alternative 2: final sill and bed protection works.

6.5. Asset Management (AM) Strategy for the Adaptable Sill Design

To ensure the long-term success of the adaptable sill, technical design needs an tailored AM framework. Insights from stakeholder interviews revealed consistent concerns about funding volatility, operational handover risks, and political interference (refer to Appendix G for the interview transcripts). These challenges echo systemic issues observed in other large-scale flood defense systems, the rational below.

Institutional Logics literature shows that infrastructure agencies often operate under dominant paradigms such as “Project Logic”, “State Logic” , or “Asset Management Logic”, which emphasize short-term delivery, compliance, or cost-efficiency (refer to Appendix A.2). While these approaches are necessary, they often overlook adaptability. Embedding a complementary *“Flexibility Logic”* requires that adaptability is not only designed but also actively governed. This means a shift in how risk and asset valuation are approached in AM. This involves maintaining institutional memory, enabling timely decision-making, and ensuring that actors have both the mandate and capacity to act. The Literature Review on multi-actor governance showed that flood defenses perform best when stakeholders engage in structured, scenario-based risk dialogues to inform long-term decisions (refer to Chapter 2).

Following this, I-STORM (i.e., international knowledge sharing network for SSBs), conducted a cost of ownership study for a SSB (i.e., AM), using the Ramspol Barrier as a case study (note: this study is not publicly available). The study identified cost categories, including primary categories such as maintenance and personnel costs, and subcategories such as management and operations teams (FTEs). Together, these literature and practitioner insights form the basis of the adaptable sill’s AM framework.

The “Flexibility Logic” Asset Management (AM) Strategy for the Adaptable Sill Design
To implement these insights, the adaptable sill’s AM framework (see Figure 6.33), adopts a three-tier model: strategic, tactical, and operational, enhanced by a *”Flexibility Logic”*. At the strategic level, the asset owner, Gulf Coast Protection District (GCPD), sets long-term performance goals to address evolving physical, and socio-economic conditions. This requires active engagement with state agencies (e.g., Texas General Land Office (GLO)), knowledge institutions, and regional stakeholders (e.g., Port of Houston Authorities), refer to Section 4.3. Also, securing long-term funding is key at the strategic level, as shifting flood defense priorities over the SSB’s lifespan may threaten O&M budgets and system reliability (refer to Sections 5.4.4 and 5.4.5). To support this, 1–2 FTEs are needed, consisting of a senior policy advisor to navigate federal and state politics and manage multi-actor processes, and strategic planner to track trends and adjust long-term strategies.

The strategic level must establish a dedicated *“Flex-Reserve”* fund. This is a capital reserve intended to finance the adaptable sill, with a distribution key between state- (e.g., O&M costs), and federal funding (e.g., construction cost). As demonstrated by Hu and Cardin (2015), future retrofit costs can be reduced when the adaptable sill is embedded from the outset. If the sill is not designed to be adaptable, retrofitting is estimated to cost $80\,\%$ of the initial construction investment. This drops to $70\,\%$ if the sill is designed with adaptability in mind. Embedding flexibility increases initial construction costs by $10\,\%$, this up-front investment is offset by $-10\,\%$ in future retrofit expenses (Hu and Cardin, 2015).

The strategic level must commission a five-yearly *“Stress Test”* of the Floating Sector Gates (i.e., which aligns with political election cycles, hence possible change in policies). This test integrates asset data with future projections (e.g., sea-level rise, shipping traffic) and enables a multi-actor *“Risk Dialogue”* with regional stakeholders (refer to Section 4.3), to assess risks, determine if sill reconfiguration is needed, and barrier conservation plans needs to be adjusted. If the *“Stress Test”* and *“Risk-Dialogue”* identifies the need for sill reconfiguration, the strategic level can release the *“Flex-Reserve”* and initiate the retrofit construction. To prevent declining urgency over time, this process need to be anchored by an independent advisory group (i.e., dutch: “klankbordgroep”) comprising stakeholder representatives, with the mandate to enforce strategic-level decision-making.

At the tactical level (see Figure 6.33), the GCPD translates strategic goals into actionable plans and state-based maintenance policy (refer to Section 4.6), for the Bolivar Roads Gate System. These components lead to a conservation plan with Key Performance Indicators (KPI’s). Here the performance of SSB components can be categorized into technical (i.e., the duration which an asset component can fulfill its intended functions), economic (i.e., the time-frame over which costs of owning and operating the asset component remain lower than those of comparable alternatives) and functional aspects (i.e., the period in which an asset component meets its functional requirements) (Hamerslag and Bakker, 2023). These can lead to different performance failures (refer to Section 5.2). Research by Hamerslag and Bakker (2023) showed that for SSBs, the functional lifespan is the main factor for determining the end-of-life.

When a sill adaption is commissioned from the strategic level, the tactical level must shift maintenance activities, deferring or advancing maintenance as needed, so that the retrofit aligns with scheduled replacement of movable-, and electrical parts (e.g., steel deep-draft gates). In other words, making decisions in maintenance: postpone or do it now in the face of the flexibility option. This will lead to old-intermediate-new conservation plans per asset component, driven by their replacement cycles (refer to Section 4.6). Given the dynamic conditions at Bolivar Roads (refer to Sections 4.2 and 4.3), the tactical team must coordinate with Port Authorities, marine pilots, and NOAA on closures and storm protocols. A team of 3–5 FTEs: asset managers, engineers, planners, and data specialists, should ensure knowledge continuity through training, education, and timely on-boarding.

At the operational level (see Figure 6.33) service providers handle daily inspections, minor maintenance, and emergency response, feeding field data into readiness metrics and higher-level planning. A team of 2–5 FTEs ensures the Floating Sector Gates remain in standby and operational condition through routine monitoring, site checks, and minor repairs. During storm events, when forecasts signal critical water levels, the automated closure protocol is triggered. A team of 15–25 FTEs including asset managers, engineers, meteorologists, and data analysts, mobilizes to issue warnings, halt navigation, and close the gates. The barrier reopens once water levels recede. While maintenance tasks (i.e., minor to major) can be outsourced, full outsourcing risks loss of operational knowledge (refer to Section 5.4.6). To preserve expertise, the O&M team should undergo regular training and participate in annual test closures, with lessons feeding into the five-yearly strategic stress test.

6.6. Summary and Conclusions

This chapter identified how options for flexibility in design can be embedded into the Floating Sector Gates at Bolivar Roads, translating the need of an options for flexibility mode in the barrier design and planning, as concluded in Section 5.6. It addressed sub-questions SQ3 and SQ4, in particular *[SQ3] Which specific component of the Bolivar Roads Gate System, as well as the overall system, offer design flexibility to address uncertainties over the next 150 years, and which components are anticipated to manifest flexibility?* The results show that options for flexibility in storm surge barrier (SSB) design, comprising fixed, movable, and electrical components, must be embedded in the fixed elements, such as the [S7] Sill & Mat Foundation. Alternatively, these fixed components need to be over-engineered to support multiple generations of shorter-lived, replaceable elements. Because fixed components are typically permanent (e.g., 100 years) and difficult to modify post-construction, making retrofits costly.

Movable and electrical components, with shorter replacement cycles (e.g., 50 years), offer regular opportunities for technological and spatial upgrades. This inherent turnover supports the principle of flexibility by allowing these parts to evolve alongside changing system demands. Thus, options for flexibility in SSB design must be built into fixed components or achieved through over-engineering, while movable and electrical parts can adapt through regular upgrades. Thereby addressing the chapter's trade-off: prioritizing flexibility in components where functional performance is highly sensitive to system drivers and future modifications would be most costly.

To illustrate this design option principle, this chapter presented an adaptable [S7] Sill & Mat Foundation design that enables future deepening of the SSB. This component is most impacted by the system driver "Increased Vessel Draft" in the Bolivar Roads case, requiring built-in flexibility. The design features a two-stage structure: permanent concrete sill blocks founded on piles and a graded open filter, topped with prefabricated caisson modules. In Stage 1, the caissons are sand-ballasted and secured with shear keys, setting the crest at $-18.3\,\mathrm{m\,NAVD}$ adequate for the MGX-24 vessel. When deeper drafts are needed, Stage 2 is activated: the ballast is removed, caissons are floated off, and the underlying sill blocks, precast to $-25.3\,\mathrm{m\,NAVD}$, become the new crest, accommodating Suezmax vessels. As stated above movable and electrical components must be retrofitted accordingly. Foundation stability is ensured by a pile foundation and a four-layer open granular filter graded from 0.5–$5\,\mathrm{mm}$ to 10–$60\,\mathrm{kg}$, placed between the sill blocks and the fine-sandy subsoil. Above this, loose rock bed protection is applied: HMA 1000–3000 upstream, HMA 3000–6000 downstream of the sill. The protection extends $250\,\mathrm{m}$, sufficient to contain scour holes from closure currents up to $v_{s,\max} = 13\,\mathrm{m/s}$, driven by a head differential of $\Delta h = 9\,\mathrm{m}$ between the Gulf and Galveston Bay during storm conditions.

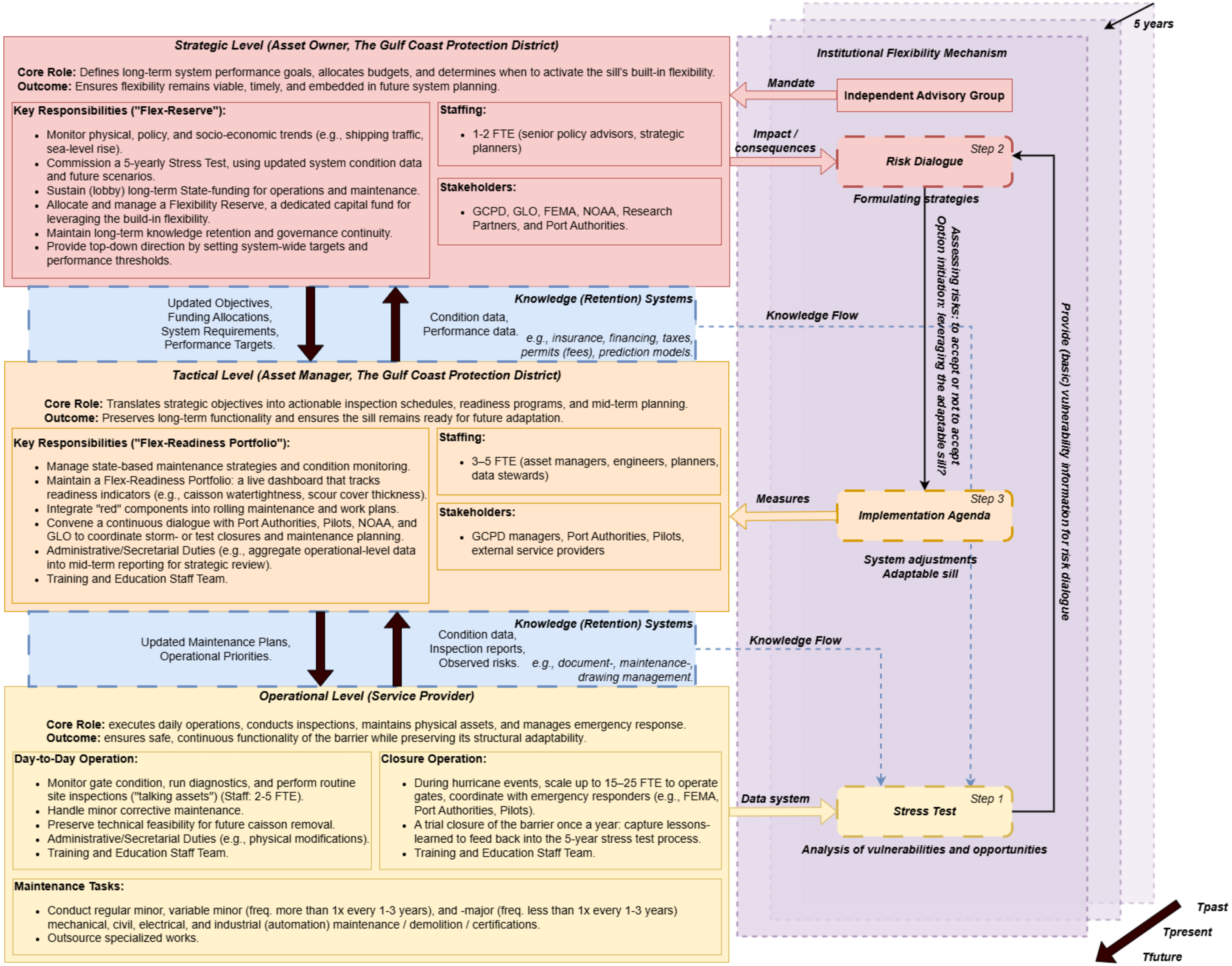


Figure 6.33: Conceptual Asset Management (AM) framework for Floating Sector Gates with adaptable sill at Bolivar Roads (i.e., Phase 3).

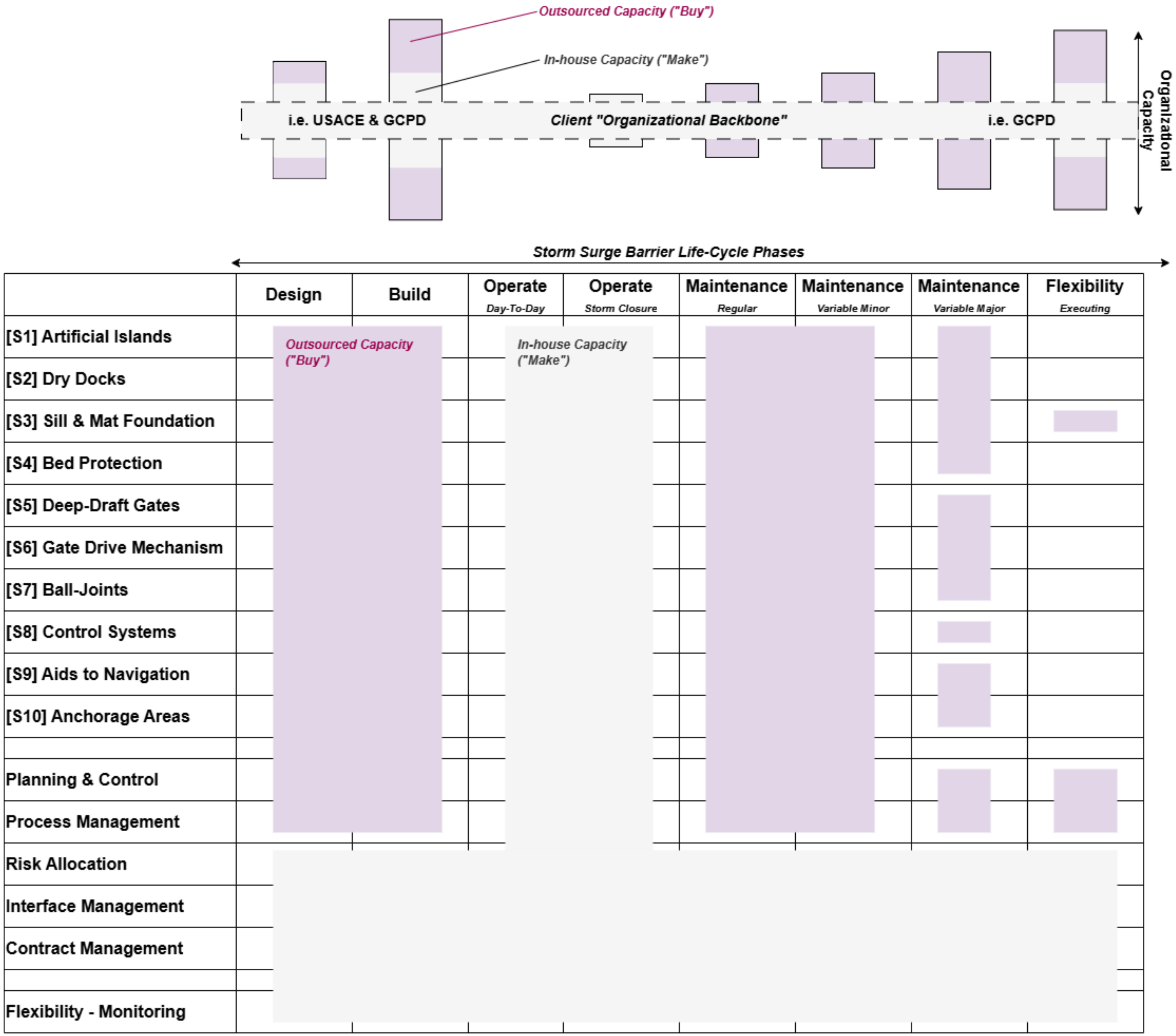


Figure 6.34: Contract strategy option Floating Sector Gates at Bolivar Roads (i.e., Phase 4).

7 Phase 4: Implementing Flexibility

The goal of Phase 4 is to develop guidance to a conceptual project delivery method (PDM) for the Floating Sector Gates at Bolivar Roads (i.e., dictated to CME). Unlike conventional infrastructure such as bridges or navigation locks, storm surge barrier (SSB)s carry a design life of over a century, demand high-reliability, and impose catastrophic socio-economic consequences if they fail. In this context, the public client (e.g., Gulf Coast Protection District (GCPD)), confronts a sharper “Make” or “Buy” dilemma: retain operational-critical tasks and knowledge in-house to safeguard accountability and continuity, or outsource them to market parties that can inject specialized innovation and risk-bearing ability? Phase 4 supports the answering of sub-questions 2, 4 and 5, particular SQ4. First, this chapter outlines the methodology used (Section 7.1), explores the complexities of large-scale infrastructure projects (Sections 7.2 and 7.3), and leverages the Kraljic Matrix to determine client accountability (Section 7.4).

7.1. Research Methodology

Phase 4 developed guidance to a conceptual PDM for the Floating Sector Gates at Bolivar Roads. It built upon the acquired insights from the previous research phases (refer to Chapters 4, 5, 6). Phase 4 conducted the following activities: (I) collecting data; (II) synthesizing academic literature on (mega-)project complexity; (III) analyzing client accountability in SSB project scope; (IV) develop conceptual PDM framework regarding SSB, and (V) examine the application of Digital Twin Model for continuous knowledge-retention in project life-cycle of SSBs.

7.1.1. Data Collection Method

Phase 4 builds upon the insights and data gathered in the preceding research phases. These include the System Diagram from Phase 1, the system drivers identified in Phase 2, and both the adaptable sill design and Asset Management Strategy developed in Phase 3. This phase primarily draws on academic literature related to project complexities, dynamic conditions, and lessons learned from previous mega-projects (refer to Chapter 2).

Existing Data

Using variables from the Theoretical Framework (refer to Chapter 3), this research phase incorporates literature findings related to project complexities, contract profiles, and project delivery models. The source of these variables is primarily academic literature and case studies involving complex infrastructure projects (i.e., Baccarini, 1996, Bakker and de Kleijn, 2014m Bakker and de Kleijn, 2018, Bosch-Rekveldt et al., 2011, Flyvbjerg et al., 2003, Hertogh and Westerveld, 2010).

7.1.2. Applied Method

The analysis for synthesizing the PDM followed a systematic, three-step approach:, resulting in a PDM guidance: (I) the study identified project complexities which are embedded is design-build-operate-maintenance phases such as technical and financial challenges. This step helps to understand mega-projects like Bolivar Roads, as these projects have become increasingly complex since World War II (Baccarini, 1996).

(II) The analysis incorporated the sourcing framework developed by Kraljic (1983) to assess per project phase the contract profile (e.g, scope, term, specification). The Kraljic Matrix supported a "Make" or "Buy" analysis to determine client accountability needed due to the unique SSB project scope. It also identified how the "Organizational Backbone" (i.e., essential organizational staff provided by the client) should evolve over time due to the demand of "Organizational Readiness", including, for instance, knowledge-continuity. (III) These insights were integrated into a conceptual PDM that aligns with the design option principles and Asset Management Strategy developed in previous research phases.

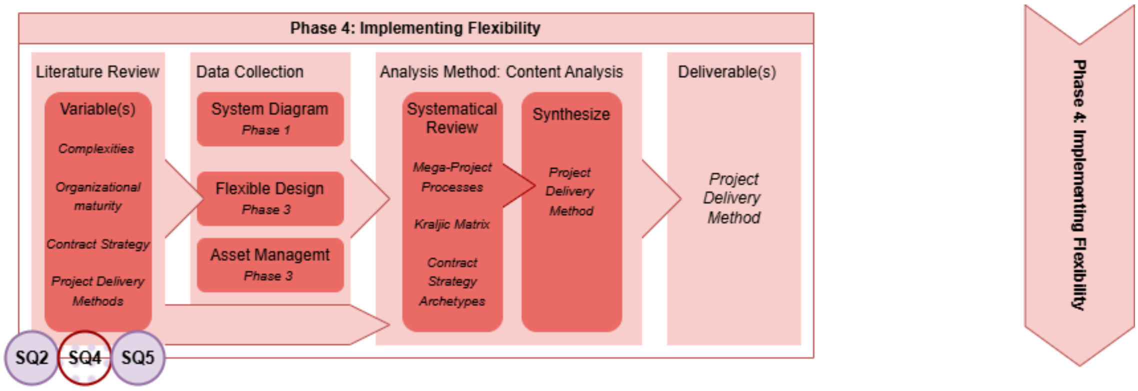


Figure 7.1: Research methodology Phase 4: Implementing Flexibility.

7.2. Decoding Complexity: Navigating the Bolivar Roads Project

Mega-projects like storm surge barrier (SSB)s involve large-scale infrastructure investments (DeSoto-Duncan et al., 2011), typically exceeding $1 billion (Flyvbjerg et al., 2003), and substantial Operations & Maintenance (O&M) expenses, influenced by the size and complexity (Aerts, 2018). For example, the Bolivar Roads Gate System is estimated at $14 billion (USACE, 2021a). Mega-projects are complex, and managing this complexity has become central to effective project delivery. Baccarini (1996), distinguishes complexity from size (i.e., scale of the project), uncertainty (i.e., degree of unpredictability), and difficulty (i.e., subjective perception of challenge), projects are complex if projects consists of many varied interrelated parts. These can be operationalized through differentiation and interdependency. Differentiation means the number and variety of elements within the project (e.g., tasks). Interdependency refers to the degree to which these elements are interconnected and must interact.

SSBs, particularly the Bolivar Roads Gate System, exemplifies this high structural and organizational complexity. As they function as part of a broader flood defense system (Jonkman, Hillen, et al., 2013). A SSB consist a wide array of components, ranging from civil, mechanical, and electrical subsystems (Mooyaart and Jonkman, 2017), to human decision-making (refer to Section 4.5.1). All are interlinked to fulfill functions such as flood protection, navigation, and water exchange (refer to Section 4.4.4). As such, the SSB is not only a physical structure but captures also socio-technical complexity.

Ultimately, the public client must choose to "Make" or "Buy" early, committing to contracts and guarantees before these structural and organizational complexities fully emerge. The choice between "Make" or "Buy" defines how much project complexity the public client retains or shifts to the market, a decision made before the full contours of that complexity is clear. Following Hertogh and Westerveld (2010), complexity in large infrastructure projects spans six domains: social, financial, legal, technical, time, and organizational. Social and organizational aspects are often the hardest to manage due to their dynamic and unpredictable nature. Below an elaboration per complexity (see Figures 7.2).

Social Complexity in Mega-Projects: Choosing Who Manages Stakeholder Tensions
Social complexity arises from the involvement of numerous stakeholders (Hertogh and Westerveld, 2010), each with different interests, influence (de Bruijn and ten Heuvelhof, 2008), and culture backgrounds (Meyer, 2014). SSBs, like the Bolivar Roads project, exhibit a diverse coalition of actors. Including federal agencies, local communities, and port stakeholders (refer to Section 4.3). These stakeholders often hold different priorities, leading to conflict over issues such as navigational access.

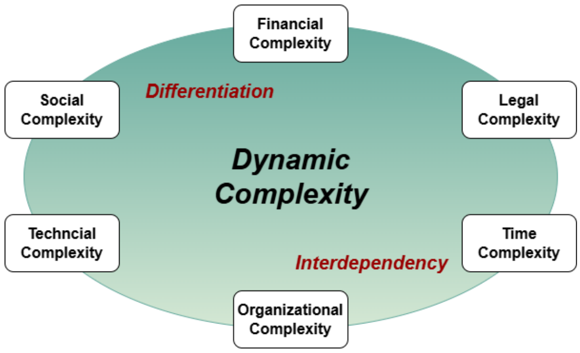


Figure 7.2: Project complexities in large infrastructure projects.

Tensions are increased by historical path dependencies and competing socio-economic agendas (Hertogh and Westerveld, 2010). As detailed in Section 5.4.4, slow-moving political processes, fragmented public funding mechanisms, and evolving regulatory frameworks complicate consensus-building. Resulting in delay of projects. Interview findings reinforce this (refer to Appendix G for the interview transcripts), highlighting how dependency on federal-level approvals and fluctuating political priorities introduced eroding stakeholder confidence. This generates resistance regarding the Bolivar Roads project. Industrial actors prioritizing navigational efficiency, environmental groups ecological integrity, and local communities seeking flood safety all bringing different frames of reference. To illustrate, similar institutional fragmentation among federal and First Nations (i.e., indigenous peoples) was evident in Canadian water governance, where overlapping mandates hampered coordination in water infrastructure projects (Bakker and Cook, 2011).

These conflicting "Logics" not only reinforce fragmentation but also dynamically shift alliances and opposition throughout the project's life-cycle (refer to Appendix A.2). Therefore, social complexity, which is embedded in SSB project phases, as illustrated for the the Bolivar Roads project, is not only a function of stakeholder quantity but of deeper institutional asymmetries in power, knowledge, and interests. These interdependencies contribute to social complexity, making it challenging to govern. The extent to which the client decides to keep project elements like O&M in-house ("Make") or outsource them to the market ("Buy") determines how much of these social tensions they need to manage later on.

Budgeting the Unknown: Financial Complexity and the Burden of Early Locked-In Choices
Long before final scope or risks are clear, the public client must decide whether to "Make" or "Buy", that early choice locks in who absorbs future cost overruns, and scope shifts, hence financial complexity. Financial complexity refers to the challenges associated with estimating, allocating, and managing costs and benefits throughout a project's life-cycle (Hertogh and Westerveld, 2010). In the case of the Bolivar Roads project, this complexity is seen in the variability of early cost estimates. For instance, USACE (2021a) projected approximately $14 billion, while Merrell et al. (2021) estimated a $5 billion. These variations not only reflect scope uncertainties but also reveal deeper institutional tensions.

In particular, short-term efficiency, feasibility, and task delivery often dominate initial project phases (Coenen et al., 2023), driven by what is known as "Project Logic." This Logic emphasizes strict project boundaries and visible progress, frequently at the expense of long-term cost-effectiveness and maintainability (refer to Appendix A.2). In contrast, the Asset Management Strategy for the adaptable sill (refer to Section 6.5), highlights the importance of "Asset Management Logic." This Logic advocates for long-term planning of maintainability, institutional knowledge retention, and valuing flexibility. These conflicting Logics contribute to a broader financial complexity. This includes the uneven distribution of financial risks and benefits among stakeholders, divergent interpretations of financial projections (Hertogh and Westerveld, 2010), and vulnerability to optimistic or strategically biased forecasts (Flyvbjerg et al., 2003). As stakeholder demands and regulatory requirements evolve (refer to Section 4.3), project scope adjustments often introduce additional cost volatility. As such, financial complexity is not only a matter of technical estimation but also a product of competing institutional priorities.

Legal Complexity in Motion: Delegating Risk Amid Evolving Laws
Legal complexity arises from the presence of changing, absent, or conflicting laws and procedures (Hertogh and Westerveld, 2010). It becomes difficult to manage when legal requirements shape stakeholder interactions such as environmental regulations, are incomplete and must be developed during the project (Hertogh and Westerveld, 2010). In the Bolivar Roads project, this is illustrated by the intersection of federal safety standards to with stand events with return periods of 500 years (Morang, 2016) and environmental statutes, including the Endangered Species Act (refer to Section 4.2).

Additionally, the involvement of environmental NGOs amplifies legal challenges, as demonstrated by the protest movements opposing the closure of the Eastern Scheldt, which ultimately led to the redesign and construction of the Eastern Scheldt Barrier (van der Ham et al., 2018).

Beyond the Blueprint: Who Engineers for the Unknown Technical Complexity?
Each SSB is a unique prototype facing evolving conditions. Early in design, the public client must decide whether to retain or outsource technical authority, a decision that determines who must address future unforeseen technical complexities. This technical complexity stems from the application of innovative or unproven technologies, as well as from unpredictable environmental conditions (Hertogh and Westerveld, 2010). As seen at many SSBs, from which each can be treated as prototype, combining specific environments, with customized elements (Walraven et al., 2022). The implementation of the Bolivar Roads project requires construction, operation, and maintenance within a highly dynamic and largely untested coastal-marine environment (refer to Section 4.2). One major challenge lies in managing the tight coupling between interdependent systems, which can lead to cascading risks across technical, financial, and temporal domains. For example, tidal jets and scour threaten foundation stability throughout the SSB's entire lifespan, from construction onward (refer to Section 5.3.3).

Consequently, technical complexity rooted within SSBs is not only a function of engineering scale but of embedded exposure to dynamic, interacting physical systems that evolve over time. These shifting system conditions often exceed standard engineering assumptions, requiring whoever holds technical authority, whether client or contractor, to be prepared for unforeseen and evolving technical demands.

Planning for the Unknown: Time Complexity and Ownership of Adaptability
At project start, the public client must decide whether to keep SSB know-how in-house or outsource it, despite inevitable time complexity over the lifespan. Time complexity refers to the challenges of managing long-term projects exposed to unpredictable external events (Hertogh and Westerveld, 2010), so-called unknown-unknowns, that can abruptly shift priorities (refer to Sections 5.3.4 and 5.4.7). It also encompasses the difficulty of aligning timelines among diverse stakeholders, each operating within different institutional cycles and schedules. The Bolivar Roads initiative, which has been under consideration since Hurricane Ike in 2008 (Kothuis et al., 2015), exemplifies this issue (anno 2025). Over such extended durations SSBs must continuously adapt to changing societal demands, political agendas, and technical developments, resulting in dynamic unpredictability (Kharoubi et al., 2024).

These evolving conditions highlight a project's vulnerability to a volatile, uncertain, complex, and ambiguous (VUCA) environment. Characterized by dynamic and unpredictable environments like the Houston-Galveston Bay Region (refer to Chapter 5). The long operational lifespan of SSBs further amplifies this exposure (Kharoubi et al., 2024), as even the most robust planning frameworks can be destabilized by cascading interdependencies or sudden shocks. In this light, time complexity is not only about managing milestones. It involves sustaining strategic decision-making and institutional agility over time. Tools such as the Asset Management Strategy (refer to Section 6.5), are therefore essential for embedding responsiveness into governance structures.

Organizational Complexity and the Dilemma of Long-Term Coordination
Organizational complexity refers to the challenges of coordinating across multiple departments, agencies, and hierarchical levels, both within and outside the project structure (Hertogh and Westerveld, 2010). This complexity raises the stakes of the "Make" or "Buy" decision: whichever actor holds this coordination bears long-term responsibility for integrating these fragmented layers throughout the SSB's lifespan. Miscommunication, institutional fragmentation, and political dynamics often result in inefficiencies and delays. Particularly when aligning regional and national actors. In the case of the Bolivar Roads, divided responsibilities between design-build entities (e.g., U.S. Army Corps of Engineers (USACE)) and operations and maintenance agencies (e.g., GCPD) introduce potential gaps in accountability, handover procedures, and system integration. Opting to "Buy" shifts the burden of system integration and coordination to the contractor, potentially introducing innovation and risk-bearing capacity. However, it limits the public client's direct control over future adaptations. Conversely, choosing to "Make" retains control and institutional memory within the public organization, but requires maintaining multi-disciplinary teams across several decades.

Whichever path is taken, evolving organizational complexity is compounded by broader institutional dynamics such as agency restructuring, staff turnover, and dependence on external contractors, which gradually erode the very expertise that the initial choice aimed to safeguard (refer to Section 5.4.6). The loss of tacit knowledge compromises decision-making and diminishes responsiveness during critical operational events. In this context, organizational complexity, embedded at SSBs, extends beyond coordination issues. It reflects a deeper governance challenge, one that demands sustained attention to institutional capacity, role accountability, and adaptive decision-making across both physical- and socio-economic domains. Thus the “Make” or “Buy” decision is not final but must be revisited through mechanisms like the Asset Management Strategy (refer to Section 6.5), ensuring whichever path was chosen remains adaptive as organizational complexity evolves.

From Dynamic Complexity to Prepare & Commit Strategies: SSB Design in a VUCA World
To conclude, the different dimensions of complexity together create dynamic complexity, hence how project elements evolve over time under shifting conditions (Bosch-Rekveldt et al., 2011). Unlike static complexity, which counts interfaces, dynamic complexity captures how a SSB must adapt to internal and external change. Hence, mega-projects are not just large but living systems embedded in a VUCA environment. Thus, managing them requires adaptive, forward-looking strategies (refer to Section 7.3).

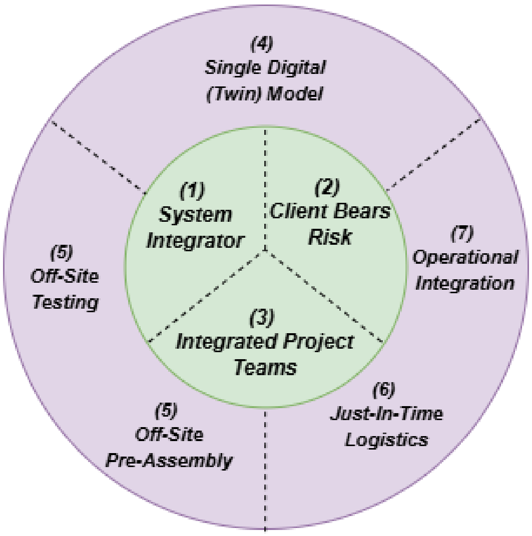
7.3. How to Manage Mega-Project Complexity at Bolivar Roads?

As discussed in Section 7.2, mega-projects demand early “Make” or “Buy” decisions regarding design-build-operate-maintenance, long before full project complexity is known. Thereby making traditional project control ineffective. To address such complexity, Baccarini (1996) emphasizes integration through three interrelated processes: coordination, communication, and control. Coordination ensures that interdependent tasks are sequenced and aligned across different work packages. Communication facilitates the timely and accurate exchange of information among stakeholders. Control enables the monitoring of progress, the management of deviations, and the enforcement of quality standards.

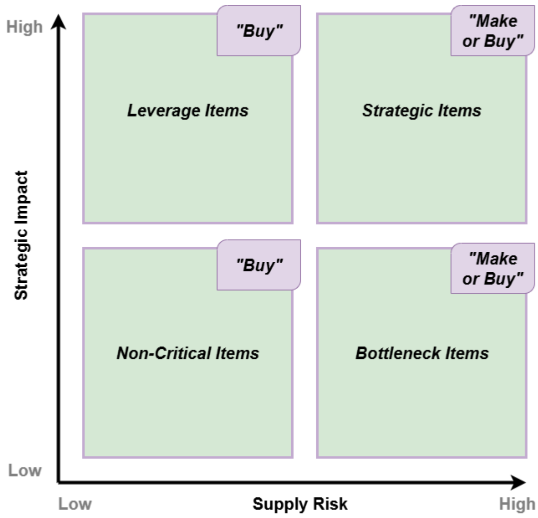
These three mechanisms resonate with the works of Hertogh and Westerveld (2010) and Bosch-Rekveldt et al. (2011), who argue that managing complexity in mega-projects such as Bolivar Roads requires a dual strategy. A “Predict and Control” approach is suitable for more stable domains like budgeting and technical specifications. In contrast, a “Prepare and Commit’ mindset is more appropriate for areas of high uncertainty such as political decision-making, both further discussed in Section 7.4. Beyond its complexity, the Bolivar Roads initiative also qualifies as a mega-project due to its multi-year timeline, broad scope, and multi-institutional governance structure.

Lessons from the Heathrow Terminal 5 (T5) project highlight that success in such projects depends less on rigid control and more on establishing a temporary but robust production system (Davies et al., 2009). A key element at T5 was the appointment of a system integrator to coordinate contractors, align governance, and manage interface complexity (see (1) in Figure 7.3a). At T5, the integration of design, engineering, and operations under a unified system integrator enabled seamless transitions across project phases. This is especially relevant for Bolivar Roads, where the early involvement of O&M teams could support SSB maintainability, and streamline the operations (Walraven et al., 2022). Early integration of these teams supports the concept of integrated project teams (3) and helps reduce risks of operational inefficiencies, aligning with Jonkman et al. (2016)’s call for integrated SSB design.

The use of digital tools (4) at T5 further reinforced integration across the integrated project teams. A similar approach at Bolivar Roads, using a Single Digital Twin Model, could support knowledge continuity across design, construction, and O&M. Particularly important in securing operational readiness (7), which is further discussed in Subsection 7.4.3. Given the non-negotiable flood protection function of SSBs, operational readiness must be embedded into all phases of delivery. Failure to operate could have catastrophic consequences. A strategy for ensuring operational readiness is the adoption of just-in-time logistics (6). This is relevant at Bolivar Roads due to the limited construction window imposed by hurricane seasons and the logistical constraints posed by the isolated, artificial islands located in the heavily trafficked Houston Shipping Channel (HSC) (refer to Section 4.2). Because these islands are not easily accessible, stockpiling components or conducting long on-site assembly is not feasible.



(a) Processes identified by Davies et al. (2009) as essential for executing a mega-project.



(b) The Kraljic Matrix (Kraljic, 1983).

Figure 7.3: Strategy development project delivery Bolivar Roads.

Off-site testing (5) of bespoke components such as ball-joints, is inline with an adaptive mindset. These tests ensure that systems will perform reliably once installed, especially given the difficulty of making modifications in the offshore environment. Off-site pre-assembly (5) may play a less central role, as final assembly will have to occur on-site using marine equipment. As demonstrated by the construction of the Eastern Scheldt Barrier, which required specialized vessels and the creation of the work island "Neeltje Jans" (van der Ham et al., 2018).

Finally, following the T5 project, assigning risk ownership to the client (2), could help reduce contractual disputes. By taking on interface responsibilities and remaining flexible to unforeseen site conditions, the client can create a more adaptive project environment. This approach is appropriate given, for instance, the environmental uncertainties present to the Bolivar Roads setting (refer to Chapter 4). To conclude, complexity is not just a challenge to be acknowledged, it is a design variable for how project delivery should be structured.

7.4. Make or Buy? Client Accountability at Bolivar Roads

As discussed in the Literature Review (see Chapter 2), SSBs differ from other infrastructure, like navigation locks, in that they operate infrequent but must always meet extremely high-reliability requirements. They are designed for a service life of roughly 100 years as an integral part of the national flood-defense system. They are classified as public infrastructure subject to high safety standards. A single failure could lead to nationwide disruptions. Thus SSBs fall under the category of critical infrastructure. The consequences of operational failure are not only economic but they are existential. Flooding, loss of life, and large-scale societal breakdown are plausible outcomes. This research argues that these are risks that cannot be transferred to the market. To cope with these unique SSB characteristics continuous preparedness, knowledge retention, and adequate staffing capacity becomes performance metrics for SSBs, ensuring accountability to the public.

This study insists that accountability must remain with the client organization, the public entity itself (e.g., GCPD, RWS). Unlike the state, private firms are finite. They can go bankrupt, be dissolved or be taken over. Their primary duty is to shareholders, not citizens. By contrast, a state has in principle an unlimited lifespan, cannot be declared bankrupt in the ordinary sense, and derives it legitimacy from democratic processes. Only such a body can guarantee the lasting care, risk absorption and transparency that high-reliability infrastructure demands. For this reason, responsibility for operational failure, and the Organization required to manage it, cannot be outsourced to a first-tier supplier. It must remain within the public entity itself. The rational will be further outlined in Subsection 7.4.2.

This study applies the Kraljic Matrix to determine which project elements (design, build, operate, maintenance, flexibility) must remain with client organization, and to what extend, to embed the accountability that the client organization must endure regarding above stated unique nature of SSBs. These project elements are classified as “Strategic Items” in the Kraljic Matrix. The rational below. The decisions are informed by the preceding Sections 7.2 and 7.3, and are consistent with Section 6.5.

7.4.1. Applying the Kraljic Matrix to Determine Client Accountability

The Kraljic Matrix supports “Make” or “Buy” decisions from the client’s perspective by evaluating (I) an item’s strategic importance (i.e., its role in operational failure accountability), and (II) supply risk, such as supplier dependency (Kraljic, 1983). Applied to Bolivar Roads, this framework requires considerations of scope, time span, requirement specificity, risk(-sharing), and performance expectations.

By plotting ”Make” or ”Buy” elements along these two axes, the matrix enables to classify elements into four categories. This classification serves as a guidance for the allocation of project elements. It also helps structure the possible allocation process by considering factors such as marketability, managerial capacity, and project-specific constraints (Bakker and de Kleijn, 2014). For instance, SSB components that enable adaptability such as the adaptable sill design (refer to Section 6.4) that must be accessed after 50 years, are strategic not because of their immediate cost but because of their embedded role in future performance. The four categories (see Figure 7.3b):

- *Strategic Items (High Impact, High Risk):* require long-term partnerships or in-house development. These are often bespoke components or systems that directly impact the SSB objective, such as the movable gates or control software. For example, in the Maeslant Barrier, the rotating ball joints can be considered strategic items due to their critical role;
- *Bottleneck Items (Low Impact, High Risk):* are hard to source but less influential on overall SSB functioning. Examples include specialized inspection tools. Their failure can delay operations, so emergency planning, stockpiling, or alternative sourcing strategies are key;
- *Leverage Items (High Impact, Low Risk):* have a large budget share but are widely available, such as mass concrete. These are ideal for competitive outsourcing.
- *Non-Critical Items (Low Impact, Low Risk):* are standardized and commoditized. These can be outsourced through bulk contracts or framework agreements without strategic concern.

7.4.2. The Need of Public Client “Organizational Backbone” for SSBs

This section defines which project elements can be outsourced and which must remain under client control, as their lifespan, risks, and operational context limit what can be delegated (see Figure 6.34).

Design In-House or Outsource? Client-Driven Interface Management for SSBs

At project initiation, the public client must choose between outsourcing design work or retaining design authority in-house. Outsourcing offers advanced expertise and reduces internal workload but limits control over integration and long-term system integration. In-house design preserves interface oversight but demands sustained multidisciplinary capacity. This trade-off is critical for SSBs, where fixed, movable, and electrical systems require tight integration under strict performance standards. The design phase has a multidisciplinary scope (see Figure 6.34) and spans multiple years, as seen at the Eastern Scheldt Barrier 1953-1976 (van der Ham et al., 2018). Functional requirements dominate at this stage (refer to Section 4.4), with technical details evolving over time. Supply risk is also high, given the scarcity of companies capable of delivering the multidisciplinary design required. Hence, designing the SSB exceeds the in-house capacity of the client (i.e., USACE and GCPD). It is therefore recommended to engage first-tier suppliers for their specialist expertise, while maintaining a small in-house engineering team to validate design decisions and safeguard interface management.

A decision concerns whether to adopt a relational contract model or follow a traditional design–bid–build approach. A relational contracting model (i.e., integrated with construction, see next section) such as the NEC3 framework used in the Ipswich Tidal Barrier, facilitates early contractor involvement, knowledge-sharing and collaborative risk management through mechanisms like early warning processes (Usborne, 2019). Simultaneously, fragmented stakeholder coalitions, demands that the client does not fully give away control, and implements a “Prepare and Commit” project set-up.

The client, must therefore retain accountable for the role of system integrator, ensuring interface management across delivery stages. The role of system integrator is a “Strategic Item”. This requires the client to scale up its “Organizational Backbone.”. The Marina Barrage in Singapore illustrated this, where the client retained central control throughout design-build, ensuring integration across phases (Moh and Su, 2009). Adopting such a model is recommended as it enables the public client to leverage market-led innovation while maintaining sufficient control to safeguard public accountability.

Build Phase Execution: A Choice Between Control and Delegation
Following the design phase, should the client keep interface authority in-house, or hand it to the build-consortium and accept the trade-off between execution control and outsourced risk? Since the build phase is not just mono-disciplinary execution of technical detailed fixed, movable, and electrical partial- and final products (see Figure 6.34). But it is also continuous human-based coordination across disciplines (i.e., Planning & Control, Process Management, see Figure 6.34). This requires contractors not only to execute but to contribute in integrated project teams. Considering the multi-year construction like the Maeslant Barrier 1991-1997, which is constrained by site logistics, contractors must be engaged at the start of the design phase to leverage execution know-how. Hence, bespoke elements such as ball-joints, have higher risk-profiles, requiring coordination throughout design and execution.

Planning & Control and Process Management tasks are better coordinated via integrated project teams. A hybrid delivery strategy is suitable: leverage elements can be outsourced and managed through “Predict and Control” via integrated contracts. “Strategic Items” such as interface management, require in-house oversight governed via “Prepare and Commit”. In (mega-)projects, risk ultimately flows back to the client (Davies et al., 2009), so can best be remained by the client. Outsourcing design-build entirely would risk blind spots across delivery phases, fragmented accountability, and misaligned decision-making. Therefore, this phase typically sees a temporary expansion of client-side “Organizational Backbone”, with a focus on interface oversight, and increased outsourced capacity. In consequence this study argues to retain interface authority in-house and outsource execution via integrated contracts.

Operating the System: Unconditional Public Accountability
The client must decide whether to operate the barrier itself or delegate that task to an external operator. This decision sets who ultimately carries the accountability of the high consequences of failure. SSBs operations, especially during storms, qualifies as a “Strategic Item” within the Kraljic Matrix. Operating a SSB during both normal and storm conditions is a high-responsibility function. The operational scope spans to end-of-life, requiring capabilities that can scale in response to extreme events, despite long periods of “stand-by” mode. This long time horizon, combined with the low frequency but high-reliability on activation moments, makes outsourcing non-negotiable. The associated scope, forms inspection protocols (i.e., Day-to-Day Operation) to closure execution (i.e., Storm Closure Operation). Performance cannot be quantified through conventional deliverables. Instead, as emphasized in the ProBo framework used for Dutch SSBs (refer to Chapter 2), performance is embedded in proactive risk management (van den Bogaard and van Akkeren, 2011).

The risks associated with operational failure are severe (Alcaraz and Zeadally, 2015), emphasizing the need to balance “Predict and Control” with “Prepare and Commit” strategies. This study pleads that operations must be retained in-house by the client, which implies a long-term organizational commitment (see Figure 6.34). Although day-to-day staffing levels may be low under “stand-by” conditions, the organization must preserve scalable staff to rapidly increase its “Organizational Backbone” during storm closures. Retaining operations in-house therefore remains the only defensible course. It keeps operational failure accountability with the public client, preserves know-how, and ensures the organization can scale rapidly when operations turns “stand-by” into “closure”.

Maintenance: Balancing Outsourcing with Knowledge Retention
Beyond operations, the client must choose between outsourcing routine maintenance or developing an in-house team to retain hands-on expertise. The maintenance phase of SSBs ranges from mono-disciplinary mechanical inspections (i.e., regular minor) to multi-disciplinary system renewals involving fixed, movable, and electrical parts (i.e., variable- minor and major) (refer to Section 4.6).

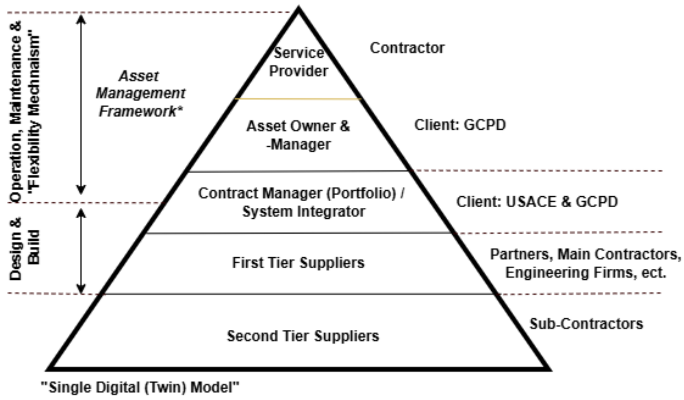


Figure 7.4: Conceptual PDM Framework.

In the Kraljic Matrix, these activities fall into the bottleneck or strategic categories, depending on their technical specificity, and timing sensitivity. Given the 100 year operational lifespan of SSBs, maintenance needs to be organized across multi-year frameworks to ensure sufficient knowledge retention. In the Netherlands, for example, the ProBo framework ensures risk-based maintenance planning across technical, functional, and economic lifespans (Hamerslag and Bakker, 2023). Regular- and variable minor can best be outsourced via a multi-year framework agreement. In contrast, major variable, driven by different deterioration mechanisms (i.e., fixed-, movable-, electrical parts have different deterioration cycles), demands more clustered contracting. Maintenance must remain under client oversight, underscoring “Predict and Control”. The client retains strategic oversight, while leveraging market capacity for execution. This study argues that the client should maintain a minimum viable “Organizational Backbone” and coordination function to prevent erosion of SSB-specific knowledge. This challenge is recognized in Dutch cases, where reliance on outsourcing has led to diminished SSB understanding (Kamps, van den Boomen, et al., 2024).

The Flexibility Dilemma: Who Governs When to Act?
The “Flexibility Mechanism” (refer to Section 6.5), embodied by the adaptable sill, enhances the adaptability of the Floating Sector Gates at Bolivar Roads. Classified as “Strategic Item” within the Kraljic Matrix. Due to its high-impact, high-risk capability. The “Flexibility Mechanism” spans multi-disciplinary domains, including coastal engineering, ecological planning, and risk governance. Its scope is unique: while interventions may only occur after 50 years, the system must be monitored, governed, and prepared for activation throughout its lifespan. The decision to activate the adaptable sill option (i.e., when, how, and under which scenarios) is shaped by institutional knowledge.

While technical tasks such as component fabrication, can be specified in detail once and thus outsourced, the “Flexibility Mechanism” itself operates on functionally defined thresholds such as changes in shipping demand, flood-risk tolerance, or political priorities. Kingdon (1997) multiple-streams model explains why: only when the problem, policy, and politics streams converge does a “policy window” open for major action such as leveraging the adaptable sill. The precise timing and content of that window cannot be pre-engineered but must be seized by the client’s in-house governance structure. Consequently, this study argues that given the uncertainty of activating the adaptable sill option, the governance of decision-making must remain under the full control of the client. Leveraging “Prepare and Commit” approaches. Throughout the life-cycle this asks a continuation of the “Organizational Backbone”, and during the activation of the design option an increase of the client organization.

Unique SSB Scope Demands Targeted Client Accountability
To recall, with long lifespans and high failure risks, SSBs sharpen the client’s “Make” or “Buy” choice: retain control or outsource for expertise and risk-sharing. This studies assessment shows that the answer at Bolivar Roads, and SSBs in general must be selective: (I) design expertise may be outsourced to first-tier suppliers but a compact client engineering core must stay in place to validate interfaces and capture learning; (II) during the build phase, construction can be delivered through integrated contracts, yet system-integration and interface authority remain with the client to prevent fragmented accountability; (III) operations, infrequent but high-stake storm closures, cannot be delegated, GCPD must own procedures, staffing, and liability for the barrier’s entire life; (IV) maintenance can be split: routine and variable-minor work is suited to multi-year contract frameworks, whereas major renewals require direct client oversight, and must be outsourced separately.

(V) Finally, the “Flexibility Mechanism” (i.e., the adaptable sill) depends on policy windows that open only when Kingdon’s problem–policy–politics streams converge. Its activation timing is unknowable upfront, so governance of that decision must stay fully under client accountability.

7.4.3. Single Digital Twin Model: Setting up the “Organizational Backbone”

To cope with the stated project complexities, and ensure knowledge continuity across the life-cycle, the project can employ a Single Digital Twin Model from the outset. This digital model can serve as a unified data repository, to standardize processes, and streamline stage delivery (see Figure 7.4). By integrating design assumptions, construction deviations, and condition monitoring from the outset, the digital model will capture tacit knowledge, informed decision-making, and minimizes risk throughout the asset’s life-cycle by the client, hence state-based maintenance (refer to Section 4.6).

To illustrate, this digital (twin) model approach was reversed-engineered for the Maeslant Barrier (i.e., the model was developed 20 years after construction) by Ponsioen (2023). This digital twin prototype of the Maeslant Barrier demonstrated potential benefits, such as enhanced knowledge transfer, efficient data visualization, and improved barrier status monitoring (Ponsioen, 2023). But Ponsioen (2023) stated challenges remain, particularly regarding cyber security, organizational readiness, and the integration of existing IT infrastructure. For the Floating Sector Gates at Bolivar Roads, the business case for implementing a full-scale digital twin from the outset (i.e., design-build-operate-maintenance-flexibility phases) suggests potential cost saving, driven by maintainability aspects.

7.5. Summary and Conclusions

This chapter developed guidance for a project delivery method (PDM) for the Bolivar Roads project. This included the identification of project complexities, application of the Kraljic Matrix to determine client accountability regarding unique storm surge barrier (SSB) scope, resulting in a conceptual PDM (see Figure 7.4), and contracting strategy (see Figure 6.34). Giving effect to sub-questions 2, 4, and 5. In particular, *[SQ4]: How do institutional logic, policies, and contracting impact the flexible capacity and life-cycle of the storm surge barrier?* Unlike conventional infrastructure, SSBs have a lifespan exceeding 100 years, require high reliability, and have severe socio-economic risks if they fail. In this context, the public client (e.g., Gulf Coast Protection District (GCPD)), faces an “Make” or ”Buy” dilemma: retain critical tasks and expertise in-house to ensure accountability and continuity, or outsource to market actors offering innovation and risk-bearing capacity. This early decision determines whether the client or the contractor will assume responsibility for managing project complexity domains.

The design phase presents a dilemma: outsourcing brings specialized expertise but full delegation risks losing control over system integration. Due to the multidisciplinary scope, covering fixed, movable, and electrical elements, detailed design should be outsourced to qualified first-tier suppliers. Meanwhile, the public client must retain a small but competent in-house team to manage interfaces, oversee contracts, allocate risks, and validate deliverables to safeguard public accountability. The build phase poses a choice: delegate interface authority to transfer risk, or retain it to maintain execution control. Given the complexity of SSB projects and the need for ongoing cross-disciplinary coordination, the client should keep responsibility for interface management and risk governance, supported by a temporarily expanded in-house team. Physical execution, construction, fabrication, and logistics, needs to be outsourced to first-tier contractors through integrated design-build contracts, allowing the market to deliver technical expertise while the client safeguards system integration.

Operating a SSB requires the client to choose between outsourcing and risking diluted accountability, or retaining full control. However, due to the high stakes of failure, operational authority and staffing must remain in-house. For maintenance, minor routine tasks can be outsourced to framework contractors, while major variable work is contracted separately. Interface management and risk allocation stay with the client to preserve knowledge-continuity, and accountability. Lastly, the client must decide whether to delegate control of the adaptable sill (i.e., “Flexibility Mechanism”), or retain authority to ensure public accountability during activation. As activation depends on unpredictable policy windows, governance must remain in-house, as illustrated by the proposed Asset Management Strategy (refer to Section 6.5). Once activation is approved, execution can be outsourced to contractors.

8 Discussion

This chapter discusses the applied methodology (Section 8.1) and research findings (Section 8.2) in light of the research objective.

8.1. Methodological Limitations

To answer the research question: *"How can flexibility in design, asset management, institutional logic, and contracting enable an integrated delivery method for resilient, long-term operations & maintenance of a coastal storm surge barrier?"* This study applied the four-phased *"Flexibility in Engineering Design"* methodology by De Neufville and Scholtes (2011), which is visualized in a Flow Chart (see Figure 3.2 in Chapter 3), and elaborated on in Chapter 3. As outlined in Chapter 1, five sub-questions guided the research: [SQ1] system drivers, [SQ2] O&M requirements, [SQ3] design flexibility, [SQ4] institutional capacity, and [SQ5] Bolivar Roads-specific delivery. The four-phase method was supported by Engineering Systems, Institutional Logic, and Contract Theories (refer to Appendix A). A system analysis at Bolivar Roads, combined with uncertain system driver assessment, informed flexibility in design options. This lead to the adaptable sill design and a supporting Asset Management (AM) Strategy. These findings came together in a proposed project delivery model.

Phase 1: A Baseline Design of the Bolivar Roads Gate System

The goal of Phase 1 was to construct a system analysis of the Houston-Galveston Bay Region to set the solution space for the subsequent phases 2 and 3 (i.e., constrain system driver identification and options for flexibility in SSB design). Analysis followed the Systems Engineering (SE) methodology of de Graaf (2014), including the following activities: (I) boundary condition mapping, (II) stakeholder analysis, (III) function analysis via Functional Breakdown Structure (FBS), and (IV) function allocation to SSB components using a System Breakdown Structure (SBS). This resulted in a System Diagram.

The SE approach was selected for its ability to structure complex systems and the easier identification of the impact of system drivers in Phase 2. Applying SE to context-specific SSBs resulted in some overgeneralization (i.e., dicto simpliciter). The generalization of the results is limited by it tends to frame unique SSBs as universally applicable, which is contrary to Literature Review findings. This was reinforced by interviewees referencing established barriers like the Maeslant Barrier, which do not reflect the Bolivar Roads context. Still, the FBS and SBS provided a solution space for assessing system driver impacts in Phase 2, helping to reduce the risk of overlooking aspects. Since the SE activities are generic, the FBS is generalizable to other SSBs (i.e., SSBs can have the same functionalities) but the resulting SBS and system driver assessments remain context-specific.

Phase 2: The Shape of Uncertainty

Phase 2 aimed to identify the key system driver affecting future SSB performance. Following the set solution space from Phase 1 (i.e., FBS, SBS, System Diagram), the heuristic method of Vader et al. (2023) was applied. System drivers were inventoried and examined by (I) historic trends, (II) forecast (un)certainties, and (III) impacts on the SSB performance. This resulted in a shortlist of dominant system drivers. Finally, (IV) 4-delta scenarios were developed to identify the most critical system drivers.

A qualitative approach was adopted, as existing studies sufficiently covered the coastal Texas context. No extra data modeling was required but this limited the determination of inconsistencies, as some studies contradicted each other. The reliability of this data is impacted by biases from the original studies, modeling the raw data directly could have avoided this. Due to the reliance on existing studies Relative Sea Level Change (RSLC) emerged as dominant due to its extensive literature coverage. Less-documented factors (e.g., politics), were down-weighted. Consequently, Phase 3 focused on the physical- over socio-economic factors. The methodological choice was further constrained by the application of the Dutch Delta Scenarios, which are tailored to the Rhine-Meuse Delta and not reflect conditions in the Houston-Galveston Bay Region. Hence, differences in, for instance, climate (i.e., mild vs. hot, humid). Nevertheless, the Delta Scenarios provided a sound basis for narrowing the solution space. Further research is needed to establish sounded Delta Scenario for Bolivar Road case.

Phase 3: Options for Flexibility in Design
The goal of Phase 3 was to develop an adaptive SSB component with a supporting AM strategy. Phase 3 built on Phases 1–2, expert interviews, and unit-cost data to derive element-level CAPEX shares. Using the Engineering System Matrix (ESM) from Bartolomei et al. (2012) (I) dependencies between governing system drivers and SSB components were mapped. Interview data were collected and thematically analyzed to asses the dependencies. (II) Combined with unit-cost shares via the risk-susceptibility method of Hu and Cardin (2015), this produced a ranked list of flexible SSB component options. Following the Hydraulic Design Method (III) four conceptual designs for the sill were developed.

The ESM enabled the capturing of cross-domain dependencies without full system simulation, but constrained by expert input. It simplified system driver - SSB dependencies to first order pairwise links. Thus, it overlooks time and second-order cascading effects between SSB components. The ESM, combined with tools like Bayesian networks, can capture interdependencies between SSB components. However, it is beyond the scope of this study to model single changes as they propagate across the SSB. Potentially leading to different impacts and SSB component selection as identified by the applied first-order method. Future studies should take into account these second-order cascading effects. Nevertheless, once the sill was selected as the designated SSB component, second-order cascading effects were qualitatively described.

Due to lack of quantitative data on system driver - SSB relational dependencies, the results cannot confirm the interviewees judgments. This introduces bias as responses do not comprise all perspectives. The use of a single facilitator for all interviews further introduced the potential for unintentional response steering. Translating qualitative judgments into numerical values (i.e., 0.2; 0.4; 0.7), further assumed uniform interpretation, despite possible variation in interpretation across respondents. Interviewee selection enabled expert insight but may have reinforced dominant narratives.

The cost estimates were based on 35-year-old Maeslant Barrier tender data. This likely underestimates current U.S. labor and inflation (anno 2025). The steel deep-draft gates dominated CAPEX estimates, resulting in prioritizing them in the risk-susceptibility index over fixed elements like the Sill & Mat Foundation. Yet, fixed components lack replacement cycles, making them more critical for build-in flexibility. This highlights a limitation of the method for long-lived infrastructure. Further research is needed to establish CAPEX breakdown per SSB component of the Floating Sector Gates at Bolivar Roads. The adaptable sill design relied on simplifying design assumptions and Maeslant Barrier analogies, refer to Section 6.4.6 for the discussion. While indicative only, these assumptions allowed testing of flexible design feasibility. Avenues for future research include checking the strength of the structural elements, connections (i.e., leakage) deformations, and displacements. Supported with computer calculations based on 3D Finite Element Methods.

Phase 4: Implementing Flexibility
The goal of Phase 4 was to synthesizing a project delivery framework using insights from Phases 1–3 and literature on (mega-)project complexity. The three-step qualitative activities included: (I) project complexity mapping based on Hertogh and Westerveld (2010), (II) “Make” or “Buy” assessment via the Kraljic Matrix, and (III) synthesis into a conceptual PDM. The Kraljic Matrix linked project risks (i.e., high-impact elements) with procurement logic (i.e., market power, supplier scarcity). Heathrow Terminal 5 served as a reference for its extensive pre-project research and rare success in meeting schedule.

Literature based synthesis has limitations. It overlooks the specific physical and socio-environmental context of the Bolivar Roads case. For example, an airport terminal like Heathrow differs from a SSB in function, structure, and constructability. Applying the Kraljic Matrix also generalized SSB procurement. Overlooking unique needs like specialized marine equipment, which such frameworks may not fully capture. Nevertheless, the Kraljic Matrix provided a useful initial indication of project needs, aligning with the goal of Phase 4. Finally, desk research may bias PDM guidance by reinforcing old narratives and missing recent innovations.

Reflection and Conclusions
To conclude, applying the *"Flexibility in Engineering Design"* method supported the research objective in three ways. First, defining the solution space (i.e., FBS, SBS, System Diagram), before identifying system drivers or flexibility options in design kept the analysis open-ended. This allowed guided examination within the set solution space before directly committing to specific solutions. This helped avoid early path-dependence. Second, the Hydraulic Design Method made the abstract concept of ”flexibility” tangible by directly testing its feasibility for SSBs. Third, integrating technical options into the Asset Management Strategy ensured the solution remained actionable over the asset's life-cycle.

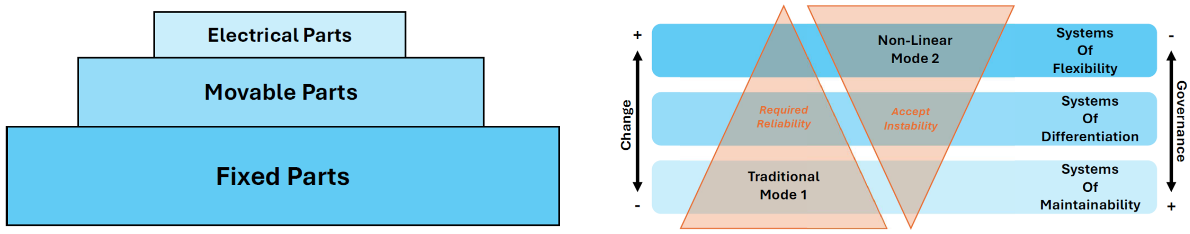
8.2. Antifragile: Managing SSBs from Maintainability to Flexibility

SSBs are "sleeping giants": large, long-lived, high-cost prototypes that rarely operate but must always be ready. While reliable over decades, current design practices often focus on construction and neglect O&M, overlooking physical and socio-economic shifts (outlined in Chapter 5). This leads to growing design complexity, obsolescence, and rising O&M costs. Fragmented governance worsens the issue (outlined in Chapter 7). The following subsections integrate this Thesis findings into a bimodal strategy, combining mode 1 (i.e., maintainability; outlined in Chapter 4) and mode 2 (i.e., flexibility; outlined in Chapter 6) to guide long-term SSB upkeep. The syntheses below.

Mode 1 – Maintainability (Phase 1): Coping with Volatility through State-Based Maintenance
SSBs are primarily designed to prevent storm-surge inflow into estuaries, yet this objective immediately competes with stakeholder-driven add-on functions. The results of "Phase 1: A Baseline Design of the Bolivar Roads Gate System" (refer to Chapter 4) supports the claims of Kharoubi et al. (2024) that SSB integration into the surrounding socio-economic environment inevitably results in extra functions. This is reflected in the Phase 1 FBS, which presents base functions applicable to any SSB and in doing so, show the first prioritization decisions. These findings build on the evidence of Mooyaart and Jonkman (2017), redirecting the discussion from technical feasibility toward identifying the functional choices that must ultimately be made. For SSBs, these functional choices lead to bespoke components serving as "function fulfillers."

The FBS shows that the functions implemented in a SSB depends on two main systems drivers: physical conditions specific to the location (e.g., water levels), and socio-econonomic factors (e.g., shipping). For example, at the Eastern Scheldt Barrier, water exchange was not initially deemed necessary based on physical conditions alone, but was later added under public pressure to preserve estuarine ecosystem, a clear clash of flood protection logic versus societal demand. The results suggest this translation from functional requirements to actual design components is dominated by socio-economic volatility and randomness, which explains unique barrier designs. When such volatility meets the high consequence of failure and the uncertain degradation of components, the maintenance demand becomes unpredictable. As concluded in Section 4.7, the study recommends a state-based maintenance policy to enhance stability, predictability, and risk-minimization in barrier design and planning, as regular inspections and action thresholds help prevent unexpected issues from escalating into failures.

This raises the question: despite location-specific conditions, how far can SSB designs be standardized? As noted in the literature and this study, standardization streamlines O&M but by accepting less location-specific optimization. The FBS and existing SSB examples provide guidance, as functions like navigation directly shape design (e.g., choosing a sector instead of rotary segment). For Bolivar Roads, with similar needs as Maeslant and St. Petersburg Barriers, adopting a sector gate leverages current know-how, while substitute some site-specific optimization. Ultimately, standardization depends on political will to standardize SSB configurations worldwide. Though it is challenged by constrained funding and the rarity of SSB projects, which can make each new barrier feel like a one-off prototype.



(a) SSB fixed-, movable-, and electrical parts build-up.

(b) Managing SSBs via a Bimodal Strategy.

Figure 8.1: Connecting hierarchical design build-up to Bimodal Strategy for SSBs.

Mode 1 – Maintainability (Phase 1): Designing for Component Degradation to Ease Replacement
SSBs are multi-layered systems designed for a 100 year service life and composed of fixed, movable, and electrical layers (see Figure 8.1a), each aging at different rates. About 100 years for the fixed (i.e., largest spatial share in design), 50–100 years for the movable parts, and just 8-15 years for electrical systems (i.e., smallest spatial share in design). The research results suggest that this hierarchy should be reflected in the physical design: place long-life components at "the bottom" and shorter-life components "on top", so that frequently serviced elements (e.g., control systems), remain reachable without major disassembly. Walraven et al. (2022) demonstrated that, in practice, this layering is often diffuse, revealing compromises made during barrier design and planning. For example, the gates of the Maeslant Barrier rest on rubber supports within their dry docks that wear out far faster than the gates they hold, turning a routine replacement into a high-cost operation.

In line with the FBS reasoning, the diffuse design of SSBs can be understood. If maintainability is not defined in the requirements, or if it is included but later weakened by socio-economic volatility and randomness (e.g., funding constraints), it will likely disappear from the final design. The results from "Phase 1: A Baseline Design of the Bolivar Roads Gate System" (refer to Chapter 4) underline that the barrier must be deliberately structured around expected maintenance intervals in the preliminary design phase to avoid these pitfalls. This means that maintenance and replacement targets must be treated as design parameters, on par with hydraulic loads. This is displayed in the FBS of Phase 1, and inline with the literature findings. As concluded in Section 4.7, this calls for a maintainability-first mode in the barrier design and planning process, based on principles like component interchangeability. So, integrating maintainability options (i.e., providing the flexibility to shift maintenance direction when needed), thereby optimizing the SSB for more predictable and well-understood component degradation. These results challenge the conventional design focus on robustness and constructability alone.

Synthesis - Maintainability & Flexibility (Phase 2): Why SSBs Need a Bimodal Strategy
SSB are situated where natural processes meet densely populated, economically vital areas. As the literature emphasizes, expanding coastal communities add to socio-economic exposure to physical extremes such as storm surges. The performance of SSB is therefore influenced by a combination of volatile physical- and socio-economic drivers. In "Phase 2: The Shape of Uncertainty" (refer to Chapter 5) of this study, these system drivers were inventoried and conceptualized in an overview diagram. The diagram, based on the FBS, lists the specific drivers capable of shaping SSB functional performance. While the diagram is generic, its application is location-specific, yielding distinct driver profiles. The results suggests that adding more functionalities to the barrier increases exposure to more volatility and randomness, which otherwise would not be visible. Thereby, the long-lifespan of SSBs acts as expanding volatility: the longer the lifespan, the more shocks and disorder can accumulate.

A comparison between this study (i.e., the Bolivar Roads Gate System in Texas) and the study by Vader et al. (2023) (i.e., Hollandse IJsselkering in the Netherlands) makes it explicit. While the previous research of Vader et al. (2023) emphasized river discharge, a driver irrelevant to Bolivar Roads, Phase 2 instead identifies hurricanes as a dominant driver along the Texas coast. Consequently, this leads to differences in operational procedures (e.g. at Bolivar Roads, storm surge may begin 1–2 days before landfall, potentially requiring gate closure ahead of the hurricane's arrival). The comparison shows that while the overview diagram is universal, each SSB is unique in its application. This further stipulates in the difference in outcome from Phase 2 in how physical- and socio-economic drivers can be understood. Physical drivers, like temperature, can be measured directly and therefore easier to quantify.

In contrast, socio-economic drivers, like policy shifts, are harder to measure. Exhibit non-linear behavior and inject greater randomness and volatility. As a result, in SSB planning, design and maintenance can more easily address physical changes, hence degradation of components. But socio-economic uncertainties are harder to manage. This asymmetry (i.e., physical is capped, while socio-economic is open-ended), must be taken into account when considering the design and planning process of SSBs. Risk-based approaches, like ProBo, address these uncertainties using probabilistic modeling. However, such models can create a false sense of certainty, as they rely on assumptions that overlook the hidden randomness and volatility of SSBs, making these models prone to wishful thinking.

In consequence, Phase 2 results indicate that SSBs can benefit from a bimodal strategy (see Figure 8.1b): managing the barrier through two distinct yet complementary modes across its life-cycle. The first mode follows traditional, linear processes that prioritize stability, and predictability. It focuses on routine upkeep, reliability assurance, and risk minimization, reinforcing the maintainability-first mode as concluded in Section 4.7. In contrast, the second non-linear mode copes with asymmetric exposure by emphasizing options for flexibility in design as concluded in Section 5.6, and stipulated in Chapter 6. This mode enables the system to respond to evolving changes, benefiting from volatility. These results build on existing evidence of Taleb (2012) concept of “Antifragility”: adapting and improving in response to changing system drivers rather than being weakened by them. Ultimately this means a shift in current SSB design and planning practices (i.e., design lock-in) toward organizational differentiation and barrier designs that embed optionality from the outset.

Mode 2 – Flexibility (Phase 3): Where and When Are Options for Flexibility Worth It?
“Phase 3: Options for Flexibility in Design” (refer to Chapter 6) demonstrates that the bimodal strategy’s non-linear mode only becomes viable once flexibility options are built in, confronting designers with an upfront cost versus adaptability trade-off. As illustrated through the adaptable sill concept, the barrier can cope with asymmetric shocks and benefit from volatility. The adaptable sill design option, in line with Taleb (2012) Antifragility, let the barrier adjust to the uncertainty of deeper vessel drafts instead of resisting them. Uncertainty switches from liability to asset. Thereby maintaining functional performance over time not only through traditional reliability-focused approaches but also by embracing flexibility.

Phase 3 results do not fit with the *“Flexibility in Engineering Design”* framework (refer to Chapter 3) that flexibility could be incorporated across all SSB components (i.e., fixed, movable, and electrical). Phase 3 reveals that the fixed parts are the most strategic location for embedding design options. These components, typically with a 100 year lifespan, cannot be replaced without major disruption. Yet when system drivers negatively impact their performance, retrofitting may become necessary. As shown in Figure 8.1a, fixed components form the rigid base of the structure, making them difficult to access and modify once constructed. Therefore design options must concentrate in the fixed parts. Transferring the rigid fixed parts of SSBs to components which have the ability to increase functional performance over time. These results should be taken into account when considering options in SSB design.

These results extends the study by Mooyaart et al. (2024) by shifting from optimizing existing SSBs to embedding options for flexibility at conceptual design stage, especially in fixed parts. While the previous research by Mooyaart et al. (2024) has focused on identifying performance improvements through reliability analysis, this study demonstrates how design options like the adaptable sill at Bolivar Roads, enable barriers to adapt under evolving system drivers. This Antifragile approach adds a proactive, option-based layer to Mooyaart’s reactive focus, making SSBs benefiting from uncertainty.

From both a technical lifespan (i.e., how long a component can perform its function) and a functional one (i.e., how long it meets evolving requirements) incorporating flexibility into SSB design seems beneficial. Rather than focusing solely on reducing uncertainty, this approach promotes designing to coexist with uncertainty. Phase 3 demonstrated that this is technically feasible with the adaptable sill concept. However, it also revealed that flexibility in one component (e.g., lowering the sill) can trigger cascading effects on others (e.g., requiring a longer gate). These findings warn that every option carries cascading costs that must be priced in alongside its benefits. Given the long lifespan, high initial investment, and ongoing O&M costs of SSBs, flexibility options can be economically justified if it helps extend technical-, functional- and economic lifetime performance. This contradicts with the tendency of cost cutting at the design stage towards value optimization over the life-cycle.

This reasoning is consistent with the principles of Real Options Approach (ROA), which views design options as strategic assets rather than sunk costs (Ajah and Herder, 2005). A design option like the adaptable sill exposes only the limited downside of upfront and upkeep costs while enabling large upside: continued vessel growth and wider regional prosperity in the Houston-Galveston Bay Region. As a result, there is no need for highly detailed forecasting models to determine the exact design parameters in advance. Instead, the focus should be on keeping valuable options available and using them when conditions justify it, as exemplified by the Asset Management Strategy in Section 6.5. Applying ROA requires rethinking how risk and value are assessed in Asset Management (AM): uncertainty is not only a threat but also a source of opportunity, emphasizing Mode 2 - Flexibility, as concluded in Section 5.6, and stipulated in Chapter 6. This contrasts with traditional engineering mindsets that aim to eliminate all potential risks upfront, stressing Mode 1 - Maintainability, as concluded in Section 4.7.

While this study did not quantify the value of the adaptable sill using ROA, it confirmed that such options are technically and organizationally feasible. The downside of this optionality is the cost you incur to keep the option available. If this cost is manageable, there is no need to rely on precise forecasts, as the barrier “has the option to change”, and benefit from volatility when it presents itself.

Governance Differentiation (Phase 4): Client “Skin in the Game” to Sustain Flexibility
The results from “Phase 4: Implementing Flexibility” (refer to Chapter 7) confirm that the functional performance of SSBs is shaped by their unique characteristics such as their severe consequences of failure. The results indicate that the flexible capacity, and the SSB in general, depends on which elements of an SSB life-cycle can be outsourced (e.g., design, construction, major maintenance), and which must remain under the accountability of the public client (e.g., operations, contract management). Phase 4 therefore suggests that due to these unique characteristics, certain responsibilities cannot be delegated to the market without risking public safety. Design and construction tasks may be outsourced but the public client must retain the role of system integrator, overseeing interface and contract management. Thereby, asset-specific knowledge is gained and retained throughout the life-cycle, which is in line with the claims of Kamps, van den Boomen, et al. (2024). While previous research has focused mainly on the technical complexity of SSBs, Phase 4 results demonstrate that this technical complexity is intensified by the absence of a strong client accountability expressed as a minimum viable organization that generates the readiness required by the unique SSB characteristics.

Phase 4 further contributes a clearer understanding of earlier findings: incorporating design options that may only be activated once after 50 years is feasible only if the public client retains sufficient situational awareness and institutional knowledge. The public client needs to adopt a role of system integrator for interface management, thereby rewarding adaptability in line with the ROA. These results contradict the tendency to leave infrastructure development entirely to the free market and build on the evidence of Kamps, van den Bogaard, et al. (2024), namely that the exceptional demands of SSBs call for a PDM that combines market engagement with a sustained readiness capacity within the public client.

The analysis also clarifies that a client’s fate needs to be tied to the consequences of its decisions. The findings support the Antifragile Theory of Taleb (2012), which conceptualizes this exposure as “skin in the game.” As clients become more exposed to the consequences of their actions, they tend to behave in more Antifragile ways (i.e., design optionality, redundancy, organizational differentiation, retain craftsmanship). Phase 4 thus provides new insights into the relationship between valuing SSB design and fragmented accountability throughout the life-cycle, a relationship that narrows the design space for incorporating options. This explains why SSBs converge on common functions, as displayed in the FBS, yet still emerge as unique prototypes, as noted in the literature.

Reflection and Conclusions
This Thesis shows that long-term SSB performance depends not only on robustness but also on integrating options for flexibility in design to adapt to uncertainty. This leads to a bimodal strategy that combines maintainability (i.e., mode 1) with flexibility (i.e., mode 2). Mode 1 secures reliability through state-based maintenance and component degradation driven design. Mode 2 enables adaptation through the incorporation of design optionality to absorb deep uncertainty over the 100 year lifespan. Together these two modes form an Antifragile approach, a barrier that improves through change rather than merely resists it. Without integrating both modes, SSBs risk lock-in, obsolescence, and escalating costs. Yet technical solutions alone are not enough. An accountable public client is needed to preserve knowledge, manage project complexity, and activate design options over time.

9 Conclusion

This chapter presents the final conclusion of the Thesis, addressing the main research question. The chapter synthesizes findings from the discussed five sub-questions, drawing on case-based insights from the Bolivar Roads Gate System. This Thesis aimed to enhance the operational and maintenance (O&M) needs into the design and planning process of storm surge barriers (SSBs), thereby ensuring organizational stability and adaptable operations throughout the life-cycle in dynamic coastal environment. To recall, the main question:

> **"How can flexibility in design, asset management, institutional logic and contracting form an integrated project delivery method to enhance operations & maintenance resilience and long-term performance of storm surge barriers in a coastal system?"**

To answer the main research question, five sub-questions were formulated. The following paragraphs present the conclusions for each sub-question, synthesizing the answer to the main question.

SQ1 What is the distribution of potential future scenarios for physical and socio-economic system drivers that the Bolivar Roads Gate System in the Houston-Galveston Bay Region may encounter over the next 150 years? (CE + CME)

Once constructed, each SSB design exposes location-specific vulnerabilities tied to the volatility of physical and socio-economic drivers over its lifespan. But with options for flexibility in design, only a limited range of future developments needs to be anticipated, as the SSB *"has the option to change"*. Instead of aiming to precisely forecast uncertainty, this study identified the drivers based on heuristics (i.e., qualitatively based on historical trends, projected impacts, and expert input), with the drivers anticipating the greatest impact on functional performance to inform options for flexibility in design. For the Floating Sector Gates at Bolivar Roads, eight system drivers emerged: Temperature, Hydrodynamics & Morphology, Relative Sea Level Change (RSLC), Hurricanes, Multi-Stakeholder Dynamics, Politics, Policy and Law, Organizational Shifts (i.e., O&M), and Economic Growth (i.e., Increased Vessel Draft).

Next, the eight drivers were assessed against four qualitative future scenarios for the Houston–Galveston Bay Region, adapted from the Dutch Delta Scenarios, combining socio-economic and climate change trajectories. Two key drivers stood out: RSLC and Economic Growth (i.e., Increased Vessel Draft). These differ in volatility: RSLC evolves slowly over a century, while Economic Growth is more unpredictable (i.e., hard to measure and quantify), and may exceed SSB design limits within decades. As such, Economic Growth is determined the governing driver, posing a design dilemma: build for current conditions and risk early design obsolescence, or anticipate future uncertain vessel draft behavior at higher initial cost. The study results underscore the need to embed design flexibility, allowing for adaptive responses, thereby *"having the optionality to change"* (refer to SQ3).

SQ2 How can operational and maintenance requirements be most efficiently and effectively integrated into the barrier design and planning process to ensure optimized continuity and stability over the next 150 years? (CE + CME)

SSBs have long lifespans, operate infrequently, yet must remain reliable. This makes maintenance planning difficult, as future system drivers are uncertain (SQ1) and each design introduces unique maintenance needs. If maintainability principles (e.g., component standardization) are not strongly embedded in the requirements, or are later compromised by socio-economic volatility such as funding cuts, they often disappear from the design. In response, the study findings argue that SSBs must be deliberately designed with maintenance intervals for fixed (100 years), movable (50-100 years), and electrical (8-15 years) components in mind as each component has different degradation rates. Therefore, place long-life components at the *"bottom"* and shorter-life components *"on top"*, so that frequently serviced elements remain reachable without major disassembly. Thus, maintainability must be treated as design parameter on par with hydraulic loads, which calls for a maintainability-first approach!

This maintainability-first design must be complemented with a state-based maintenance policy due to the volatility of physical and socio-economic drivers (SQ1), uncertain component degradation, and the high consequences of failure. Regular inspections and action thresholds help prevent these drivers from escalating into operational failure, combining preventive, corrective, and failure-based maintenance. Fixed components require repairs every 25–35 years and full replacement after 100 years. Movable parts need inspections every 10–15 years, recoating every 20–40 years, and replacement after 50–100 years. Drive systems should be refurbished every 15–20 years, replaced after 20–50 years. Electrical systems are replaced every 8–15 years, with software/hardware updates annually. Inspections guide these maintenance actions: periodic (every 2–3 months), condition-based (every 2 years), pre-measure (2–3 years before planned work), and conservation (every 5 years). Corrective or opportunistic maintenance is applied to low-critical components when feasible. Failure-based maintenance remains essential for emergency repairs, especially during storms, to avoid functional breakdown.

SQ3 Which specific component of the Bolivar Roads Gate System, as well as the overall system, offer design flexibility to address uncertainties over the next 150 years, and which components are anticipated to manifest flexibility? (CE)

Based on SQ1 results, with options for flexibility in design, only a limited range of future developments needs to be considered, as the SSB *"has the option to change."* Next a trade-off arises where to implement these design options: prioritize flexibility in components most sensitive to system drivers and costly to modify later. The study found that that flexibility in SSB design, comprising fixed, movable, and electrical components, must be embedded in fixed elements like Sill & Mat Foundation. Alternatively, these fixed components, which are permanent (100 years; SQ2) and hard to alter post-construction, must be over-engineered to accommodate future generations of shorter-lived, replaceable elements. Movable and electrical components, with their shorter replacement cycles (e.g., 50 years; refer to SQ2) manifest this flexibility through planned, periodic upgrades over the next 150 years.

The potential manifestations of flexibility in the fixed components of the Floating Sector Gates at Bolivar Roads can take various forms. Based on SQ1 and SQ2, this study proposed an adaptable sill that allows future deepening of the sill elevation. This design copes with the driver, "Increased Vessel Draft" (refer to SQ1), giving the SSB *"the optionality to change"* without costly or disruptive retrofits. The design features a two-stage structure: permanent concrete sill blocks founded on piles and a graded open filter, topped with prefabricated caisson modules. In Stage 1, the caissons are sand-ballasted and secured with shear keys, setting the crest at $-18.3\,\mathrm{m\,NAVD}$ adequate for the MGX-24 vessel. When deeper drafts are needed, Stage 2 is activated: the ballast is removed, caissons are floated off, and the underlying sill blocks, precast to $-25.3\,\mathrm{m\,NAVD}$, become the new crest, accommodating Suezmax vessels. As stated above movable and electrical components must be retrofitted accordingly. Foundation stability is ensured by a pile foundation and a four-layer open granular filter graded from 0.5–$5\,\mathrm{mm}$ to 10–$60\,\mathrm{kg}$, placed between the sill blocks and the fine-sandy subsoil. Above this, loose rock bed protection is applied: HMA 1000–3000 upstream, HMA 3000–6000 downstream of the sill. The protection extends $250\,\mathrm{m}$, sufficient to contain scour holes from closure currents up to $v_{s,\max} = 13\,\mathrm{m/s}$, driven by a head differential of $\Delta h = 9\,\mathrm{m}$ between the Gulf and Galveston Bay during storm conditions.

SQ4 How do institutional logic, policies and contracting impact the flexible capacity and life-cycle of the storm surge barrier? (CME)

The flexible capacity and the life-cycle performance of SSBs are shaped by volatile physical- and socio-economic drivers, with the latter being harder to predict and exhibit non-linear behavior (refer to SQ1).

This creates an asymmetry: physical drivers are capped, while socio-economic ones are open-ended, driven by competing Institutional Logics. Hence the behavior, culture, and interactions of actors across institutions. In public infrastructure, dominant Logics include: State Logic (emphasizes bureaucratic values), Project Logic (prioritizes task delivery within strict project boundaries), and Asset Management Logic (focuses on long-term maintenance, adopting a risk-averse, life-cycle oriented perspective). Together with the SSBs' 100 year lifespans, high reliability demands, and significant failure risks, public clients face an "Make" or "Buy" dilemma: retain critical tasks and expertise in-house to ensure accountability and continuity, or outsource to market actors offering innovation and risk-bearing capacity.

The design phase poses a dilemma: outsourcing offers expertise but full delegation risks losing interface integration. Given the multidisciplinary scope (i.e, fixed, movable, electrical components), detailed design must go to qualified first-tier suppliers, while the public client maintains a small, skilled in-house team to manage interfaces, oversee contracts, allocate risks, and validate deliverables. In the build phase, the client must decide whether to transfer interface authority or retain control. Due to SSB complexity and cross-disciplinary needs, the client must continue to retain interface and risk management, supported by a temporarily expanded in-house team. Physical execution can be outsourced via integrated design-build contracts, enabling market expertise while preserving client-led system integration. Operating a SSB forces a choice: outsource and risk diluted accountability, or retain control. Given the high failure stakes, operational authority and staffing must stay in-house. Routine maintenance can be outsourced, while major tasks are contracted separately. The client again continuous to retain interface management and risk allocation to ensure continuity and accountability. Lastly, governance of the adaptable sill (refer to SQ3) must remain with the client, as activation depends on unpredictable policy windows, though execution can be outsourced once activation is approved (refer to Section 6.5).

SQ5 What key findings, practical insights, and policy recommendations from the project delivery method enhance the operational resilience and increase the value of the Bolivar Roads Gate System? (CE + CME)

Five key take away for the Bolivar Roads case study are:

- *Implement an adaptable sill from project initiation:* construct the two-stage sill (i.e., caisson modules on permanent sill blocks) so that in the future, when deeper vessel draft are needed, you avoid costly and disruptive retrofits and preserve the optionality to change;
- *Design with a "maintainability-first" mindset:* make shorter-life components (i.e., electrical systems) easy maintainable from the outset. This minimizes disassembly and reduces downtime;
- *Implement a state-based maintenance policy:* this combines preventive (i.e., routine-, condition-based inspections), corrective, and failure-based maintenance to ensure continuous reliability;
- *Keep interface management and risk allocation in-house:* maintain a small client team to oversee system integration and public accountability. Outsource detailed design and construction through integrated design-build contracts, this leverages market expertise without losing project control;
- *Retain client control over "design options":* keep decision-making authority and activation criteria for design options like the adaptable sill fully in-house. Set-up a clear governance process and reserve funding so the client can act quickly when a policy window opens (refer to Section 6.5).

Synthesizing the Findings: A Bimodal Strategy for SSBs - Linking Maintainability & Flexibility
This study concludes that maintaining SSB performance (SQ1) requires a bimodal strategy: managing the barrier through two distinct yet complementary modes (refer to Figure 8.1b). *Mode 1 - Maintainability* follows a traditional, linear approach focused on reliability, routine upkeep, and risk minimization. This means that SSBs must be deliberately designed with maintenance intervals of its components in mind as each component has different degradation rates (SQ2). A state-based maintenance policy, combining preventive- corrective- and failure-based maintenance, supports this reliability approach.

Mode 2 – Flexibility addresses non-linear exposure by embedding design options that allow the system to adapt over time and benefit from volatility. The adaptable sill, for example, enables the barrier to accommodate deeper vessel drafts rather than resist them (SQ3). Mode 2 complements *Mode 1* by preserving performance under uncertain conditions. This dual strategy depends on the public client acting as system integrator (SQ4). This requires a differentiated governance structure where the client is exposed to the outcomes of its decisions. Such accountability encourages more adaptive solutions, including maintainability, design optionality, and retained craftsmanship.

10 Recommendations

This Thesis explored how flexibility can be embedded in the design, asset management, and institutional context of a storm surge barrier (SSB). Based on the conclusions (refer to Chapter 9) academic (Section 10.1) and practical application (Section 10.2) recommendation are proposed.

10.1. Avenues for Further Academic Research

Develop Houston-Galveston Bay Region Delta Scenarios
Phase 2 leveraged Dutch Delta Scenarios, which do not fully capture Gulf-specific climate, or socio-economic trajectories. Future works can co-produce a set of regional Delta Scenarios that combine local Relative Sea Level Change (RSLC) projections, hurricane trends, Port of Houston economics, and demographic developments. Thereby refining findings in SQ1 and SQ3.

Quantify Second-Order Component Interactions with Bayesian Networks
Phase 3 relied on first-order Engineering System Matrix (ESM) dependencies, missing cascading effects between SSB components. Avenues for future work can build a probabilistic Bayesian network of components dependencies for the Floating Sector Gates at Bolivar Roads. Thereby running scenarios to see how local failures propagate through the SSB, deepening insights from SQ3 where options for flexibility in design delivers the greatest benefit.

Value Options for Flexibility in SSB Design (e.g., Adaptable Sill) with Real Options Approach
The conclusion highlights the adaptable sill as design option. A real-options analysis can show its financial value and the conditions under which it becomes cost-effective. It is recommended to compare the Net Present Value of the adaptable sill against a conventional sill across the four Delta Scenarios. This would provide deeper insights into SQ3 and SQ5.

Comparative Case Studies on Institutional Memory Retention
The conclusion states that the public client must remain the system integrator. Evidence-based patterns can help define how to embed this role in contracts and organizational structures. Therefore, it is recommended to study large-scale civil projects that either retained or lost tacit knowledge over time. This way identify effective governance design patterns. This would further support SQ4.

Refining and Testing Asset Management Strategy
The conclusion express the importance of organizational continuity, through the Asset Management Strategy. Understanding cognitive biases and communication gaps can help shape better training. Therefore, using serious gaming (e.g., den Heijer, Podt, et al. (2023)) is recommended to explore decision-making during rare, high-stakes storms and extended stand-by periods. This supports SQ4 by addressing the human factor in Operations & Maintenance (O&M) readiness.

10.2. Practical Applications and Technical Recommendations

Develop Digital Twin for State-Based Maintenance of the Bolivar Roads Gate System
The conclusion recommends state-based maintenance, which can be supported by a digital twin that enables testing of inspection intervals and intervention strategies. A digital twin allows operators to simulate real-world scenarios in advance, hence "experiencing everything once already", which helps minimize operational risks. Future applications could therefore develop a physics-informed digital twin of the Bolivar Roads Gate System, aligned with SQ2's focus on condition-based O&M.

Pile-Supported Foundation Design to Cope with Soft Soils
It is recommended to implement a deep pile-supported sill foundation (refer to Appendix D of the Coastal Texas Study Report; USACE, 2021d) to resist uplift and settlement under both initial (with caisson) and future (no caisson) conditions. As shallow foundation determinations has shown to fail for vertical stability in initial and future states, driven by the soft subsoil conditions in at Bolivar Roads.

Shear-Keys at Sill Block - Caisson Interface
It is advocated to integrate vertical shear keys atop the sill blocks for each caisson unit. This simplifies installation and removal during de-ballasting of the caisson units. Moreover, shear keys provide horizontal shear while enabling caisson removal without undermining structural sill integrity.

Loose Rock Bed Protection for Low Maintenance
Favor graded loose rock as the primary material for bed protection around the adaptable sill structure. Because loose rock has a proven durability, does not require periodic replacement, and can be sourced from regional quarries. Use per bed protection layer a minimum layer-thickness of $1.5 - 2.0 \quad D_{50}$, typically $1.5 - 2.5\,\mathrm{m}$. Indicative technical specifications:

- Upstream of the sill: $HMA \quad 1000 - 3000$ (i.e., 1- 3 ton stones);
- Downstream of the sill: $HMA \quad 3000 - 6000$ (i.e., 3 - 6 ton stones);
- Outer transition zones: $300 - 1000\,\mathrm{kg}$ and $60 - 300\,\mathrm{kg}$ stones.

Open Granular Filter Layers for Low Maintenance
It is recommended to implement a open granular filter system beneath the permanent sill blocks to cope with uplift and seepage. As open granular filters have a long-term durability, minimal maintenance, and consist of abundant materials (i.e., loose rock/fines). It is advised to use a minimum layer-thickness of $0.5\,\mathrm{m}$. Indicative technical specifications:

- Top Filter Layer: $60 - 300\,\mathrm{kg}$ stones;
- Intermediate Filter Layer 1: $30 - 40\,\mathrm{mm}$ grading;
- Intermediate Filter Layer 2: $3.5 - 35\,\mathrm{mm}$ grading;
- Base Filter Layer: $0.5 - 5\,\mathrm{mm}$ grading.

Phased Construction and Caisson Deployment
Adopt a two-phase construction sequence to implement the adaptable sill principle. Thereby implementing adaptability into theSSB from the start. This approach reduces downtime and simplify future deepening interventions, in short:

1. Place the prefrabicated, sand-ballasted caissons on the permanent sill blocks;
2. Upon future deepening of the sill elevation, dredge sediment cover, de-ballast caissons, float and remove caissons.

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A
Research Theories and Concepts

This appendix expands on the Research Theories introduced in Section 1.6. It elaborates on Engineering Systems Theory (Appendix A.1), Flexibility in Engineering Systems Concept (Appendix A.1.1), *Institutional Logics* (Appendix A.2), and Contract Theory (Appendix A.3). Collectively, these perspectives address the socio-technical challenges of large-scale infrastructures, emphasize adaptability under uncertainty, explain stakeholder interactions, and offer governance guidance. Together,informing the Theoretical Framework developed in Chapter 3.

A.1. Engineering Systems (ES) Theory

Engineering Systems (ES) is a discipline focused on addressing the socio-technical challenges posed by complex, large-scale systems. It integrates insights from behavioral, social, and life sciences, as well as management disciplines. Thereby guiding the design and management of systems characterized by technical sophistication, social intricacy, and essential societal functions (Engineering Systems Division, 2008; Bartolomei et al., 2012; De Neufville and Scholtes, 2011). Examples include airports, critical infrastructure (Engineering Systems Division, 2011; De Neufville and Scholtes, 2011), and SSBs like the Bolivar Roads Gate System in the Houston-Galveston Bay Region.

These type of systems, including SSBs with lifespans exceeding 100 years (Hamerslag and Bakker, 2023), are long lived, and require significant, often irreversible investments and face substantial uncertainties (Cardin, 2014). To illustrate, the USACE cost estimate of the Bolivar Roads Gate System SSB is $13.8 billion (Merrell et al., 2021). The performance of ES is influenced by numerous variables and dynamic socio-technical factors such as markets, regulations, and technological advances (Mina et al., 2006). Particularly for SSBs, integrating innovative solutions into SSBs has proven challenging due to their unique custom-made components (Walraven et al., 2022).

ES Theory identifies principles, governing systems with interdependent functions such as flood protection, urban development, and environmental sustainability (Meyer and Nijhuis, 2013). This aligns with Jonkman, Hillen, et al. (2013), who emphasizes the need for integrated SSB life-cycle management. ES Theory spans diverse domains, including Systems Engineering, Technology and Policy, and Systems and Decision Analysis. ES connects to related theories like Sociotechnical Systems Theory (STS) and Large Technological Systems (LTS) (Council of Engineering Systems Universities (CESUN), 2024).

STS focuses on the social and psychological dynamics of human-technology interactions (Bartolomei et al., 2012). Highlighting the workforce as a critical asset in SSBs AM (Kuhn et al., 2021). In contrast, LTS examines interconnected components across domains such as physical infrastructure and legislative frameworks, functioning as open systems that adapt to changing environments (Bartolomei et al., 2012). For example, in the Netherlands flood defense systems must adhere to risk-based safety standards (Jonkman et al., 2016), as stated in the Water Act (Kharoubi et al., 2024), which is inline with policy of Ministry of Infrastructure and the Environment and Ministry of Economic Affairs (2014).

Bartolomei et al. (2012) conceptualized ES through an abstract framework depicted in Figure A.1 and elaborated in Table A.1. This framework defines domains common to all engineering projects such as the Bolivar Roads Gate System which comprises various domains within the Houston-Galveston Bay Region. While ES theory offers a robust framework for addressing SSB complexity, its abstraction may oversimplify operational challenges such as aligning diverse stakeholder goals in multi-level systems.

System Domain	Description
Environmental	External elements influencing or influenced by the ES.
Social	Human actors and their relationships within the ES.
Functional	Objectives and outcomes alongside functional structures.
Technical	Physical components, including hardware and data.
Process	Activities and workflows carried out by the system.

Table A.1: Conceptualization of Engineering Systems (ES) domains by Bartolomei et al. (2012).

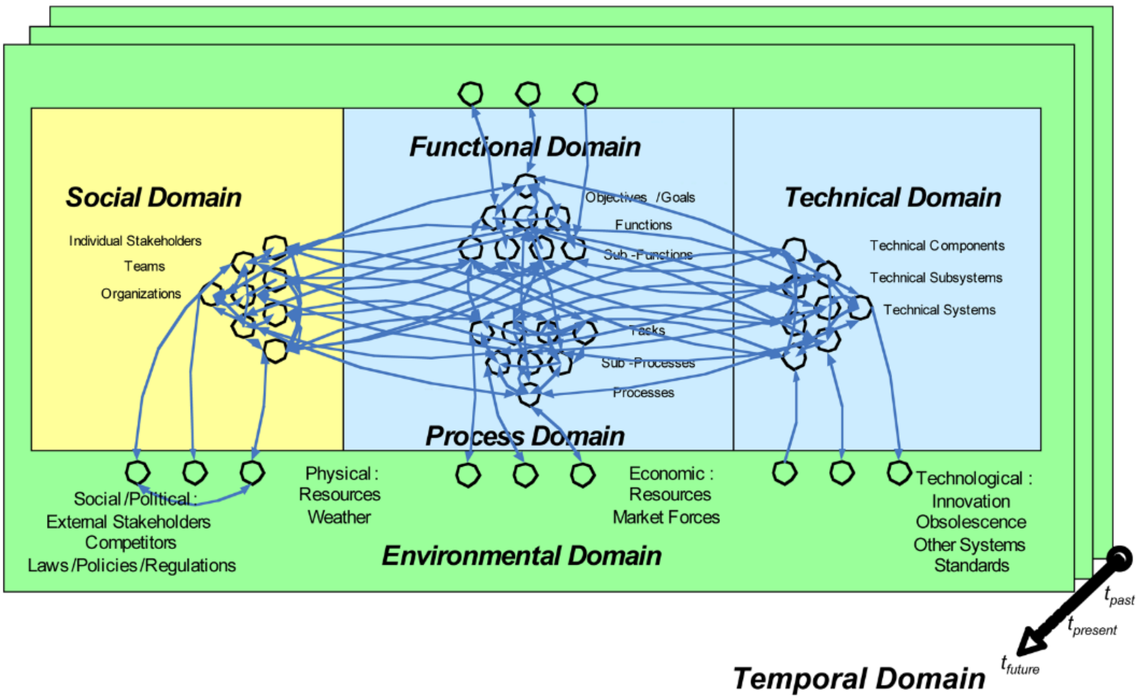


Figure A.1: Engineering Systems (ES) conceptual model by Bartolomei et al. (2012).

ES evolve over time, with components being modified, removed, or introduced as needed (Bartolomei et al., 2012). For example, maintaining SSBs like the Maeslant Barrier involves replacing motors, gears, and pumps or repainting gates (Trace-Kleeberg et al., 2023). These systems exhibit emergent properties arising from the interplay between social and technical components.

ES operate as cohesive, open systems interacting with external drivers (Bartolomei et al., 2012). SSBs, for instance, function within flood defense systems, which are part of broader coastal systems (Mooyaart and Jonkman, 2017). Over time, obsolescence can hinder the objectives of ES (Bartolomei et al., 2012). As seen in electronic components of SSBs that require replacement but where no longer supported (Walraven et al., 2022).

Path dependence, a key feature of ES, reflects how historical development shapes current states, enabling systematic tracking of modifications (Bartolomei et al., 2012). ES also span varying levels of complexity, from individual interactions to transnational systems (Bartolomei et al., 2012; see Table A.2). For example, Houston's petrochemical industry represents 40% of the national oil capacity (USACE, 2021e), meaning flooding or disruptions in this sector would affect the entire U.S..

Level	Description
Individual	A person engaging with technical components to achieve specific goals.
Group	A set of individuals interacting with each other and the system.
Organization	Groups collaborating locally toward shared objectives.
Enterprise	Multiple organizations working together, contributing to the ES.
Higher-order	Enterprises and organizations collaborating for overarching goals.

Table A.2: Levels of interaction in Engineering Systems (ES) by Bartolomei et al. (2012).

To further elaborate, the Bolivar Roads Gate System impacts entities across levels, including local fisheries (i.e., group level), the Port of Houston (i.e., organizational level), maritime trade in the Houston Shipping Channel (i.e., enterprise level), and the Coastal Texas Project partnership (i.e., higher-order level) (USACE, 2021a; USACE, 2021e). ES Theory provides an ideal framework for analyzing SSBs, addressing their complexity, interdependencies, and socio-environmental dynamics. Its holistic, life-cycle perspective aligns with the long lifespans and path dependence of SSBs while accommodating multi-level interactions, exemplified by the Bolivar Roads Gate System.

A.1.1. Flexibility in Engineering Systems Concept

Engineering Systems (ES) such as bridges, dams, and SSBs, are typically fixed and irreversible once constructed (Zhao and Tseng, 2003). These systems require significant investments (Kharoubi et al., 2024) and are critical for societal reliance. Hence, the flood protection function of SSBs. They face heightened risks due to dynamic uncertainties compared to other systems such as economic fluctuations and environmental changes (Ajah and Herder, 2005), as extreme temperatures and increased precipitation are identified as potential physical drivers for SSBs (Bakker et al., 2023), to name a few. As a result, incorporating built-in flexibility is essential to adapt to these changing conditions and reduce long-term risks (Ajah and Herder, 2005).

Flexibility in ES Concept is particularly valuable because it enables systems to adapt to future changes in needs or conditions, addressing the deep-rooted unpredictability of socio-technical environments (Zhao and Tseng, 2003; De Neufville and Scholtes, 2011). In contrast, systems operating in stable and predictable environments may not require such adaptability. As De Neufville and Scholtes (2011) highlights, designers cannot reliably forecast the long-term costs and benefits of large-scale systems, which poses challenges for decision-makers, including analysts, investors, and regulators. Flexibility options allows systems to respond to uncertainties that traditional deterministic approaches often fail to address.

Effective flexibility design begins with acknowledging and modeling uncertainties, avoiding oversimplifications like the "flaw of averages" (Taleb, 2007). A realistic evaluation of uncertainty distributions is important to ensure flexibility delivers value under diverse scenarios (Zhao and Tseng, 2003; De Neufville and Scholtes, 2011). Conventional approaches, which focus on static, robust solutions, often underestimate the socio-technical uncertainties immanent in dynamic environments (De Neufville and Scholtes, 2011), limiting their adaptability. To illustrate, in the Eastern Scheldt (the Netherlands), technical modifications to the barrier gates and dike adjustments can manage up to 50 cm of sea-level rise (Verbruggen et al., 2012), though sea-level rise estimates range from 30-120 cm (Haasnoot et al., 2020). These uncertainties indicate that even robust designs may face limitations.

Flexibility differs from robustness. While robust designs aim to maintain consistent functionality despite external changes, flexible designs enable systems to adapt, reconfigure, or expand as necessary (Cardin, 2014; Saleh et al., 2009). For instance, flexible designs can accommodate changes in size through modular expansion, adapt functionality by adding or removing features, or include mechanisms to mitigate risks and enhance safety (De Neufville and Scholtes, 2011). Although these features may not optimize the system for immediate objectives, they provide adaptability when requirements evolve (Mark, 2005). Like, the Eastern Scheldt Barrier top beam sits 30 cm above the design water level, with 10 cm reserved for settlement and 20 cm for sea-level rise, was previously considered robust (Verbruggen et al., 2012). However, current sea-level rise scenarios (Haasnoot et al., 2020), suggesting more than a 20 cm rise, would bring the barrier to its design limit, leading to overflow and increased wave loads (Verbruggen et al., 2012). While flexibility enhances long-term value, it introduces trade-offs, including higher initial costs and potential inefficiencies.

Infrastructure projects typically follow structured design phases, including feasibility studies, and conceptual design stages (Pahl et al., 2007). Decisions made during early stages, particularly in conceptual design, have the greatest long-term impact on project outcomes. Integrating foptions for flexibility in design at this stage ensures adaptability by evaluating uncertainties and embedding mechanisms to address them (Bosch-Rekveldt et al., 2011). Flexibility has been shown to improve life-cycle performance by 10-30% compared to standard design and evaluation approaches (De Neufville and Scholtes, 2011).

Flexibility in ES can be incorporated through two approaches: real options “on” projects and real options “in” projects (Saleh et al., 2009; Wang, 2005). Real options “on” projects focus on managerial flexibility, treating the system as a “black box” and enabling strategic decisions later. Real options “in” projects emphasize flexibility within the system, allowing components to adapt to changing conditions (Cardin, 2014) such as modifying SSB gates to handle increased river discharge. This research focuses on real options “in” the Bolivar Roads project to understand how flexibility can be embedded in the life-cycle of SSBs.

Developing a options for flexibility in design concept for ES involves four to five phases for embedding flexibility, as outlined in Table A.3. Numerous design theories and methodologies have been suggested to guide activities within each phase. For instance, the taxonomy of procedures proposed by De Neufville and Scholtes (2011), and elaborated by Cardin (2014) is illustrated in Figure A.2, which will form the foundation of the Theoretical Framework in Chapter 3. Thereby the phases “Concept Generation” and “Design Space Exploration” will be merged into one phase.

Flexibility in ES is essential for managing uncertainty, adapting to evolving needs, and enhancing long-term value. Conventional design methods, which focus on deterministic assumptions, often fail to address the unpredictability of socio-technical environments (De Neufville and Scholtes, 2011). By integrating flexibility, systems like SSBs can better align with societal needs, mitigate risks, and remain resilient in dynamic conditions (Saleh et al., 2009). This research examines how these principles can be applied to the Bolivar Roads Gate System to enhance its adaptability and value over its operational lifespan. This research will leverage pieces of the taxonomy of procedures as stated by Cardin (2014) as guidance of the applicability to the Bolivar Roads Gate System.

A.2. Institutional Logics Theory

Institutional Logics Theory complements ES Theory by offering insights into the behavior, culture, and interactions of various actors across multiple levels within an ES. Institutions, defined as frameworks of formal and informal rules and norms, influence social behavior while serving as the “rules of the game” in social and organizational contexts (North, 1991; Coenen et al., 2023). Although long-lasting, institutions can evolve through human agency. According to Friedland and Alford (1991), Institutional Logics are meta-level structures that comprises values, beliefs, rules, and material practices, shaping decision-making and the meaning behind actions. These Logics mix implicit and explicit values, influencing legitimacy, rewards, and organizational behavior (Thornton et al., 2015).

Phase	Description
Baseline Design	Establishing a starting point using existing configurations to guide flexibility integration. This phase ensures designers build on known concepts and systematically structure their approach.
Uncertainty Recognition	Identifying and modeling key uncertainties that impact life-cycle performance, using tools like heuristics, Monte Carlo simulations and regression analysis.
Concept Generation	Developing flexible design concepts to address uncertainties, including defining strategies and enablers, such as real options strategies (Krystallis et al., 2024), and design structure matrix-based methods (Bartolomei et al., 2012).
Design Space Exploration	Exploring potential design concepts and decision rules to optimize flexibility. This phase identifies designs that offer superior life-cycle performance compared to baseline concepts.
Process Management	Addressing the collaborative and social aspects of managing flexibility, ensuring its effective implementation through methods like Integrated Project Delivery.

Table A.3: Procedures to support options for flexibility in design of ES by De Neufville and Scholtes (2011) and Cardin (2014).

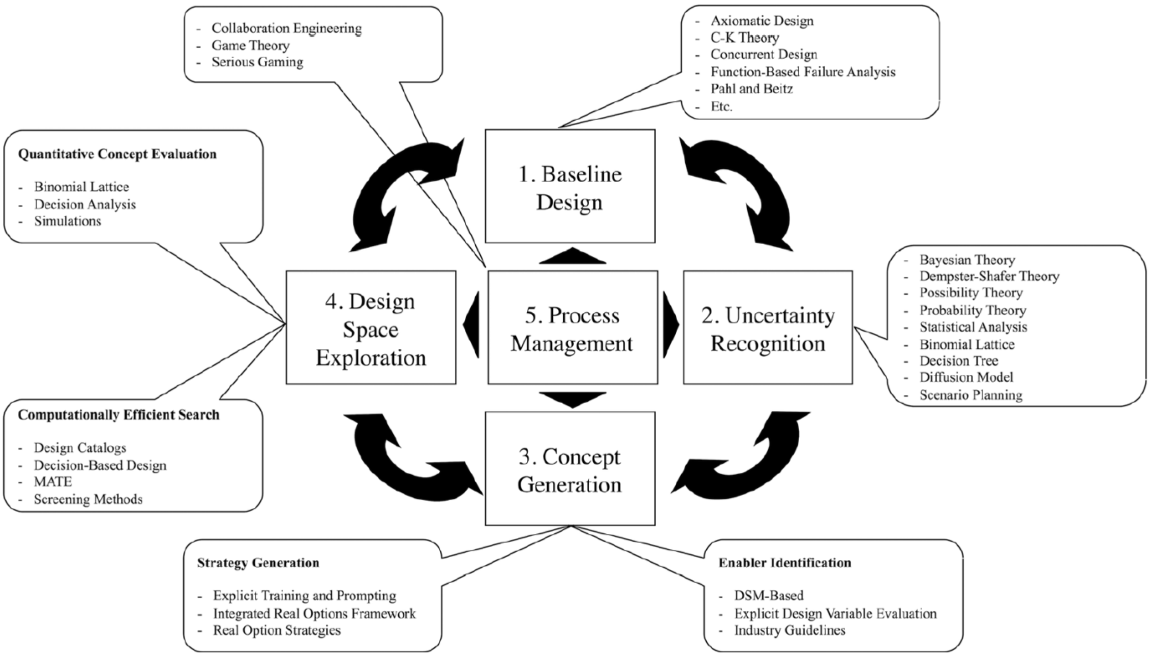


Figure A.2: Taxonomy of procedures to support development of options for flexibility in design for ES by Cardin (2014).

Organizations often face institutional pluralism. Navigating multiple, sometimes conflicting, Logics. This creates complexities in balancing diverse demands and governance (Besharov and Smith, 2014). Public infrastructure agencies, as hybrid organizations, embody these challenges by balancing public and private sector Logics while mediating between diverse stakeholders (Coenen et al., 2023). Table A.4 outlines the dominant Logics in public infrastructure, as identified by Coenen et al. (2023). These Logics provide a framework for understanding the interactions between institutions in public infrastructure. They also align with the levels of interaction within ES, as outlined by Bartolomei et al. (2012) (refer to Table A.2). By examining the cultures, conflicts, and interactions across group, organization, and higher-order levels, Institutional Logics enhance understanding of organizational dynamics.

Logic Type	Description
State	Emphasizes bureaucratic values like accountability and procedural adherence, aligning with governance mandates.
Asset Management	Focuses on long-term planning and maintenance of infrastructure, adopting a risk-averse, life-cycle oriented perspective.
Project	Prioritizes efficiency, feasibility, and task delivery within strict project boundaries, often aligning with private sector parties.
Sustainability	Driven by individual and societal concerns, promotes innovation and aligns with broader environmental goals. However, it remains underrepresented.

Table A.4: Dominant Logics in public infrastructure management (Coenen et al., 2023).

To illustrate, the Dutch infrastructure agency Rijkswaterstaat (RWS) operates under "State Logic", prioritizing procedural accountability and ministry-driven policies with limited flexibility (Coenen et al., 2023). Project-level operations align with "Project Logic", emphasizing efficiency and predefined scopes, restricting the integration of circular solutions beyond project boundaries (Coenen et al., 2023). Institutional Logics Theory offers insights into the cultural and organizational complexity of the Bolivar Roads Gate System SSB. By complementing ES Theory, it supplements the Theoretical Framework in Chapter 3.

A.3. Contract Theory

SSBs, defined as ES, require substantial investments for construction (Mendelsohn et al., 2022), and O&M (Aerts, 2018). Organizations managing these systems face dynamic project complexities (Bosch-Rekveldt et al., 2011), like cost overruns and time delays (Flyvbjerg et al., 2003). Making Contract Theory a valuable framework for addressing stakeholder arrangements and governance mechanisms. It complements ES and Institutional Logic Theories by providing practical tools for managing relationships and uncertainties in mega-projects like the Bolivar Roads project.

A contract holds different meanings for different stakeholders. Considering its economic and legal aspects is essential for all practitioners in a project environment (Bakker and de Kleijn, 2014). This research approaches contracting from a project management perspective, viewing it as a tool for achieving effective project control. Accordingly, the following definition by Bakker and de Kleijn (2014) is adopted: *"a contract is a legally binding, enforceable and reciprocal commitment governing collaboration between two (or more) parties."*

According to Buchem-Spapens and Nieuwenhuis (1991) key elements of this definition and thus contract formation, include: (I) the intent to create a legal relationship and the capacity to act; (II) an offer and acceptance; and (III) compliance with established practices and laws. The purpose of sourcing and contract management is to clarify the parties intentions, with the contract serving as an outcome rather than an objective (Bakker and de Kleijn, 2014). Aligning objectives and encouraging collaboration is achievable through various contracting strategies and remuneration models (Bakker and de Kleijn, 2014). This is briefly noted in the Literature Review (Chapter 2).

Two key contract theories underpin contract strategies: (I) relational contract theory (RCT), which emphasizes long-term relationships, trust, and mutual cooperation, focusing on the broader social and economic context rather than solely the formal contract terms (Macaulay, 1999); (II) transaction cost economics (TCE), which prioritizes minimizing transaction costs through efficient governance structures (Williamson, 1979). Both theories highlight the importance of aligning interests, establishing relational norms, and enabling flexible governance mechanisms to adapt to unforeseen events (Bakker and de Kleijn, 2018; Turner, 2017). Contracts evolve as enforceable commitments that guide collaboration between clients and contractors throughout the project life-cycle (McLennan and Scott, 2002).

While contracts bind specific parties, they operate within a network of related agreements and stakeholders (Bakker and de Kleijn, 2014), as illustrated in Figure A.3. Insurers and lenders play important roles in facilitating project execution, holding direct stakes in contractual relationships. Non Governmental Organization (NGO)s often align with community interests, and authorities ensure compliance with applicable laws and regulations (Bakker and de Kleijn, 2014). Successful project outcomes depend on active participation from all these stakeholders.

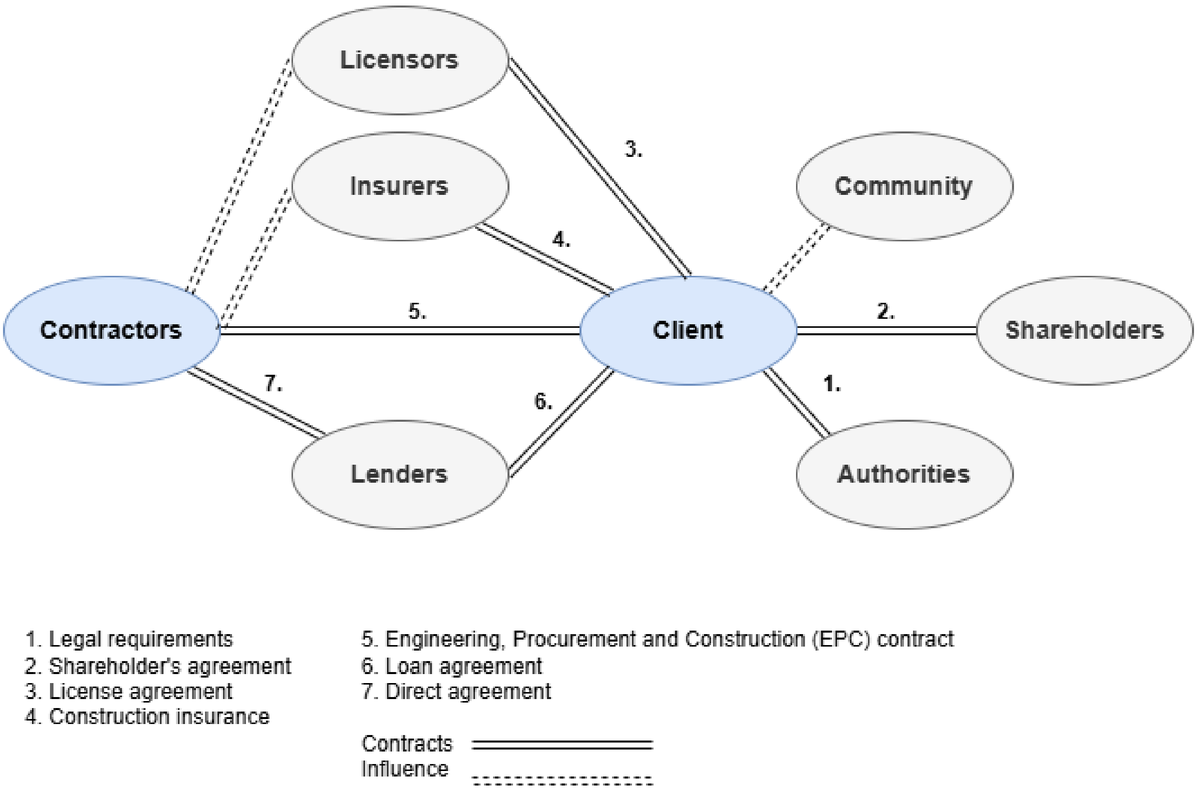


Figure A.3: Contracting map by Bakker and de Kleijn (2014), adjusted by S.D. van der Geer.

It is essential for both the client and contractor to clearly communicate their expectations and acknowledge their roles (Bakker and de Kleijn, 2014). The client's primary objective is the creation of the asset, considering the needs and interests of various project stakeholders. The contractor is focused on delivering value by successfully executing the project (Bakker and de Kleijn, 2014). Given the dynamic complexity inherent in projects (Bosch-Rekveldt et al., 2011), effective collaboration between the client and contractor is important, as it can significantly benefit both parties.

The application of relational contracting in the Bolivar Roads Gate System could enhance collaboration by embedding flexibility into agreements, allowing stakeholders to adapt to unforeseen changes. Contract Theory's reliance on clear initial terms may limit adaptability in rapidly changing conditions, underscoring the need for iterative contract evaluation processes. By complementing ES Theory, it will support the Theoretical Framework in Chapter 3.

B

Literature Research Methodology

This appendix outlines the methodology used for the literature research. It begins by stating the objectives of the literature research, which are inline with the research objective and questions as stated in Chapter 1. Followed by a discussion of the search engines and keywords employed. Finally, the approach for evaluating and selecting sources is detailed.

B.1 Objectives of the Literature Research

The objective of this literature research was to investigate and explain the relevant factors and variables within the context of the research problem and scope, with an emphasis on design considerations, asset management (i.e., O&M), interconnected subsystems in barrier design, physical and socio-economic drivers, and multi-actor management of SSBs. This research examined complexities, challenges, organizational maturity, as well as contract and contract strategies related to SSBs.

The following objectives were outlined by examining the state-of-the-art:

- Gather empirical insights into SSBs and their characteristics;
- Obtain empirical insights into conventional designs and design considerations of SSBs and their interconnected subsystems;
- Develop insights into methodologies related to asset management (i.e., O&M) and multi-actor management that impact the life-cycle of SSBs;
- Collect empirical insights into the physical and socio-economic system drivers that create uncertainty in the design and O&M of SSBs;
- Identify common complexities and obstacles throughout the life-cycle of mega-projects such as SSBs, and explore the development of organizational maturity in such projects;
- Obtain empirical insights into project delivery method (PDM), contracts, and contracting strategies for mega-projects like SSBs.

B.2 Literature Sources

To achieve the literature objectives, the following sources were utilized: Scopus, ScienceDirect, ASCE Libary and the TU Delft Library and TU Delft Repository. Google (Scholar) was used to search grey literature (e.g., technical reports, manuals, websites, newspapers) from governments and research institutes.

B.3 Keywords

The literature research focused on identifying papers that contain a defined combination of keywords in the title or abstract. In accordance with the literature research objectives, the following key words were prepared for the purpose of the boolean strings for the search for relevant literature:

- *Storm Surge Barrier(s)*: `”storm surge barrier*” OR ”flood barrier*” OR ”storm surge protection” OR ”flood defen?e system*” OR ”hydraulic structure*” OR ”infrastructure” OR ”large-scale project*” OR ”major project*” OR ”long-lasting project*”`
- *Life-Cycle Principles*: `”asset management” OR ”life?cycle principles” OR ”life?cycle management” OR ”life?cycle assessment” OR ”life?cycle approach” OR ”life?cycle phas*” OR ”design” OR ”build” OR ”construct*” OR ”maintain” OR ”operat*” OR ”DBOM” OR ”DBMO”`
- *Institutional Logic*: `”institution* logic” OR ”institution* frameworks” OR ”organization* logic” OR ”organization* governance” OR ”institution* governance” OR ”polic*” OR ”polic* framework” OR ”regulation*” OR ”stakeholder* arrangement*”`
- *Contracting and Procurement*: `”form* of collaboration” OR ”procurement” OR ”public procurement” OR ”contract*” OR ”contract* management” OR ”acquisition”`

The boolean strings were specified per objective with the operators `AND “ “, OR “|”, NOT “-”` to focus the search.

B.4 Evaluating and Selecting Sources

The sources and papers found were analyzed using the questions below, focusing on certain parts of the source or paper:

What is the central theme of the paper?	Title
What are the main concepts in the paper?	Abstract
What are the most important theories and methods?	Abstract
What are the results and conclusions?	Abstract
How does this paper relate to other papers?	Background / Section 2
What are the most important insights?	Conclusion
What are the weak and strong points of this paper?	Own thoughts

Additionally, the reference list was reviewed to identify more relevant papers and sources. Notable citations were summarized in a research gap table (e.g. Zotero software), which included the following elements:

- Author(s);
- Title;
- Year of publication;
- Classification (type of method);
- Quantification method;
- Main findings regarding the method;
- Main findings regarding the content.

C

Theoretical Framework

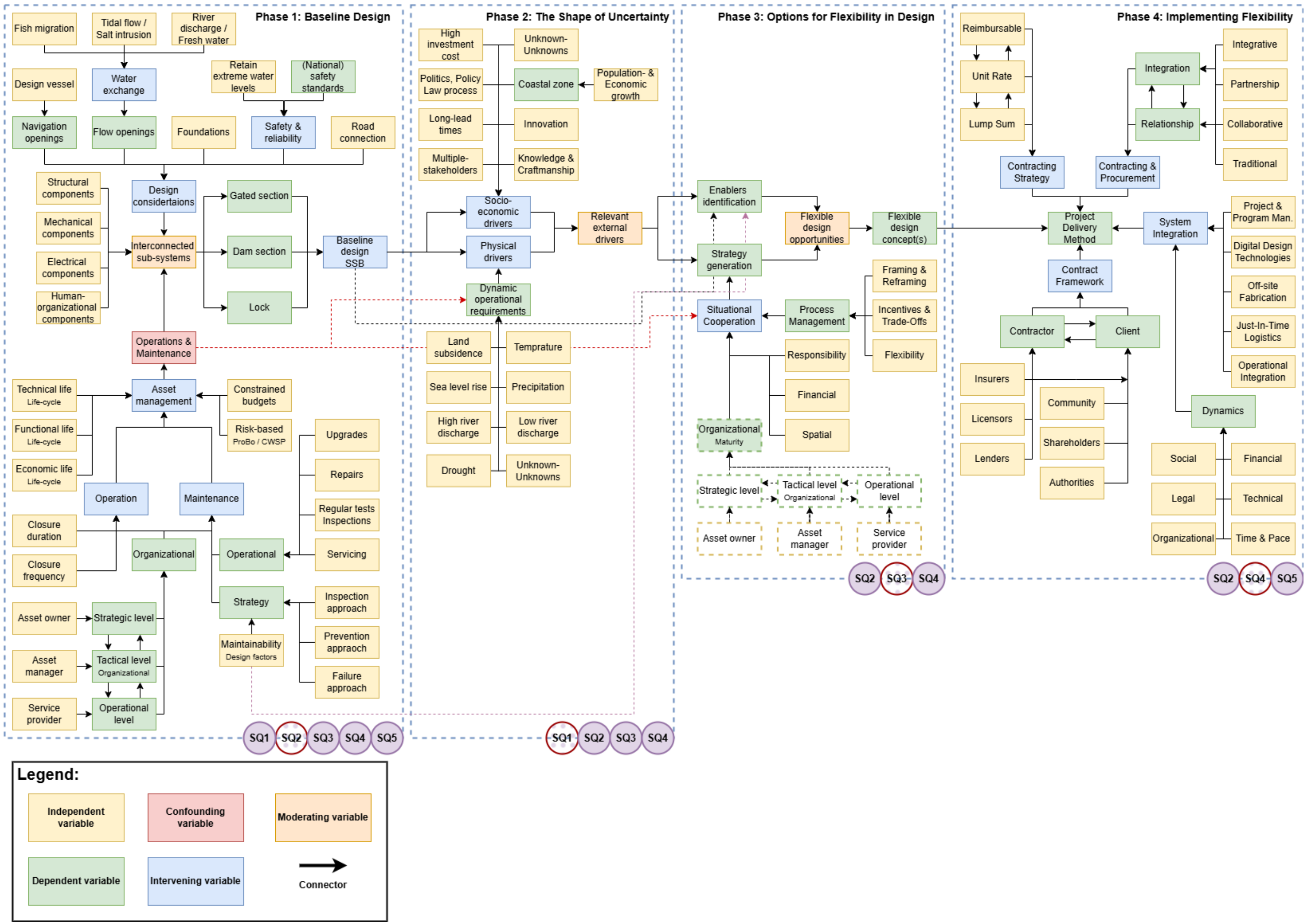


Figure C.1: Theoretical Framework: Flexibility in Engineering Systems.

D Research Phase 1

This Appendix provides a detailed overview of the methodology, and supplements of Phase 1: Baseline Design. It begins by outlining the applied methodology and techniques, including the variables identified through the Literature Review, the data collection approach, and the methods of analysis. Next, it states the supplements of the research methodology for Phase 1.

D.1. Methodology and Technique

The paragraph below discusses the methodology applied within Phase 1 of the research design. Based on the relevant factors identified in the Literature Review (see Figure D.1), and the systematic System Engineering method of de Graaf (2014), a baseline design concept (i.e., social-, environmental-, functional-, process-, and technical ES domain) was logical modeled. This is visualized in the System Diagram.

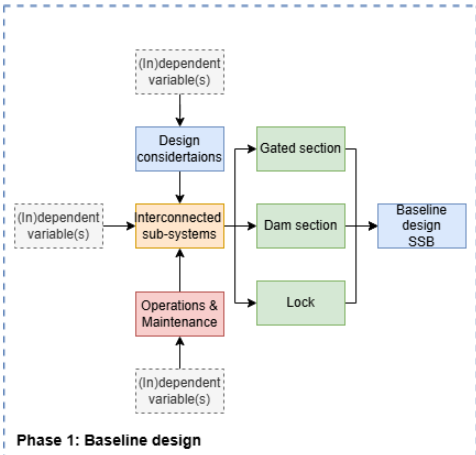


Figure D.1: Phase 1 literature review variable(s).

D.1.1. Variable(s) from the Literature Review

The variables identified during the Literature Review (refer to Chapter 2), form the starting point of the analysis. These variables, categorized as independent or dependent, will be incorporated into the ES analysis framework. Refer to Theoretical Framework in Appendix C for a review of all the identified variable(s). This structured approach ensures that the variables are systematically evaluated to address the complexities within the system and derive meaningful insights for flexible design solutions.

D.1.2. Data Collection Method

Phase 1 of the study leveraged qualitative and quantitative archival data. Current conceptual design of the Bolivar Roads Gate System exists, and was leveraged for extraction of data. Data on this conceptual design is publicly available from the Coastal Texas Project, engineering firm Arcadis, and the TU Delft Repository. This data is readily available, and was used for feasibility studies of the preliminary design of the SSB, refer to Table D.1. Tacit stakeholder knowledge was gather via semi-structured interviews, further elaborated in Appendix G.

Data Source/Owner	Type of Source	Data Collection Objective
Coastal Texas Project	Final Feasibility Report(s)	Social-, Environmental-, Functional-, Process-, and Technical domain
	Appendices	
USACE & GLO	ArcGIS-map	Social-, Environmental-, Functional-, Process-, and Technical domain
Arcadis	Technical Reports	Functional-, Process-, and Technical domain
TU Delft Repository	MSc Thesis, Technical Report(s), Article(s)	Social-, Environmental-, Functional-, Process-, and Technical domain

Table D.1: Overview of data sources and collection objectives phase 1.

D.1.3. Applied Method: System Engineering

To develop the baseline design, and thus the System Diagram, elements from the ES theory methodology were applied, outlined in de Graaf (2014)'s manual. Successively, the following analyses were performed:

Analyzing the Project Environment

The first Systems Engineering (SE) activity involved analyzing the project objectives, and environment. This defined constraints and regulatory frameworks the system must follow. For example, the system must align with zoning requirements and integrate into urban plans. Additionally, external factors, like competing projects, may impact the system, mapping these policies and developments to ensure proper alignment. Hence, the following steps:

- Determine the system;
- Analyze the environment;
- Determine the interactions;
- *Deliverable: visualize system boundaries in System Diagram*.

Conducting Stakeholder Analysis

A system, like a SSB, is only successful if it meets the needs and expectations of its stakeholders (i.e., individuals or organizations that impact or are impacted by the system). Stakeholders include a wide range of parties such as clients, users, local residents, municipalities, utility companies, fire departments, and water authorities. Addressing the diverse requirements of these stakeholders makes sure the system's usability. Moreover, encourages support for the project. Therefore, assessing and meeting the main stakeholder needs is essential. Hence, the following steps were conducted:

- Identify the main stakeholders;
- Determining the positions of the main stakeholders;
- Deciding how to involve the main stakeholders in the System Diagram;
- *Deliverable: stakeholder diagrams*.

Determine Functionality of the System

A systems functionality defines what it must be capable of doing. Functional analysis results in a description of the SSB in terms of its functions. When modeling the SSB in the System Diagram, it is essential to outline the functions the system must perform to meet its objective, as stakeholders typically communicate in terms of functions. Through functional analysis, the system was broken down:

- Determine the task;
- Determine the functions;
- Divide the functions into basic functions and supporting functions;
- Determine the primary basic functions;
- Sort the remaining functions;
- *Deliverable: Functional Breakdown Structure (FBS)*.

Develop System Breakdown Structure (SBS)
A function fulfiller is responsible for performing the function, as defined in the FBS. In other words, it ensures that a function is carried out. Function fulfiller are also referred to as objects. Each object is responsible for one or more functions within the overall system, and together, all objects ensure that every function of the system is fulfilled, this is displayed in a SBS. All the determined functions were allocated to objects within the system:

- Link functions to objects;
- Create the System Breakdown Structure (SBS);
- *Deliverable: System Breakdown Structure (SBS)*.

D.2. The Project Environment

Component	Definition	Details
Barrier	Physical Object	Includes construction elements such as pillars, sill beams, top beams, gates, and hydraulic systems, along with bed protection and scour pits.
	Operations & Maintenance	Covers operating and maintenance regimes and associated water level predictions.
Hydrodynamics	Hydrodynamic Processes	Encompasses water flow, wave behavior, and tidal dynamics in the affected system.
Morphology	Large-Scale Development	Includes channel formation, intertidal and supratidal areas, seabed characteristics, and sediment transport.
Inland Dikes & Dams	Structural Elements	Covers entire constructions, from the toe to the inner slope.
Ecology	Ecosystem Characteristics	Considers species, biological processes, and landscapes within the ecosystem.
Usage Functions	Key Functions	Addresses ecological value, (commercial) fisheries, shipping and recreation.

Table D.2: Definitions of components in SSB System Diagram (de Jong et al., 2012).

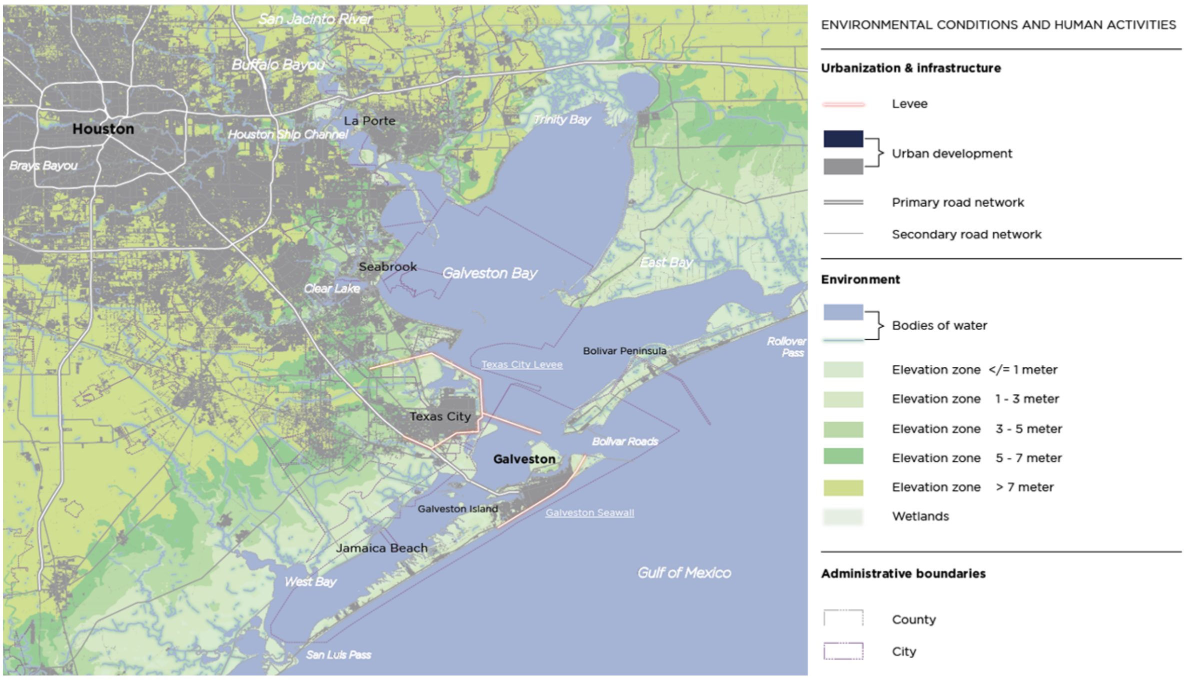


Figure D.2: Houston Galveston Bay Region: flood zones and topography (Kothuis et al., 2015).

Figure D.3: South-east Texas vicinity map (USACE, 2021c).

Hurricane	**Cat**	**Landfall Location**	**Peak Surge Open Coast**	**Peak Surge North Bay**	**Peak Surge South Bay**
Ike (2008)	2	0 km	4.5 meter	5.0 meter	3.5 meter
Rita (2005)	5	120 km East	1.5 meter	1 meter	1.3 meter
Alicia (1983)	3	50 km West	2.5 meter	4 meter	3 meter
Carla (1961)	5	180 km West	3 meter	4 meter	3 meter
Cindy (1963)	2	50 km East	0.8 meter	-1 meter	1 meter
“Surprise” (1943)	2	30 km East	unknown	-1.5 meter	-1.5 meter

Table D.3: Recent historic observations of storm surge within Galveston Bay (Jonkman, van Ledden, et al., 2013).

D.3. The Stakeholders

Stakeholder	Description	Role in Project	Engagement Strategy
Key Stakeholders			
USACE	Federal agency leading SSB initiative.	Project initiator and funding authority.	Direct collaboration & decision-making.
GLO	State agency supporting ecology resilience.	Co-funding and implementation partner.	Direct collaboration & decision-making.
GCPD	Regional agency leading SSB initiative.	Co-funding & oversees project strategy.	Direct collaboration & decision-making.
Primary Stakeholders			
Residents	Local communities vulnerable to flooding.	Primary beneficiaries of SSB initiative.	Public consultations & outreach programs.
Tourism & Fishers	Economic actors reliant on healthy ecosystems.	Support restoration efforts.	Targeted meetings & outreach programs.
Industry	Industries reliant on the Houston Ship Channel.	Advocate for minimal disruption from SSB.	Transparent communication & Public consultations.
Port of Houston Authority	Manages key economic and shipping activities.	Advocate for minimal disruption from SSB.	Transparent communication & Public consultations.
Engineering & Contractors	Teams delivering design, build & O&M.	Responsible for project delivery.	Contractual agreements & Public consultations.
Houston & Galveston Pilots	Navigational experts ensuring port navigation.	Advocate for minimal disruption from SSB.	Transparent communication & outreach programs.
FEMA	Federal emergency management agency.	Coordinates disaster preparedness and evacuation.	Continuous updates & policy alignment.
TDEM	State-level emergency management agency.	Supports disaster management efforts.	Continuous updates & policy alignment.
LEPCs	Regional emergency planning committees.	Coordinate local preparedness efforts.	Continuous updates & outreach programs.
Secondary Stakeholders			
EPA	Federal environmental regulatory agency.	Ensures compliance with regulations.	Regulatory reporting & policy alignment.
TCEQ	State-level environmental regulatory agency.	Ensures compliance with state regulations.	Regulatory reporting & policy alignment.
NOAA	Federal agency for environmental analysis.	Conducts flood risk analysis.	Outreach programs.
TPWD	Conservation-focused state agency.	Protects critical habitats.	Regulatory reporting & policy alignment.
NGOs	Engage communities & ecology stewardship.	Activistic role on the environment.	Continuous updates & outreach programs.
Academic Institutions	Academic research & contributing expertise.	Conduct research on SSB initiative.	Outreach programs.
Houston Port Bureau	Represents port industries.	Advocate for minimal disruption from SSB.	Continuous updates.
GCPRD	Regional conservation organization.	Promotes ecological sustainability.	Continuous updates.

Table D.4: Stakeholder overview Coastal Texas Study.

D.4. The Functionality of the System

Label	Function	Description	Stakeholders
Basic Functions			
F1.1	Flood Protection	Prevents storm surge from entering Galveston Bay, by gate closure, reducing flooding and protecting inland areas.	All stakeholders.
F1.2	Navigation	Facilitates maritime transit by accommodating large vessels, ensuring navigational safety, and minimizing disruptions to the Port of Houston and surrounding logistics.	Port of Houston Authority, Houston and Galveston Pilots, Tourism and Fishers & Industries.
F1.3	Water Exchange	Enables ecological and hydrodynamic processes, including tidal flow, sediment transport, fish migration, salt intrusion control, river discharge facilitation, and hydraulic pressure maintenance.	Residents, GLO & Tourism and Fishers.
F1.4	*Provide Road Connection*	*Serves as a transportation link for vehicles, enabling access across the barrier, supporting regional connectivity and logistics.*	*Residents, Industries, Port Authorities & Tourism.*
Supportive Functions			
F1.5	Managing Operations	Includes monitoring performance, controlling gate movements, adapting to environmental changes, and training teams to ensure operational readiness.	USACE, GCPD, FEMA, TDEM, LEPCs & Houston and Galveston Pilots.
F1.6	Maintaining Structural Integrity	Regular inspections, testing, and addressing challenges to ensure reliability and longevity. Involves fault tree analysis for risk assessment and adaptive strategies for evolving conditions.	USACE, GCPD, FEMA, TDEM, LEPCs & Houston and Galveston Pilots.
F1.7	Provide Monumental Value	Enhances cultural and aesthetic value by serving as a landmark or symbol for the region, fostering community pride and identity.	Residents, GLO & Tourism.

Table D.5: Overview of Bolivar Roads Gate System (i.e., SSBs in general) functions and related stakeholders.

D.5. The Physical Decomposition of the System

This appendix provides a physical decomposition of the Bolivar Roads Gate System, located across the entrance to the Houston Shipping Channel (HSC) between Bolivar Peninsula and Galveston Island. Refer to Figure D.4 for an overview of the current conceptual design of the Bolivar Roads Gate System (refer to Appendix D Coastal Texas Study Report (USACE, 2021b). The focus is placed on function fulfillers, which are objects responsible for executing the functions outlined in Appendix D.4. The System Breakdown Structure (SBS) ensures that all functions are allocated to corresponding design objects. This way identifies any missing function fulfillers, and provides an initial assessment of maintainability elements within the system's design. The objects are labeled with (Sx.x.x.x).

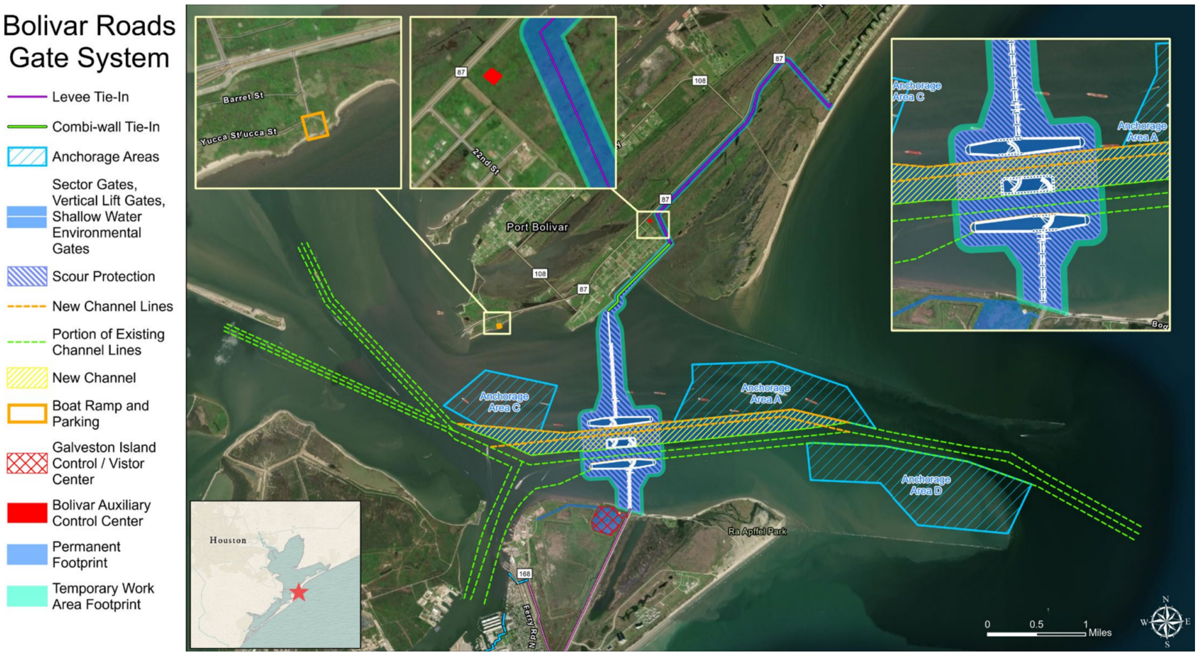


Figure D.4: Bolivar Road Gate System - overview (USACE, 2021a).

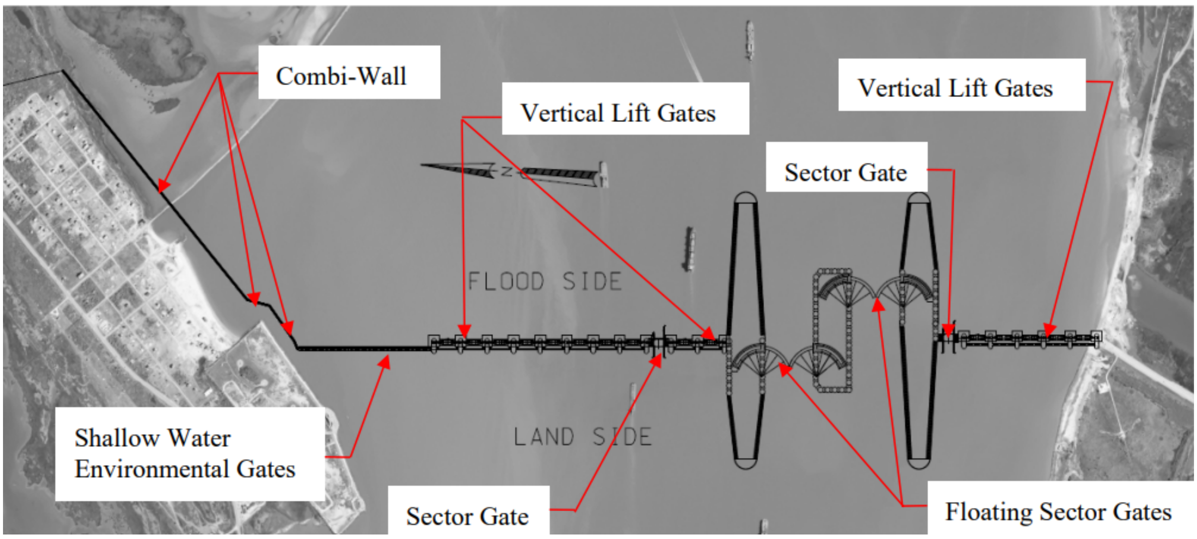


Figure D.5: Bolivar Road Crossing coastal storm reduction features (USACE, 2021d).

D.5.1. Physical Decomposition Current Conceptual Design (2021)

The physical decomposition focuses on the coastal storm reduction features of the Bolivar Roads crossing. This analysis is based on the current conceptual design published in the Coastal Texas Study Report and its accompanying appendices (USACE, 2021a), prepared by the USACE and GLO in 2021. This conceptual design is particularly well-suited for the system's physical decomposition due to its authoritative development by the project initiators, USACE and GLO.

The Bolivar Roads crossing includes the following key features: the Tie-in Levee Section, the Combi-Wall Section, the Shallow Water Environmental Gates (SWEG), the Vertical Lift Gates (VLG), and the Navigable Sector Gates. Refer to Figure D.5 for an illustration of these components. Each feature will be discussed in detail below.

Within the outlined physical decomposition, the functions from the Functional Breakdown Structure (FBS) (refer to Appendix D.4) will be matched to their corresponding physical components, or "function fulfillers". This mapping links the system's functional requirements to its physical design, ensuring all functions are effectively addressed.

Tie-in Levee Section (S1.1)

This section begins at the Bolivar Peninsula, connecting to the proposed beach and dune system at the terminus of Biscayne Beach Road (see Figure D.4). It consists of an *earthen levee (S1.1.1)* extending for 4.8 kilometers (3 miles) and serves as a critical flood protection component of the Bolivar Roads Gate System. Refer to Figure D.6 for a cross-section of the levee. The levee is designed to *retain extreme water levels (F1.1.2)*, reaching an elevation of 4.3 meters (14.0 ft.) above NAVD88, with a gradual transition to 6.4 meters (21.0 ft.) above NAVD88 near the combi-wall section. *Stone protection (S1.1.1.2)* is installed on the Gulf-facing side of the levee to *dampen wave impact (F1.1.1)* and protect the structure against erosion. The remaining portions of the levee are covered with *turf (S1.1.1.3)* to further reduce erosion, particularly along the *inland shoreline (F1.1.3)*.

This section functions as a barrier to block storm surge and protect inland areas from flooding, thereby providing critical *flood protection (F1.1)*. Its design ensures structural integrity through the use of durable materials, including stone and turf, minimizing the *frequency of maintenance (F1.6.3)*. The levee also contributes to the long-term stability of the shoreline by reducing erosion caused by storm surge and wave action.

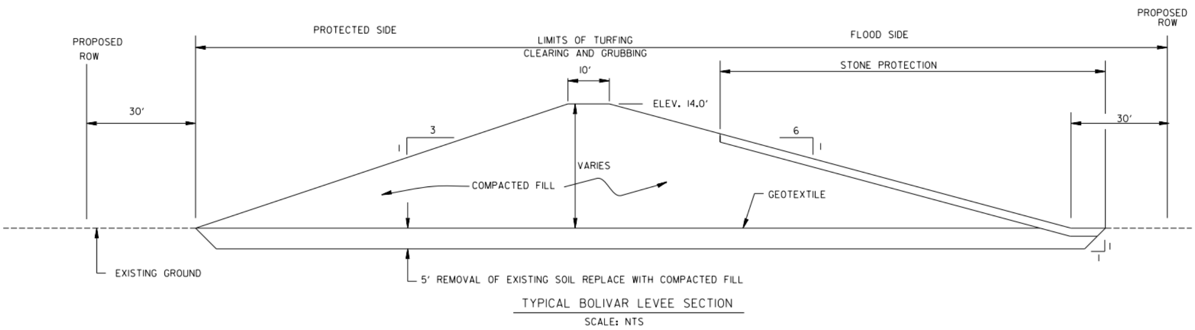


Figure D.6: Bolivar Road Crossing Tie-in levee cross section (USACE, 2021a).

Combi-wall Section (S1.2)

The barrier extends southwest as a *combi-wall (S1.2)* for 1.6 kilometers (5,300 ft.) to the gate system across Bolivar Roads (see Figures D.4, D.5, and D.7a). The system comprises vertically driven hollow *concrete spun-cast piles (S1.2.1.1)* with a diameter of 1.6 meters ∅ (66-inch) and 0.5 meter ∅ (18-inch) *closure piles (S1.2.1.2)*. Lateral resistance is provided by 1 meter ∅ (36-inch) *steel batter piles (S1.2.1.3)*, integrated with *concrete deck sections (S1.2.2.1)* and a *small parapet wall (S1.2.2.2)*.

The combi-wall is vital for *flood protection (F1.1)*, blocking storm surge and *extreme water levels (F1.1.2)* with reliable, solid construction that requires no mechanical components. *Bed protection blankets (S.1.2.1.3)* on both sides reduce erosion, safeguarding the structure and adjacent shorelines. Its concrete deck sections provide an access roadway for *maintenance activities (F1.6)* and a *transportation route (F1.6.5.2)*. Designed for durability, the combi-wall *minimizes maintenance frequency (F1.6.5.3)* and *simplifies maintenance tasks (F1.6.5.4)*.

The combi-wall design has been informed by similar structures such as the Lake Borgne Barrier in the New Orleans Hurricane Storm Damage Risk Reduction System (see Figure D.7b). This comparable structure has successfully demonstrated reliability and performance during multiple storm events.

(a) Conceptual rendering of the combi-wall section (USACE, 2021d).

(b) IHNC Lake Borgne combi-wall (Chatterjee, 2025).

Figure D.7: Combi-wall section Bolivar Roads Gate System.

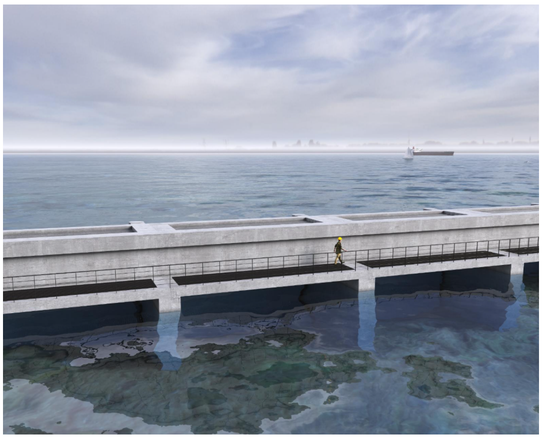
Shallow Water Environmental Gates (SWEG) (S1.3)

This gate system spans 3.4 kilometers (2.1 miles) across Bolivar Roads, starting at the combi-wall and including 16 *SWEGs (S1.3)* (see Figures D.5 and D.8a). Each *sluice gate (S1.3.2.1)*, with a *sill (S1.3.1.2)* elevation of -1.5 meters (-5.0 ft.) (NAVD88), measures 5 meters (16 ft.) by 5 meters (16 ft.), made of automated stainless steel, and housed in *concrete lifting towers (S1.3.1.1)*. Stored above the water level when not in use, the gates are protected from corrosion and debris. Lateral loads transfer to *supporting piers (S1.3.1.3)* resting on *large mat foundations (S1.3.2.1)* supported by 0.6 meter ∅ (24-inch) *pipe piles (S1.3.1.4.1)*.

The SWEGs are vital for maintaining *hydrodynamic and ecological balance (F1.3)* while providing *flood protection (F1.1)*. They enable controlled *tidal flow (F1.3.1)* between the Gulf and Bay, supporting *sediment transport (F1.3.4)*, *fish migration (F1.3.2)*, and controlling *salt intrusion (F1.3.3)* to preserve salinity balance. Positioned in shallow areas, the gates optimize these functions and sustain natural equilibrium. During storms, they close to block surges and prevent flooding. *Bed protection blankets (S1.3.1.5)* reduce erosion from water flow and *wave action (F1.1.1)*, while the design dampens wave energy and maintains the *hydraulic pressure balance (F1.3.6)*.

The gates use *hydraulic or actuated systems (S1.3.2.2)* for reliable operation, with a local manual override systemallowing closure via a portable actuator in case of remote failure. An *access road (S1.2.4.1)* on the Bay side, made of stainless steel industrial grating, enhances *system accessibility (F1.6.5.3)* while allowing sunlight to support *marine life sustainability (F1.3.2)*. The design simplifies maintenance tasks and enables efficient *inspections and repairs (F1.6)*.

The sluice gate system is modeled after the Davis Pond and Caernarvon Freshwater Diversion Structures, part of the Mississippi River and Tributaries system in New Orleans (see Figure D.8b). This structure have been successfully operated for decades to manage freshwater flow. These proven designs provide a reliable framework for the SWEGs.


(a) Conceptual rendering of the SWEG section (USACE, 2021d).


(b) Davies Pond Freshwater Diversion (USACE, 2025).

Figure D.8: Shallow Water Environmental Gates (SWEG) section Bolivar Roads Gate System.

Vertical Lift Gates (VLG) (S1.4)
The channel crossing features *VLGs (S1.4)* for intermediate and deeper sections of the Bolivar Roads crossing (see Figures D.5 and D.9a). Located on both Bolivar Island and Galveston Island sides, these elliptical *lift gates (S1.3.2.1)* are suspended between oval *supporting towers (S1.3.1.1)* and operated by *hydraulic cylinders with long pistons (S1.3.2.2)* hinged to the towers, ensuring reliable movement.

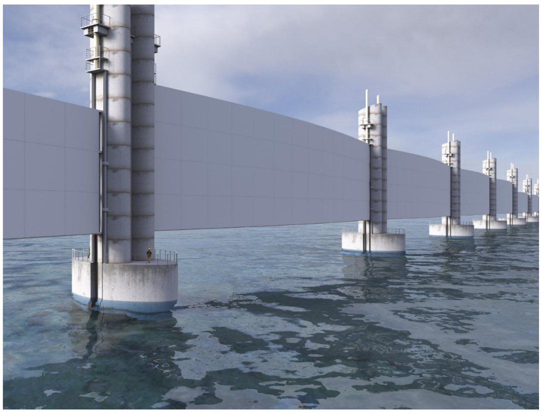
The VLGs provide a clear opening width of 91 meters (300 ft.) and have two distinct sill elevations to accommodate varying depths. The proposed configuration includes:

- Five VLGs with sill elevations at -6.1 meters (-20.0 ft.) (NAVD88) and three VLGs with sill elevations at -12.1 meters (-40.0 ft.) (NAVD88) on the east side of the first smaller vessel sector gate;
- Two VLGs at a sill elevation of -12.1 meters (-40.0 ft.) (NAVD88) between the first smaller vessel sector gate and the deep-draft navigation gates;
- Two VLGs at a sill elevation of -12.1 meters (-40.0 ft.) (NAVD88) and three VLGs with a sill elevation of -6.1 meters (-20.0 ft.) (NAVD88) on the west side of the deep-draft navigation gates, tying into the existing seawall at the San Jacinto Placement area on Galveston Island.

The feasibility-level design ensures that lateral loads are transferred to *supporting piers (S1.3.1.3)* founded on large *mat foundations (S1.3.1.5)* supported by 0.6 meter ∅ (24-inch) *pipe piles (S1.3.1.4.1)*. A *concrete sill (S1.3.1.2)* spans between the tower foundations at the gate invert, providing structural stability. To mitigate erosion, *bed protection blankets (S1.3.1.5)* will be installed on both the flood and land sides of the structure.

The VLGs enable significant *tidal flow (F1.3.1)* to support *sediment transport (F1.3.4)* and control *salt intrusion (F1.3.3)*, preserving channel stability and ecological systems. Stored in the raised position during normal conditions, the gates allow unimpeded *water exchange (F1.3)* while minimizing corrosion and debris risks. An *access bridge (S1.3.4.1)* with precast concrete girders spans the gate opening, providing roadway access for *maintenance (F1.6)* and *operations (F1.5)*, facilitating *inspections (F1.6.3)* and improving *system accessibility (F1.6.5.2)*. The VLGs feature a *battery-controlled, gravity-based automatic closure system (S1.3.3)* for reliable operation during *operating system failures (F1.5.2)*. After storms or malfunctions, the gates or machinery can be removed to a dry dock for repair during off-peak hurricane seasons, minimizing downtime and maintaining long-term structural integrity.

The VLGs proposed for the Bolivar Roads crossing are modeled after the Hartel Canal storm surge barrier in Spijkenisse, Netherlands (see Figure D.9b). Operational since 1996, the Hartel Canal gates have proven to be reliable, providing a precedent for effective design and long-term performance.



(a) Conceptual rendering of the VLG section (USACE, 2021d).

(b) Hartel barrier (Dijkstra, 2025).

Figure D.9: Vertical Lift Gates (VLG) section Bolivar Roads Gate System.

D.5.2. Maintainability Analysis

This appendix presents a qualitative maintainability assessment of the SBS. Maintainability is central to the research objective, as emphasized in the Literature Review (refer to Chapter 2). This analysis focuses on the *supportive functions* of the FBS, covering operations and maintenance tasks related to the SBS. It evaluates maintenance and maintainability of the Bolivar Roads Gate System, considering both physical and organizational factors, but excluding cost. The four main component types: fixed structures, movable parts, electrical installations, and supportive infrastructure, identified in the SBS and FBS, are subject to distinct deterioration mechanisms. For instance, concrete degrades differently than steel components or drive systems, with ageing and deterioration varying by component and affecting functionality and maintenance needs. These mechanisms and their impacts are summarized for the Floating Sector Gates in Table D.6.

Tie-in Levee Section (S1.1)

Before construction, *tests* must confirm the effectiveness of stone and turf protection, slope stability, and hydraulic integrity to ensure the levee can retain extreme water levels. While robust, *future upgrades* may address rising sea levels and stronger storms by adjusting elevations (4.3–6.4 meters NAVD88) or reinforcing stone protection with advanced materials. *Repairs* will focus on dislodged stones, turf erosion, and compacted fill stabilization to prevent settlement.

Regular *inspections* are essential for early detection. Stone protection should be checked post-storm, turf monitored for vegetation health, and subsurface layers inspected for settlement or cracks. *Servicing* tasks, including vegetation management, drainage maintenance, and stone repositioning, are critical for functionality but may strain resources during storm seasons. The levee's *interchangeability* is limited for natural materials like turf and compacted fill, though stone protection is modular. Its open design aids surface maintenance but requires excavation for subsurface issues, increasing costs. Durable materials reduce *maintenance frequency* but extreme storms may necessitate repairs or replenishment near transitions (e.g., combi-wall).

The design emphasizes *simplicity* and uses few materials with clear maintenance needs. *Visibility* is high for surface components, enabling quick damage identification but subsurface layers demand invasive, costly inspections. While leveraging traditional methods, the design lacks *innovation* such as smart monitoring systems, which could enhance fault detection and reduce maintenance.

Combi-wall Section (S1.2)

The *combi-wall* design minimizes *upgrades* due to its robust, static structure and durable materials like concrete and steel. While bed protection blankets may need enhancement to address scour, increasing the wall's height to counter rising water levels is difficult due to its non-modular design. *Repairs* focus on treating corrosion on steel batter piles and fixing cracks in the deck and parapet wall. Routine *tests* such as load assessments and erosion evaluations, ensure reliability.

Regular *inspections* target cracks, corrosion, and storm damage, though underwater components require specialized tools. Routine *servicing* including debris removal, anti-corrosion coating reapplication, and bed protection replenishment, is simplified by an integrated access roadway. The design integrates concrete spun-cast piles and steel batter piles, limiting *interchangeability*. Above-water components are accessible but submerged elements require divers, increasing costs. Durable materials reduce *maintenance frequency* but saltwater accelerates corrosion in steel, and storms necessitate periodic replenishment of bed protection blankets.

Above-water elements offer high *visibility* for inspections but submerged components are harder to monitor, raising risks of undetected issues. Although based on the proven Lake Borgne Storm Surge Barrier, the design has limited *testability* and lacks *innovation*, such as self-healing concrete or advanced corrosion-resistant alloys, which could improve maintainability.

Shallow Water Environmental Gates (SWEG)s (S1.3)
The SWEGs design minimizes *upgrades* with corrosion-resistant stainless steel gates and durable materials. Future improvements may include heightening structures or upgrading hydraulic controls for reliability. *Repairs* focus on hydraulic systems, actuators, and seal replacements, while concrete towers and foundations may require localized fixes for settlement and cracking.

Regular tests, such as gate closure, hydraulic system checks, and manual override tests, ensure reliability. Above-water *inspections* are simplified by storing gates out of water, while submerged components, like mat foundations, need specialized underwater inspections. Post-storm assessments address erosion and structural damage. Routine *servicing* includes cleaning, oil changes, and replenishing bed protection blankets to control erosion. The stainless steel grating access road aids maintenance but limits resilience due to its single roadway design. The system offers *moderate interchangeability* with standardized gates and hydraulic components, but static concrete towers and foundations are less flexible. Submerged elements require specialized equipment, increasing maintenance complexity. Corrosion-resistant materials reduce *maintenance frequency*, but movable parts and erosion-prone blankets require regular attention.

Above-water components provide good *visibility* for inspections, while submerged parts are harder to monitor, raising risks of undetected issues. The design incorporates *testability* with regular operational tests but lacks *innovation*, such as smart sensors, which could enhance efficiency and reduce maintenance demands.

Vertical Lift Gates (VLG)s (S1.4)
The VLGs are designed for reliability, minimizing the need for immediate *upgrades*. Hydraulic systems and battery-controlled closures ensure operation under extreme conditions, with potential future enhancements like advanced corrosion-resistant coatings and actuators to improve efficiency. *Repairs* focus on hydraulic components, seal replacements, and structural fixes for gates, sills, and mat foundations, while bed protection blankets require attention after storms.

Routine *tests* such as functional and hydraulic system checks, ensure emergency readiness. *Inspections* are aided by the access bridge for above-water components, though submerged elements like foundations require specialized underwater evaluations. Post-storm inspections assess erosion and damage. Regular *servicing* includes cleaning gates, oil changes, seal replacements, and replenishing *bed protection blankets*. Dry dock access simplifies major servicing but remains labor-intensive.

The design supports high *interchangeability* for gates and hydraulic systems, which can be repaired in dry docks, but static lifting towers and submerged components are less flexible. Corrosion-resistant materials minimize *maintenance frequency*, though movable parts and erosion-prone blankets require periodic servicing. Above-water components offer high *visibility*, while submerged elements are harder to monitor, increasing maintenance complexity. Limited *innovation* such as the absence of automated monitoring systems, restricts efficiency improvements.

Component	**Deterioration Mechanisms**	**Consequence**	**Maintenance Interval**
Dry-docks	Concrete deterioration	Removal of contaminated concrete. Application of new concrete cover.	25–35 years
Foundation	Settlements	Technical end of life, but structure is founded on piles.	No inspection or maintenance
Bed Protection	Erosion	Reinforced by dumping more stones or placing a slab of underwater concrete.	Yearly inspection, repair if necessary
Steel Gates	Corrosion	Local repair of coating.	15–20 years
		Coating renewal.	20–30 years
		Replacement.	100 years
	Fatigue	Maintenance (replacement).	No inspection or maintenance
	Ship Collision	Replacement.	–
Gate Drive Mechanism	Mechanical wear and fatigue	Restoration or replacement of parts.	15–20 years
		Coating renewal.	20 years
		Replacement.	50 years
Electrical Installations	General ageing and obsolescence	Replacement of electrical components.	15 years
		Replacement of hardware and software.	8 years

Table D.6: Floating Sector Gates estimated maintenance intervals (based on Vader et al., 2023, adjusted by S.D. van der Geer).

E

Research Phase 2

The Appendix presents the methodology and supplements for Phase 2. It begins by detailing the applied methodologies and techniques (Appendix E.1). This section also outlines the data collection approach and the methods employed for analysis. Following this, the Appendix supplements on the progression of the research methodology throughout Phase 2: physical drivers (Appendix E.2), and socio-economic drivers (Appendix E.3).

E.1. Methodology and Technique

The following paragraph outlines the methodology employed during Phase 2 of the research design. This phase builds upon the factors identified in the Literature Review (see Figure E.1, refer to Chapter 2), the functions and aspects defined for the SSB during Phase 1: Baseline Design, the primary failure modes described by Mooyaart et al. (2025), and the qualitative analysis framework proposed by Vader et al. (2023). Within this context, dominant system drivers are identified, and their influence on the functional performance of the SSB examined. This qualitative approach provided an understanding of all potentially relevant system drivers along with their respective impacts.

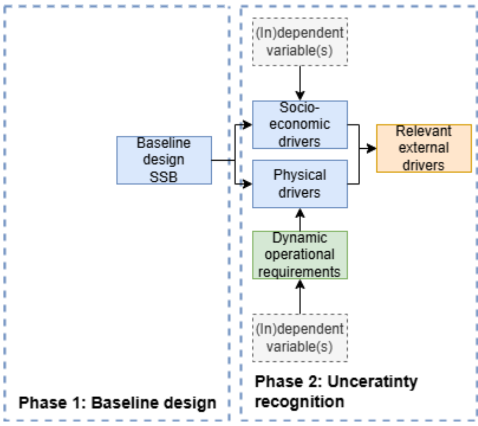


Figure E.1: Phase 2 literature review variable(s).

E.1.1. Variable(s) from the Literature Review

The variables identified during the Literature Review (refer to Chapter 2) formed the foundation of the analysis and was integral to understanding the system dynamics in the case study. These variables, categorized as independent or dependent, are incorporated into the ES analysis framework depicted in the figure. Refer to Appendix C for an extensive review of all the identified variable(s). Together with the findings of Phase 1: Baseline Design, this structured approach ensured that the variables were systematically evaluated to address the complexities within the system.

E.1.2. Data Collection Method

Phase 2 of the study leveraged qualitative archival data. The current conceptual design of the Bolivar Roads Gate System exists (USACE, 2021a), and were leveraged for identification of system drivers. Data on this conceptual design is publicly available from the Coastal Texas Project, engineering firm Arcadis, and the TU Delft Repository.

This data is readily available, and was used for feasibility studies of the preliminary design of the storm surge barrier, hence Table E.1. Tacit stakeholder knowledge was gathered via semi-structured interviews, which is further elaborated in Appendix G.

Data Source/Owner	Type of Source	Data Collection Objective
Coastal Texas Project	Final Feasibility Report(s)	Social-, Environmental-, Functional-, Process-, and Technical domain
	Appendices	
USACE & GLO	ArcGIS-map	Social-, Environmental-, Functional-, Process-, and Technical domain
Arcadis	Technical Reports	Functional-, Process-, and Technical domain
TU Delft Repository	MSc Thesis, Technical Report(s), Article(s)	Social-, Environmental-, Functional-, Process-, and Technical domain
Google (Scholar)	Grey Literature	Social-, Environmental-, Functional-, Process-, and Technical domain

Table E.1: Overview of data sources and collection objectives Phase 2.

E.1.3. Applied Method: Qualitative Assessment System Driver

In this analysis, the goal was not to predict precisely what will happen but rather to obtain reliable estimates of the distribution of possible outcomes, affecting the functional performance of the SSB. This encompasses the range of potential events and the relative likelihood of various scenarios. To estimate the distribution of future possibilities, the qualitative assessment method by Vader et al. (2023) was applied, and the principle failure modes of SSBs, as described by Mooyaart et al., 2025 were leveraged.

Categorization by Principle Failure Modes

According to Mooyaart et al. (2025), system drivers can result in three primary failure modes. To gain a deeper understanding of how system drivers influence the performance of SSBs, the failure categorization framework proposed by Mooyaart et al. (2025) is first introduced to systematically classify the effects of the external drivers on the functionality of the SSB. Consequently, the discussion begins with an outline of these failure modes, followed by a detailed classification of the potential impacts associated with external drivers.

Identify the Important/Dominant Drivers

The first step targeted the factors most critical to the future performance of the system. The analysis focused on the basic functions and the supportive functions Managing Operations (F1.5) and Maintaining Structural Integrity (F1.6) from the FBS. Given the potentially large number of variables, effective prioritization was essential to narrow them down to select a few that are critical for future performance. This prioritization demanded expertise and a comprehensive understanding of the system's broader operation including engineering, economic, and management perspectives, which are established, on conceptual level, in Phase 1: Baseline Design.

To further structure the analysis, system drivers were categorized into two main groups: physical drivers (e.g., environmental, natural hazards) and socio-economic drivers (e.g., economics, politics). Next, for each function of the SSB, the system drivers influencing its functional performance were examined. This qualitative approach aims to provide a comprehensive overview of all potentially relevant system drivers and their respective impacts. To identify main performance system drivers, the following four elements were considered:

- Type and Level of Aggregation;
  - Which elements influence functional system performance?
  - What is the optimal way to specify each type?
- Historical Trends;
  - How does the driver fluctuate over time (variability over time), and how does this uncertainty increase the value of flexibility?
- Forecast (in)accuracy
  - How will the driver fluctuate over time (variability over time), and how does this uncertainty increase the value of flexibility?
  - Develop appreciation for overall pattern.
- Criteria for usefulness;
  - Which of these variables are essential to include in the analysis?
- *Deliverable(s): reasoned list of important/dominant external drivers.*

This methodology allowed for the recognition and incorporation of significant uncertainties. By identifying the primary uncertainties after establishing the baseline design in Phase 1, the focus was directed toward the most critical uncertainties, refining and narrowing the uncertainty space.

Identify Trend-Breakers
Trend-breakers are events that disrupt the continuation of established trends, often challenging long-term forecasts and creating new conditions that the SSB must address (De Neufville and Scholtes, 2011). A analysis of the underlying causes of potential trend-breakers provided valuable insights into future scenarios based on defined assumptions.

To identify the most influential driver for Phase 3, an evaluation of four future scenarios for the Houston-Galveston Bay Region was conducted. Inspired by the Dutch Delta Scenario's (van der Brugge and de Winter, 2024), these scenarios explore varying socio-economic and environmental trajectories projected to 2050 and 2100, providing a long-term perspective on future conditions and guided flexible SSB design to integrate O&M needs.

Climate scenarios and socio-economic scenarios formed the basis of this evaluation, this information is already gathered in the first analysis step. The evaluation was done qualitative, based on information obtained from other studies. (Semi-)quantitative assessment were only required when qualitative judgments provide insufficient information for the evaluation. This process lead to the following steps:

- Anticipate trend-breakers through scenario analysis;
  - Identify possible sets of reasoned major developments that might affect the Floating Sector Gates at Bolivar Roads;
  - A general qualitative description of possible futures. A single concrete and plausible path that the system and its environment might take;
  - Mirroring the Dutch "Delta Scenarios";
- *Deliverable(s): 4 general (qualitative) possible future scenarios of the Galveston Bay area.*

Building on the functions of the SSB, the scenario analysis, and the projected changes in external drivers, an in-depth examination of these drivers and their potential impacts was conducted. This analysis aimed to identify the most relevant system driver(s) for further investigation. The findings contributed to the next stage of the research, Phase 3, where the identified driver(s) were leveraged to explore options for flexibility in design.

E.2. Physical Drivers

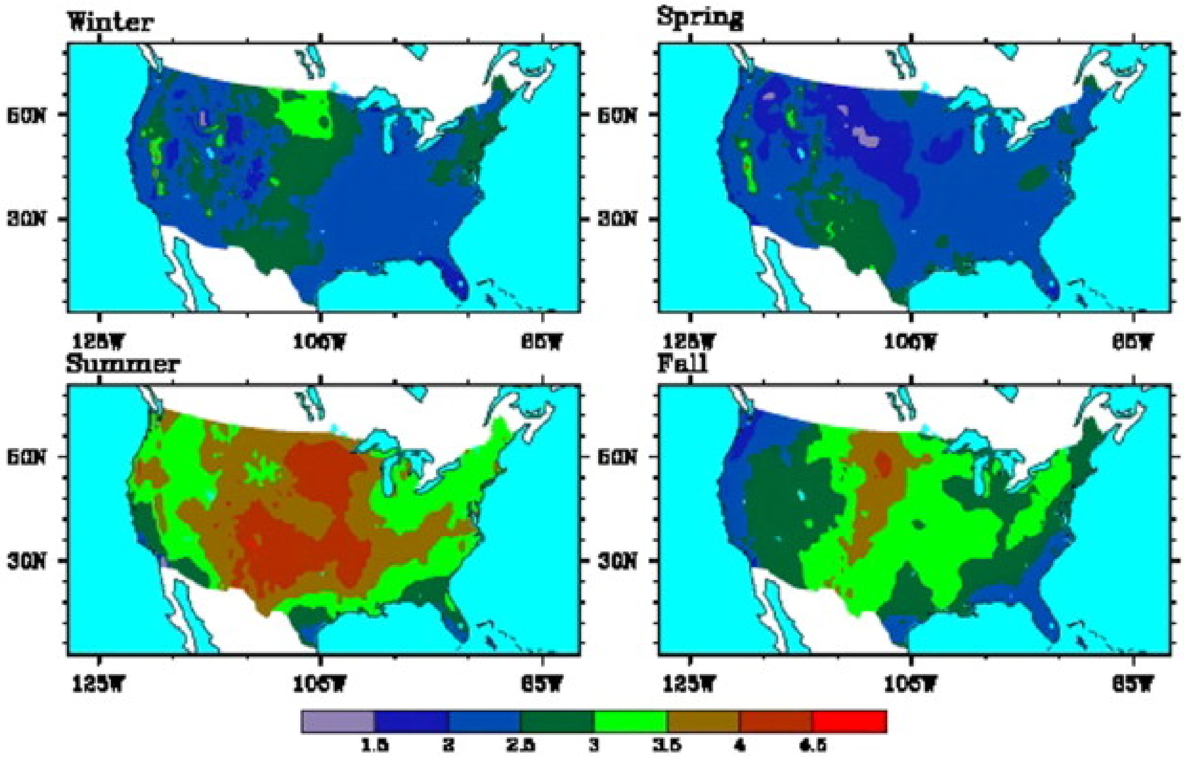


Figure E.2: Projected changes in seasonal maximum air temperature Texas-Gulf Region (Liu et al., 2013).

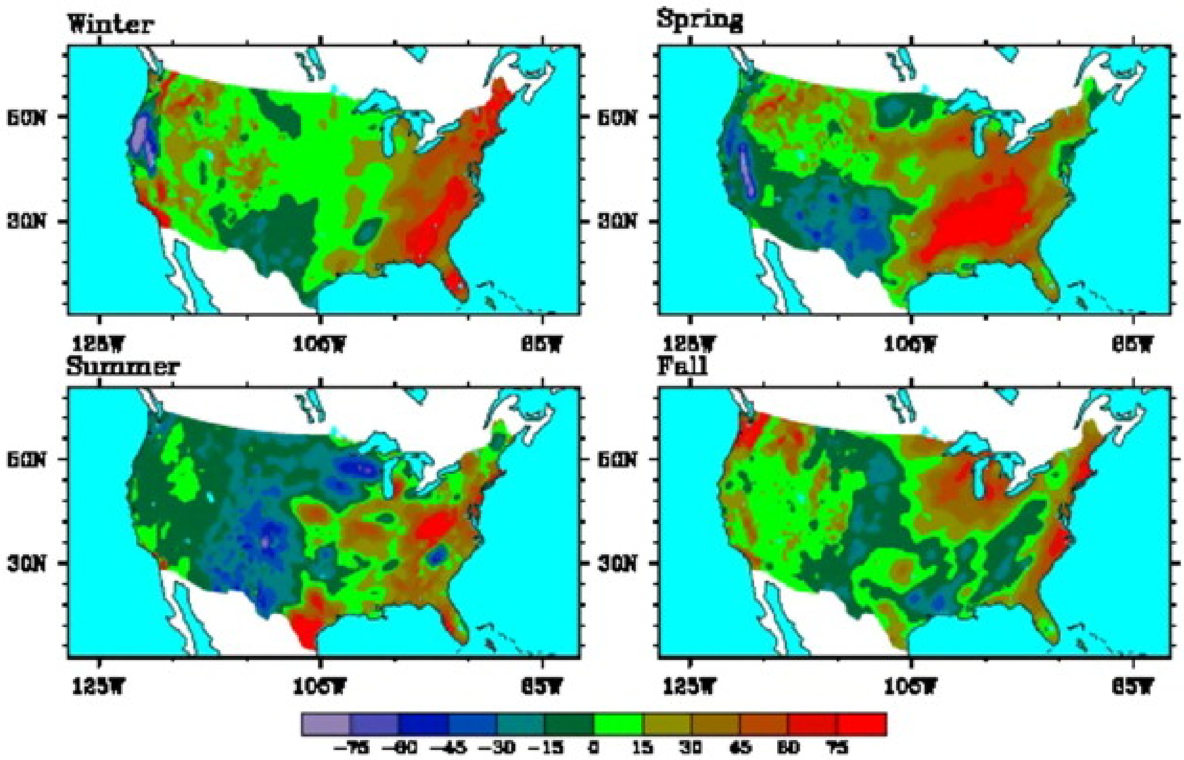


Figure E.3: Projected changes in seasonal precipitation Texas-Gulf Region (Liu et al., 2013).

Date	Name	Location	Speed (mph)	Wind Speed (mph)	Wind Speed (km/h)	Storm Type
9/16/1875	No name	Indianola	14	100	161	Category 2
8/12/1880	No name	Brownsville	10	150	241	Category 4
8/20/1886	No name	Indianola	11	150	241	Category 4
8/8/1900	No name	Galveston	13	140	225	Category 4
8/17/1915	No name	Galveston	16	135	217	Category 4
9/14/1919	No name	Corpus Christi	9	145	233	Category 4
8/13/1932	No name	Freeport S of	11	145	233	Category 4
6/26/1954	Alice	Brownsville S of	9	80	129	Category 1
9/5/1955	Gladys	Brownsville S of	15	150	241	Category 5
6/27/1957	Audrey	Sabine Pass	14	145	233	Category 4
7/25/1959	Debra	Galveston	3	80	129	Category 1
9/11/1961	Carla	Port Lavaca	5	165	266	Category 5
9/17/1963	Cindy	High Island	3	75	121	Category 2
9/20/1967	Beulah	Brownsville Corpus	11	160	257	Category 5
8/3/1970	Celia	Corpus Christi	14	125	201	Category 4
9/10/1971	Fern	Matagorda E of Sabine	6	75	121	Category 1
9/16/1971	Edith	Port Mansfield	19	100	161	Category 2
8/9/1980	Allen	Galveston	12	180	290	Category 5
8/18/1983	Alicia	Galveston	5	115	185	Category 3
6/26/1986	Bonnie	Beaumont S of	11	75	121	Category 1
9/17/1988	Gilbert	Brownsville	11	135	217	Category 4
10/14/1989	Chantal	High Island	11	85	137	Category 1
8/22/1999	Bret	Padre Island Port	9	145	233	Category 4
7/15/2003	Claudette	High Island	9	85	137	Category 1
9/24/2005	Rita	Sabine Pass	10	115	185	Category 4
9/13/2008	Humberto	High Island	10	110	177	Category 1
8/25/2017	Harvey	Rock Island	5	132	213	Category 2

Table E.2: Notable historic Texas Gulf coast storms (USACE, 2021d).

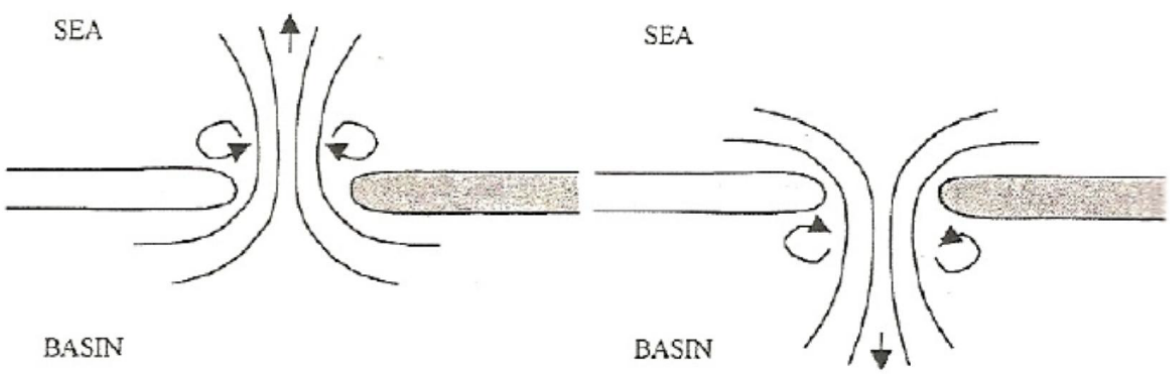


Figure E.4: Tidal-jet downstream of the barrier during ebb and flood blocks net sediment transport (Bosboom and Stive, 2023).

Situation	Cross-section (μA_s^*)	Tidal response in Galveston Bay
Current	28,000 m^2 Bolivar Roads: 22,000 m^2 Other: 6,000 m^2	90% of incoming tide (i.e., estimate made for this study)
40% closed	16,000 m^2 Bolivar Roads: 13,000 m^2 Other: 3,000 m^2	(Ruijs (2011): 80% of original) 72% of incoming tide
60% closed	12,000 m^2 Bolivar Roads: 9,000 m^2 Other: 3,000 m^2	(Ruijs (2011): 61% of original) 55% of incoming tide

Table E.3: Tidal response in Galveston Bay under different closure scenarios (Ruijs, 2011).

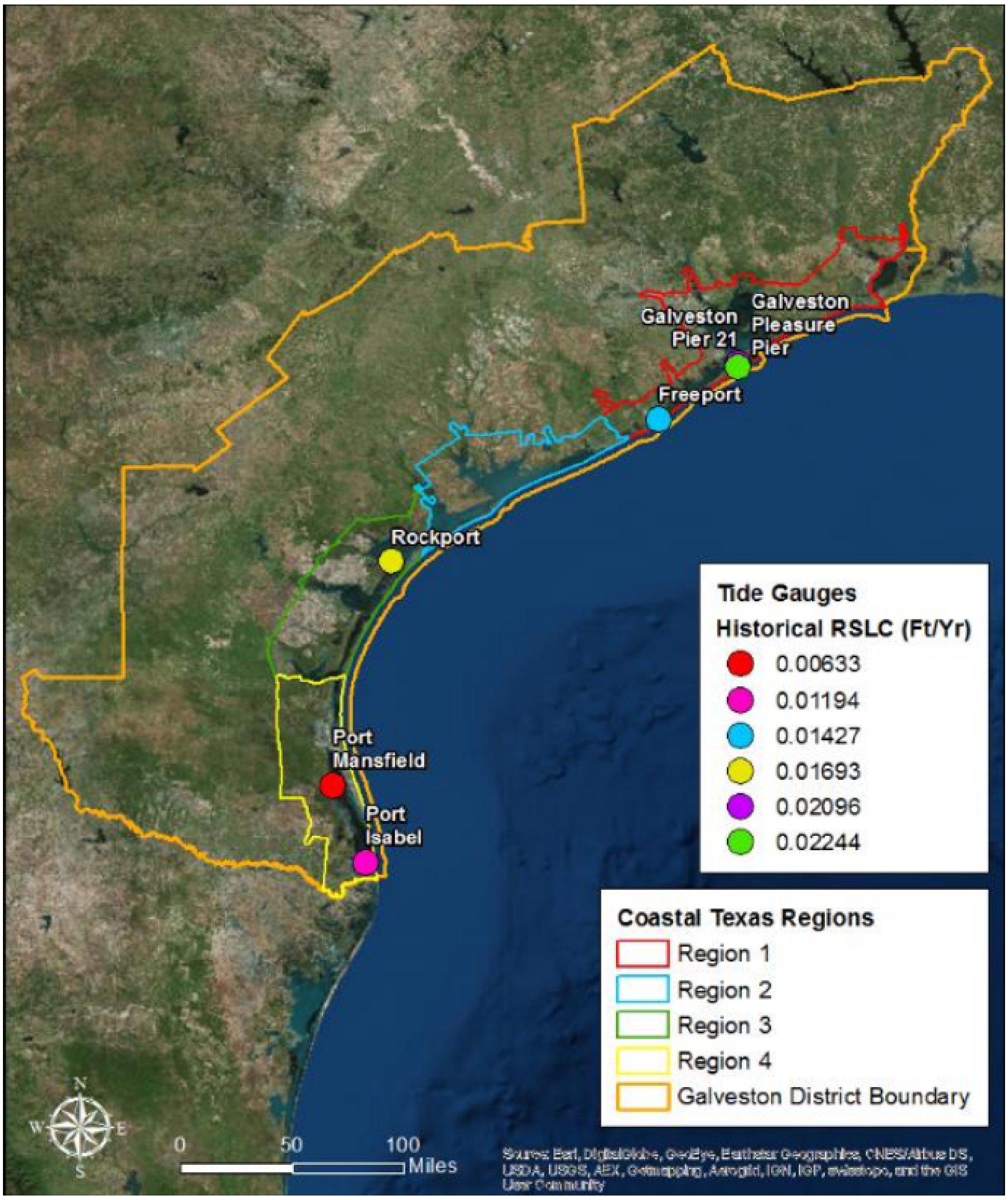
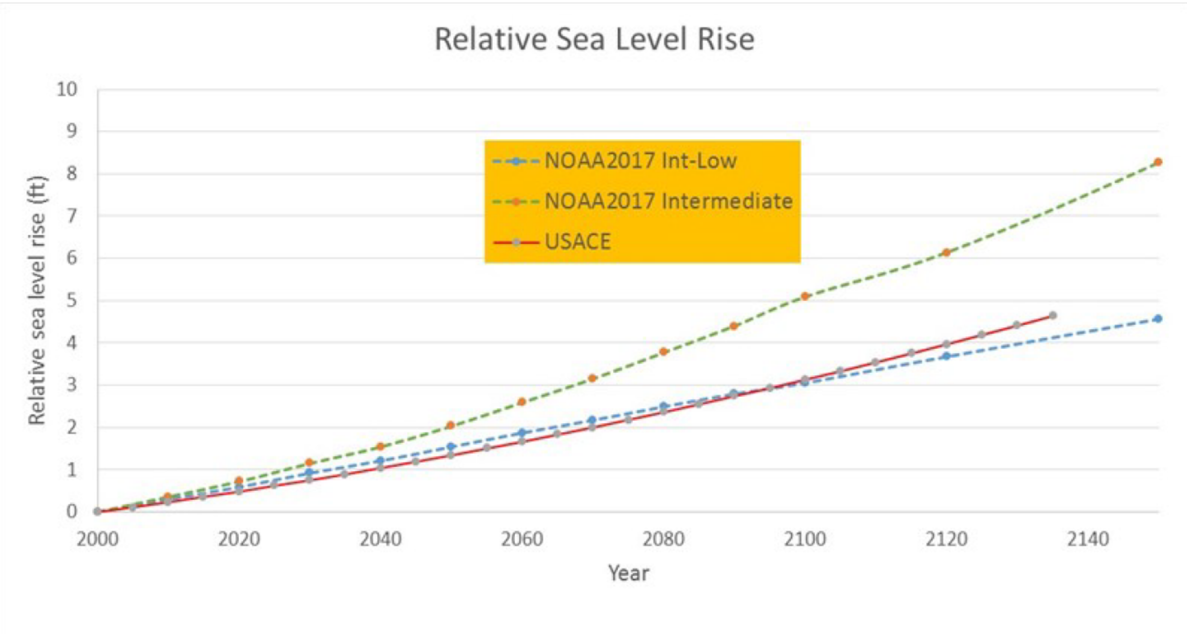


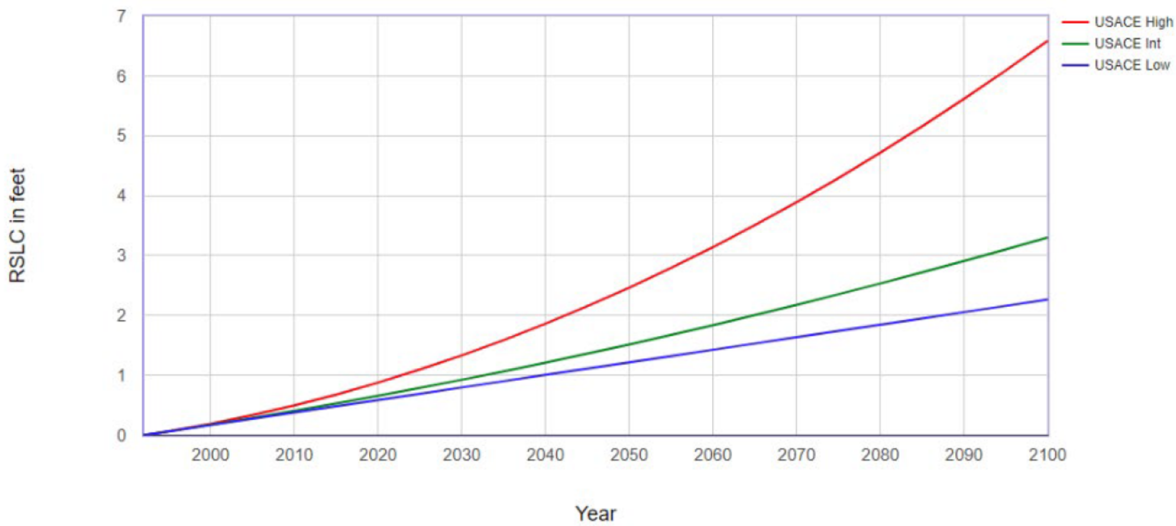
Figure E.5: NOAA tide gauge location map (USACE, 2021d).

Station	RSLC [ft./year]	Data [years]	Status	Datum
Galveston Pier 21	+0.02096	116	Active	Tidal/Geodetic
Galveston Pleasure Pier	+0.02244	63	Inactive	Tidal/Geodetic
Freeport	+0.01427	66	Inactive	Tidal
Rockport	+0.01693	83	Active	Tidal/Geodetic
Port Mansfield	+0.00633	58	Active	Tidal
Port Isabel	+0.01194	76	Active	Tidal/Geodetic

Table E.4: NOAA Tide Gauges at Texas Coast with more than 40 Years of Data (USACE, 2021d).



(a) Relative Sea Level Change (RSLC) at Galveston Pier 21 leveraging USACE and NOAA models.



(b) Relative Sea Level Change (RSLC) at Galveston Pier 21 leveraging USACE model.

Figure E.6: Projected RSLC Houston-Galveston Bay Region (USACE, 2021d).

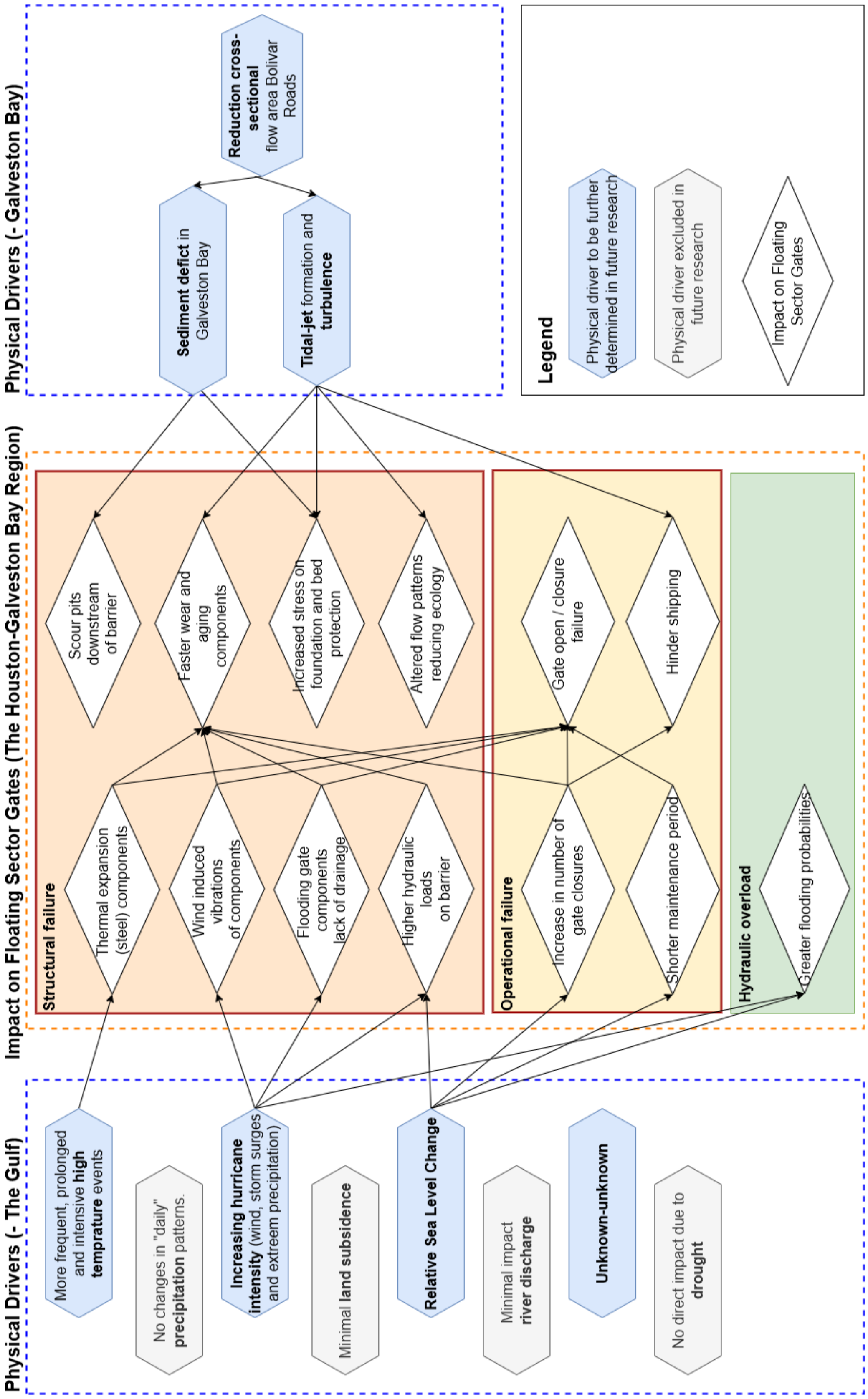


Figure E.7: Overview consequences physical drivers impacting Floating Sector Gates at Bolivar Roads.

E.3. Socio-Economic Drivers

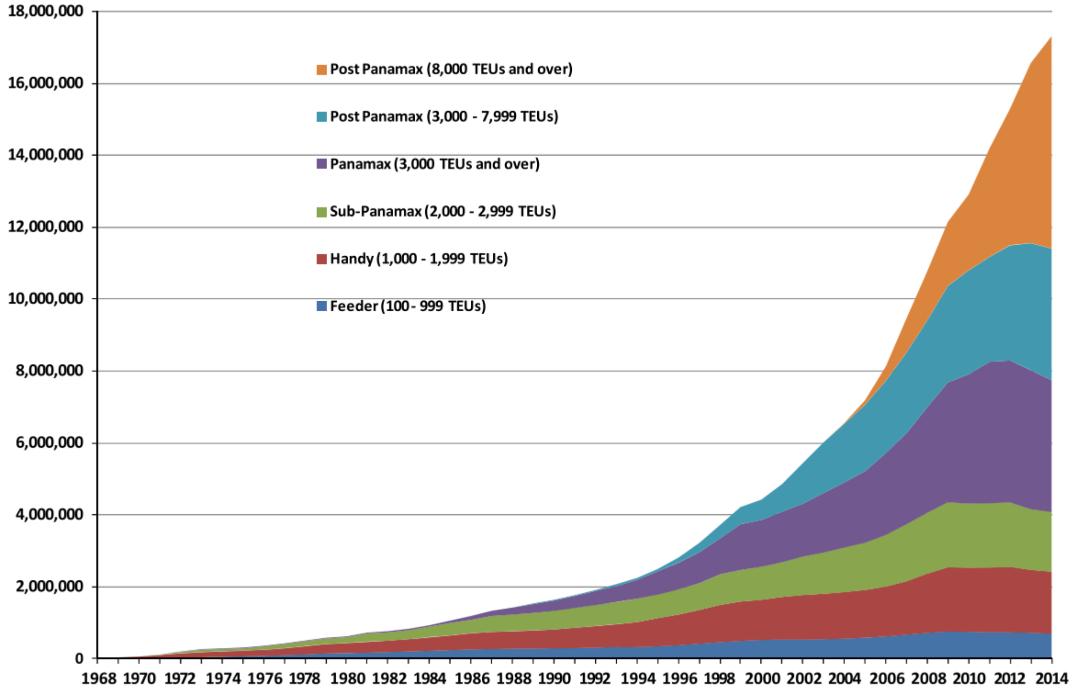


Figure E.8: Development of fully cellular container ship segments 1968–2014 (Tran and Haasis, 2015).

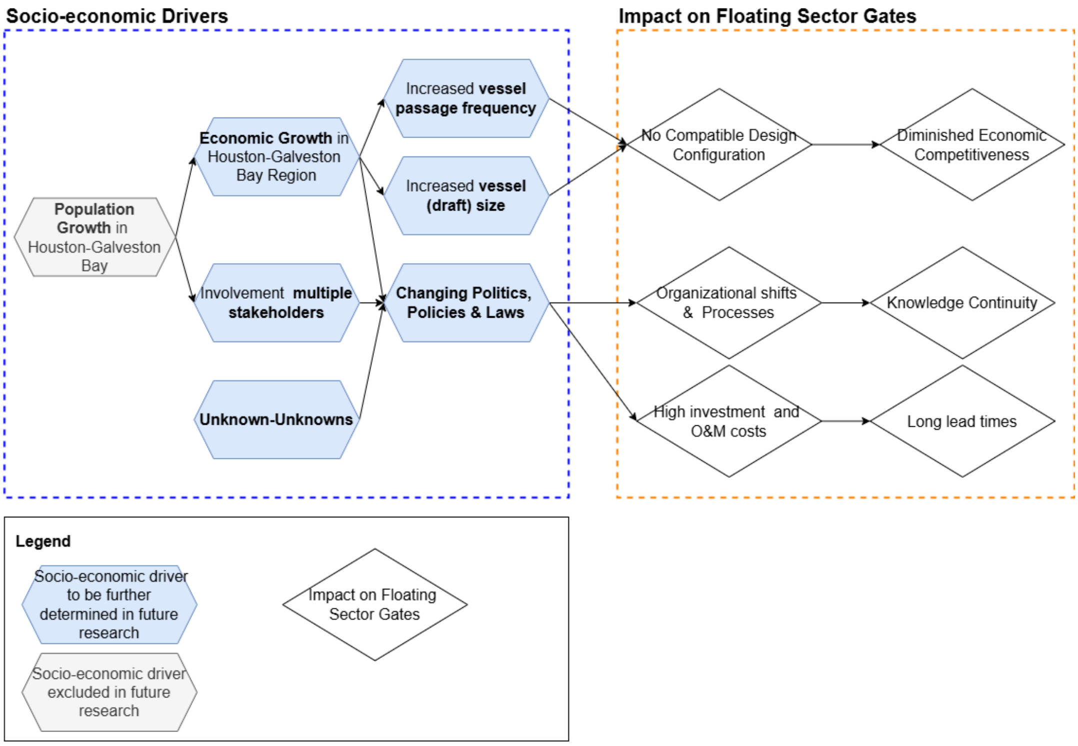


Figure E.9: Overview consequences socio-economic drivers impacting Floating Sector Gates at Bolivar Roads.

F. Research Phase 3

The Appendix presents the methodology and outcomes from Phase 3 of the research. It begins by detailing the applied methodologies and techniques (Appendix F.1), which build upon the factors identified during the Literature Review. This section also outlines the data collection approach and the methods employed for analysis. Following this, the Appendix elaborates on the supplements of the research methodology throughout Phase 3 (Appendices F.2. Finally, the Design Report of the Adaptable Sill (F.3).

F.1. Methodology and Technique

This section outlines the methodology for Phase 3, building on factors from Literature Review (see Figure F.1), the SSB components from Phase 1, and the dominant system drivers from Phase 2. To develop a conceptual flexible design, it integrates the Engineering System Matrix (ESM) methodology by Bartolomei et al. (2012), the flexible design identification method by Hu and Cardin (2015), and the hydraulic engineering design approach by Voorendt (2022). This way, the main uncertain system drivers and their interdependencies are analyzed to identify object enablers most susceptible to uncertainties, ensuring targeted flexibility implementation.

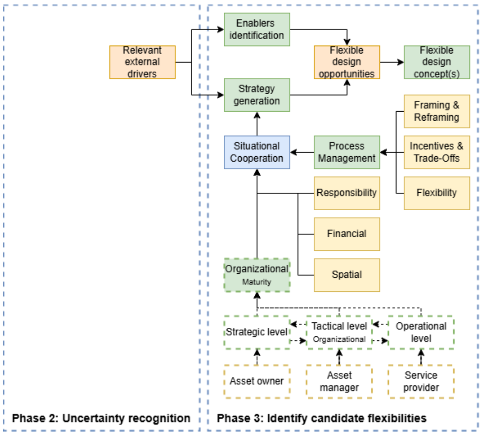


Figure F.1: Phase 3 literature review variable(s).

F.1.1. Variable(s) from the Literature Review

The variables identified in the Literature Review (refer to Chapter 2) complement the findings from Phase 1 (refer to Appendix D) and Phase 2 (refer to Appendix E). This structured approach enables a systematic evaluation of these variables, ensuring their interdependencies and sensitivities within the system are properly analyzed.

F.1.2. Data Collection Method

Phase 3 of this study primarily relied on expert and stakeholder knowledge, data on SSB construction costs, and qualitative archival data collected during Phases 1 and 2. Expert and stakeholder insights were obtained through semi-structured interviews, further detailed in Appendix G. The data collection methods used in Phases 1 and 2 are described in Appendices D.1.2 and E.1.2. The sources utilized for SSB construction cost data are listed below.

Data Source/Owner	Type of Source	Data Collection Objective
Coastal Texas Project	Final Feasibility Report(s)	Environmental-, Functional-,and Technical domain
	Appendices	
TU Delft Library	Academic papers	Functional-, Process-, and Technical domain
Arcadis	Technical Guidelines	Technical domain
Google (Scholar)	Grey Literature	Social-, Environmental-, Functional-, Process-, and Technical domain

Table F.1: Overview of data sources and collection objectives Phase 3.

F.1.3. Applied Method: Engineering System Matrix (ESM)

In Phase 2 the most influential uncertainty drivers were identified. Their possible interaction and impact on the Floating Sector Gates, the Engineering Systems (ES), will be characterized using the ESM methodology by Bartolomei et al. (2012). This approach analyzes the interdependencies with system elements across multiple domains: System Drivers, O&M Organization, Objective, Functions, and Objects. This study focuses specifically on the physical components (objects), to identify valuable system components for flexibility in this domain.

Dependency and Uncertainty Analysis

The ESM is used to model the Engineering Systems (ES), specifically the Floating Sector Gates at Bolivar Roads. It employs an adjacency matrix to represent direct dependencies between system elements across various domains (Bartolomei et al., 2012).

To enhance the ESM methodology of Bartolomei et al. (2012), the approach proposed by Hu and Cardin (2015) is incorporated. This approach accounts for the likelihood that a system element in the ESM will be impacted in response to the impact of an uncertain system driver. ESM not only models dependency relationships but also evaluates the degree of these dependencies occurring.

The strength of these relationships and dependencies is quantified using a dependency degree. This is defined as the likelihood that a system driver, when reaching its extreme condition, will impact a system element in the ESM, such as an physical component.

Based on this methodology, the following steps are taken to construct the ESM matrix (see Figure F.2):

- Uncertain System Drivers Matrix: implement the list and interactions of exogenous factors that act or acted on by the system. This comprehends the dominant uncertain system drivers as identified in Phase 2;
- Operations & Maintenance (O&M) Organization (Stakeholder) Matrix: implement the list and interactions of the O&M Organization (Stakeholder) entities within the system. This includes the main entities involved in the O&M, as extracted from the Baseline Design, Phase 1;
- Objective Matrix: implement the objective and operational goal of the system. This includes the main objective/task as extracted from the Baseline Design, Phase 1;
- Functions Matrix: implement the list of interactions of functions of the system. This includes the recognized basic- and supportive function of the system as extracted from the Functional Breakdown Structure (FBS), Phase 1;
- Objects Matrix: implement the list and interactions of the physical components of the system. This includes the main objects of the system as extracted from the System Breakdown Structure (SBS), Phase 1.

- Cross-Domain Interactions:
  - Within the ESM, relationships and dependency strengths with the uncertain system drivers are quantified using dependency degrees. These probabilities represent the likelihood that a change in an uncertain system driver will trigger a corresponding impact on a system element. The data used for this analysis is obtained from semi-structured interviews with experts and stakeholders (refer to Appendix G). The analysis of the interview data applied thematic analysis to the interview transcripts. Systematically categorizing and relating emergent themes, in order to reveal cross-domain interactions between physical barrier components, and the most principal socio-economic and physical drivers.
  - During these expert and stakeholder interviews, dependencies are classified into four categories: none, weak, moderate, or strong. Higher values indicate stronger relationships. Additionally, cross-domain interactions are identified, with particular emphasis on the Object domain to identify valuable system components for flexibility.
- *Deliverable(s): reasoned ESM matrix.*

ESM				System Drivers		O&M Organization			Objec-tive	Functions					Objects									
															Fixed				Movable			Elect.	Secondary	
				S1	S2	O&M 1	O&M 2	O&M 3	O1	F1	F2	F3	F4	F5	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
System Drivers		S1	Economic Growth (Increase in Vess																					
		S2	Relative Sea Level Change (RSLC)																					
O&M Organization		O&M 1	Asset Owner																					
		O&M 2	Asset Manager																					
		O&M 3	Service Provider																					
Objective		O1	Block Storm Surge Entry																					
Functions		F1	Flood Protection																					
		F2	Facilitate Navigation																					
		F3	Water Exchange																					
		F4	Managing Operations																					
		F5	Maintaining Structural Integrity																					
Objects	Fixed	S1	Artifical Islands (Cofferdam)																					
		S2	Dry Docks for Gate Housing																					
		S3	Sill & Mat Foundation																					
		S4	Bed Protection Blankets																					
	Movable	S5	Steel Deep-Draft Gates																					
		S6	Gate Drive Mechanism																					
		S7	Ball-Joints (Hinges)																					
	Electric	S8	Operational Control Systems																					
	Secon-dary	S9	Aids to Navigation																					
		S10	Anchorage Areas																					

Figure F.2: The Engineering System Matrix (ESM) of the Floating Sector Gates at Bolivar Roads.

F.1.4. Applied Method: Flexible Design Opportunity Identification

This analysis aims to evaluate the risk susceptibility of each system element and identify appropriate flexible design opportunities. It integrates the flexible design opportunity identification method proposed by Hu and Cardin (2015), see Figure F.3, combined with the above described ESM method.

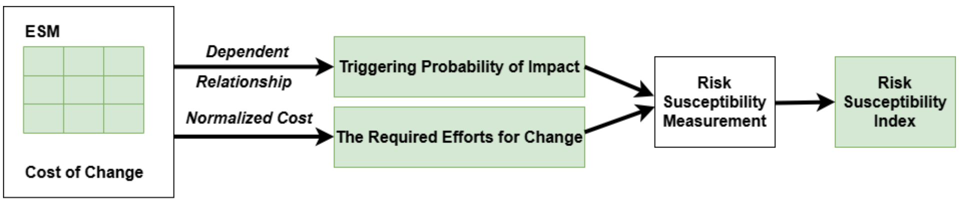


Figure F.3: Procedure for flexible design opportunities identification by Hu and Cardin (2015).

The primary inputs for this analysis comprise two key risk susceptibility measures: (1) the ESM, which encompasses dependency degrees of system drivers, and (2) the cost of modifying system elements in the future without having designed for flexibility. The ESM characterizes how different system drivers affect various system elements and quantifies their probability of occurrence. Meanwhile, the cost of change represents the future effort required to modify or upgrade an element when no flexibility has been integrated into the initial design.

By incorporating these two measures, it becomes possible to evaluate every component's vulnerability. Calculating the Risk Susceptibility Index makes it clear which elements call for flexible design strategies. In essence, those with both a high dependency degrees and a high cost of change will exhibit the greatest risk susceptibility and should be prioritized for flexibility. Below the Normalized Cost of Change and Risk Susceptibility will be further defined in detail.

Normalized Costs of Change
In the subsequent risk assessment, normalized costs are utilized, considering the cost share of each system element in the total construction cost. The cost of change can be assumed to be 80% of the initial construction cost of each element, as stated by Hu and Cardin (2015). To normalize the cost of change C_i relative to its share in the total construction cost, the normalized cost C_i^{norm} is defined as:

$$C_i^{\text{norm}} = \frac{C_i}{C_{\text{total}}} \tag{F.1}$$

where:

- C_i represents the actual cost for element i;
- C_{total} is the total construction cost;
- C_i^{norm} is the normalized cost, constrained within the range $[0, 1]$.

Normalization is a crucial step in the analysis, as it ensures that the relative cost of each system element accurately reflects its share in the total construction cost. This allows for a fair comparison between components of varying sizes and functions. According to Hu and Cardin (2015), if flexibility is incorporated into the design from the start, the cost of exercising this flexibility later in the asset's life-cycle is estimated to be 70% of the otherwise full cost of change. This reduction is attributed to the fact that a flexible design facilitates easier and less resource-intensive modifications in the future.

Implementing flexibility requires an up-front investment. Specifically, an additional 10% of the initial construction cost must be allocated at the start of the project to enable this future adaptability (Hu and Cardin, 2015). While flexibility can reduce long-term costs, it also requires thoughtful financial planning and early-stage design decisions.

- *Deliverable(s): normalized cost of change for each system element, based on cost share in total construction cost.*

Risk Susceptibility Prediction
Risk susceptibility is assessed using the triggering probability in coincidence with the normalized cost of change. The risk received by each system element when a change is triggered by an uncertain system driver is measured. This received risk, denoted as $R_{s_i}^{\text{Received}}$, is computed as:

$$R_{s_i}^{\text{Received}} = P_{s_i}\Big|_{\forall u_j \in U} C_{s_i} \tag{F.2}$$

where:

- s_i represents the ith system element;
- U is the set of uncertain system drivers;
- u_j is an uncertain system driver within U;
- C_{s_i} is the normalized cost of change for system element s_i;
- $P_{s_i}\Big|_{\forall u_j \in U}$ represents the probability that system element s_i will undergo change due to all uncertain system drivers.

$R_{s_i}^{\text{Received}}$ quantifies the degree of risk experienced by system element s_i as a result of cascading impacts from uncertain system drivers. This measure is further defined as the RSI_{s_i}, expressed as:

$$RSI_{s_i} = R_{s_i}^{\text{Received}} \tag{F.3}$$

It is advisable to incorporate flexible design solutions for system elements exhibiting high RSI_{s_i} early in the design phase. Doing so can mitigate future costs associated with changes and enhance system adaptability. This analysis thus prioritizes identifying system components where design flexibility provides the greatest value.

- *Deliverable(s):* RSI_{s_i} *of each system element under uncertain system driver(s).*

F.1.5. Applied Method: Hydraulic Engineering Design Method

This analysis explores the feasibility of integrating built-in flexibility into a system element by developing a conceptual representation that meets specified requirements and boundary conditions, without detailing a final design. The hydraulic engineering design method by Voorendt (2022) is partially applied, following a System Engineering approach.

The fundamental principles of the engineering method, applied to develop the conceptual flexible design, follow the initial three steps of the basic engineering design-cycle:

- Problem Analysis (covered in Phase 1: Baseline Design): identifying and analyzing the problem to establish a foundational understanding;
- Defining Project Objectives and System Functions (i.e., covered in Phase 1: Baseline Design): establishing the main project objective and specifying the primary functions of the intended system;
- Requirement and Boundary Condition Assessment: defining key requirements and compiling an inventory of relevant boundary conditions;
- Conceptual Transformation: translating functions into preliminary system or structural designs, starting with provisional shapes that, although initially abstract, are iteratively refined into feasible, evaluated solutions.

Design Phase 1: Problem Analysis
This phase focuses on analyzing the problem by identifying key stakeholders and conducting process and function analyses. Since these aspects have already been addressed in Phase 1: Baseline Design, they will not be re-examined in detail.

Design Phase 2: Defining the Basis of the Design
This phase involves defining the design objective, establishing a program of requirements, and identifying boundary conditions for the system element. The process consists of the following key steps:

- Design Objective: the primary design objective is established, ensuring that, alongside the main function, all critical sub-functions are considered. This is essential, as functional requirements are directly derived from the design objective.
- Requirements: the key functional requirements are determined based on the intended system functions outlined in the design objective. To maintain clarity, requirements can be categorized as follows:
  - Functional requirements: define the expected behavior or performance of the system element, either qualitatively or quantitatively, under specified conditions;
  - Structural requirements: ensure system integrity and operability, addressing aspects such as constructability, overall stability, dimensional stability, strength, maintainability, and adaptability;
- Boundary Conditions: these constraints define external factors affecting the system and can be categorized into:
  - Natural boundary conditions: constraints imposed by environmental factors;
  - Artificial boundary conditions: constraints related to existing infrastructure and engineering constraints;
  - Legal boundary conditions: regulations, policies, and legal frameworks affecting the design.

Design Phase 3: Concept Development, -Evaluation, -Selection
This phase focuses on generating design concepts by exploring possible shapes and techniques to address the identified problem. It is essential to align the concepts with the design objective to avoid developing solutions that lack critical subsystems. Structured approaches such as morphological charts can aid in systematically generating and evaluating alternative (partial) solutions. To facilitate concept development, the design process is divided into two key aspects:

- Spatial-Functional Design: concerned with fulfilling system functions:
  - Identifying a technical solution to achieve the primary functions of the system;
  - Determining the necessary components for the system or structure to perform its intended function;
  - Establishing the main dimensions required to fulfill the primary function, using engineering heuristics or by scaling reference structures;
- Structural Design: ensuring constructability and structural integrity, addressing essential factors such as constructability, overall stability, dimensional stability, strength, maintainability, and adaptability.

- *Deliverable(s): a well-reasoned, flexible, and adaptable conceptual design of the designated SSB element, with a general view on the construction process.*

F.1.6. Applied Method: Asset Management Strategy

In determining the optimal approach to implement the flexible design solution, this analysis considers the main characteristics of the asset management organization. Asset management functions are mapped at strategic, tactical, and operational levels.

Based on the strategic, tactical, operational model, a strategy is generated to implement the flexibility enablers, and complement with ongoing operational actions (i.e., monitoring the environment, maintaining the right to implement- and the knowledge to implement flexibilities).

F.2. Staat van Ontleding Aanbieding D.D. 16 oktober 1989 op Basis van Kontrakt DD 001

[S1] Artificial Islands	**[S2] Dry Docks**	**[S3] Sill & Mat Foundation**
Grondkering Aanpassen Kribben Verleggen Vaargeul	Parkeerdok	Drempel Baggeren
[S4] Bed Protection	**[S5] Deep-Draft Gates**	**[S6] Gate Mechanism**
Filter, Bodembescherming	Schermen Noord + Zuid Draagarmen Noord + Zuid Montage Noord + Zuid	Dokdeuren (vulsysteem)
[S7] Ball-Joints	**[S8] Control System**	
Bewegingswerken	Bedieningsgebouw Elkto Algemeen Energievoorziening Energiedistributie Besturingssysteem	

Table F.2: Maeslant Barrier's cost categories mapped to Floating Sector Gates (Bolivar Roads) object classes.

Civiel Droog	*Totaal Kosten [fl.]*	**Civiel Nat**	*Totaal Kosten [fl.]*	**Staal**	*Totaal Kosten [fl.]*
Scharnierfundatie Noord	24.000.000	Baggeren	5.000.000	Levering	52.000.000
Scharnierfundatie Zuid	18.000.000	Aanpassen Kribben	2.000.000	Schermen Noord	43.000.000
Filter, Bodembescherming	20.000.000	Verleggen Vaargeul	1.000.000	Draagarmen Noord	36.000.000
Grondkering Noord	20.000.000	Filter, Bodemberscherming	20.000.000	Montage Noord	11.000.000
Grondkering Zuid	18.000.000			Schermen Zuid	35.000.000
Drempel Betonblokken	11.000.000			Draagarmen Zuid	28.000.000
Drempel Plaatsen	4.000.000			Montage Zuid	10.000.000
Parkeerdok Noord	15.000.000			Laden + Transport	11.000.000
Parkeerdok Zuid	14.000.000				
Bedieningsgebouw Noord	7.000.000				
Bedieningsgebouw Zuid	5.000.000				
Terreinafwerking Waterleiding	2.000.000				
Terreinafwerking Noord	5.000.000				
Terreinafwerking Leidingstraat	6.000.000				
Terreinafwerking Zuid	4.000.000				
Totaal	153.000.000	**Totaal**	28.000.000	**Totaal**	226.000.000

Bewegingswerken	*Totaal Kosten [fl.]*	**Elektro**	*Totaal Kosten [fl.]*
Bewegingswerken	20.000.000	Algemeen	2.000.000
Dokderu (vulsysteem)	8.000.000	Energievoorziening	4.000.000
Filter, Bodembescherming	20.000.000	Energiedistributie	18.000.000
		Besturingssysteem	6.000.000
Totaal	28.000.000	**Totaal**	30.000.000

F.3. Design Report: Adaptable Sill at Floating Sector Gates

This Appendix outlines the Hydraulic Engineering Design Method adopted for the project. Beginning with the basis of design (Appendix F.3.1), solely stating the functional- and structural requirements, and selection of alternatives (Appendix F.3.2). Followed by the design verification (i.e., basic strucural calculations), of Alternative 1 (Appendix F.3.3), and Alternative 2 (Appendix F.3.4).

F.3.1. Defining the Basis of Design

Category	**Requirement**	**Description**
Functional Requirements		
Flood Protection	Design Horizon (2135)	The sill must withstand storm surges up to the design storm level, without allowing significant leakage.
	Protection Level	100-year return period.
	Closure Operation	The sill and gate system must enable rapid closure (within a specified timeframe, e.g., 4–8 hours Maeslant Barrier).
Water Exchange	Flow Regulation	Under normal tidal conditions, the sill should not restrict water exchange or create unacceptable flow velocities that affect the environment.
Facilitate Navigation	Minimum Channel Width (HSC)	The sill must accommodate current and future vessel drafts and widths with safe under-keel clearance.
	Design Vessel Container MGX-24	Being adaptable for future deepening or widening of the navigation channel (e.g., Project 11 & 12).
	Design Vessel Tanker Suezmax	Being adaptable for future deepening or widening of the navigation channel (e.g., Project 11 & 12).
	Minimal Disruption	Gate and sill operations (i.e., open/close) must minimize impact on shipping.
Managing Operations	Managing Operations	The sill supports multiple operational modes including normal operation, and storm surge mode.
	Remote Monitoring	The sill and gate interface must provide real-time status data (e.g., gate position, sill clearance, structural health sensors), to an operations control center.

Table F.3: Functional requirements for the adaptable Sill and gate system.

Evaluation Criteria	
Ease of Construction	Shortness of Construction Period
Durability	Maintainability: Interchangeability, Accessibility, Maintenance Frequency, Simplicity, Visibility, Testability, Innovation
Adaptability	

Table F.4: Overview of evaluation criteria adaptable sill design (i.e., application in Multi Criteria Analysis (MCA)).

Category	Requirement	Description
Structural Requirements		
Constructability	Soil and Foundation	The sill's mat foundation must be compatible with local soil conditions, ensuring feasible construction methods.
	Phased Construction	The structural design should allow phased construction so that part of the channel remains open during installation.
Overall Stability	Hydraulic Loads (static + waveload)	Water/resistance difference over the barrier (static) and waveload.
	(a) Closed Gate	Load case when the gates are completely closed.
	(b) Rejecting Gate	Gate is partly closed, and water flows through the opening.
	(c) Open Gate	Gates completely open.
	Horizontal Stability	The sill must resist buoyancy, overturning, and sliding under worst-case combined loads.
	Rotational Stability	The sill must resist buoyancy, overturning, and sliding under worst-case combined loads.
	Vertical Stability	The sill must resist buoyancy, overturning, and sliding under worst-case combined loads.
	Scour	The sill (foundation) must resist vortex formation, preventing undermining of the foundation.
Dimensional Stability	Settlements	The structure must be designed to limit settlement and deformation within tolerances.
	Piping	The sill must prevent the formation of pipes under the structure (internal backward erosion).
Structural Strength	Extreme Event Load Cases	The sill must withstand extreme loads such as vessel collision or debris impact.
	Fatigue and Wear	High-cycle loadings from frequent gate operations and ship passages to prevent fatigue cracking.

Table F.5: Structural requirements for the adaptable sill and gate system.

F.3.2. Selection of Alternatives - Multi Criteria Analysis (MCA)

Cat.		Alt. 1	Alt. 2	Alt. 3	Alt. 4
Ease of Construction		0	1	-1	-1
Shortness of Construction Period		1	0	-1	1
Durability		1	1	-1	-1
Maintainability		2	2	-3	-5
1	Interchangeability	-1	1	0	-1
2	Accessibility	0	0	-1	-1
3	Maintenance Frequency	1	-1	0	-1
4	Simplicity	1	1	-1	-1
5	Visibility	0	0	-1	-1
6	Testability	1	0	-1	1
7	Innovation	0	1	1	1
Adaptability		-1	1	1	1
Total Scores		**3**	**5**	**-5**	**-5**

Table F.6: Multi-criteria analysis of evaluation criteria across design alternatives.

F.3.3. Design Verification: Alternative 1 (Base)

Structural Design Parameters and Boundary Conditions

The following section presents the key design parameters employed in the subsequent calculations, refer also to Figure F.4. Most of these parameters are derived from the current conceptual design as detailed in Appendix D of the Coastal Texas Study report (USACE, 2021d), while some are adapted from analogous elements of the Maeslant Barrier design (i.e., “Sector Gate”, “Width Channel”, and “Sill-Length, Height, Width”; Ministerie van V&W, 1997).

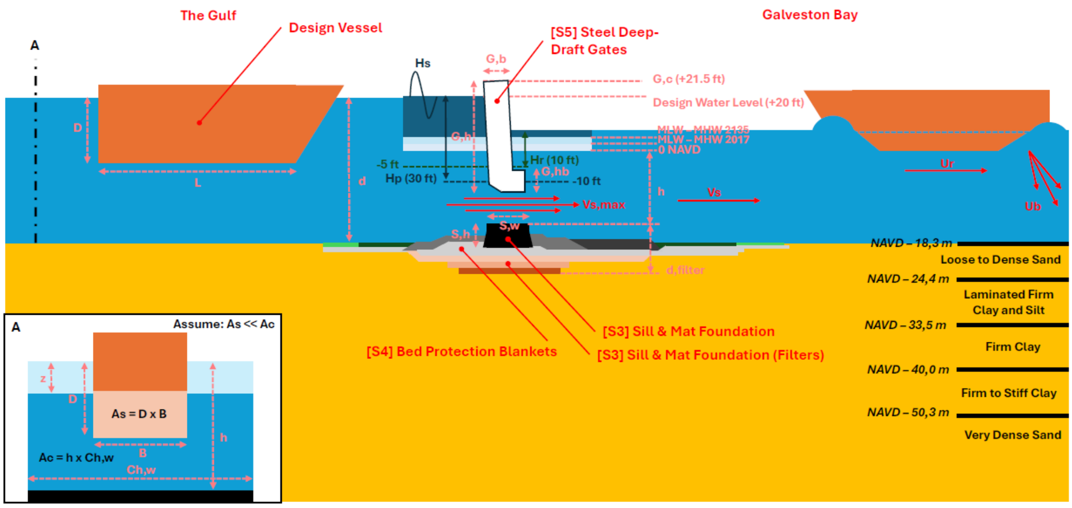


Figure F.4: Schematic Alternative 1 boundary conditions - side view.

Sector Gate Characteristics		Imperial	Metric
Sector Gate			
Arm Length	L_{arm}	690 ft	210 m
Gate Height	G_h	81.5 ft	25 m
Gate Width (z-axis)	G_b	26 ft	8 m
Gate Width (y-axis)	G_w	49 ft	15 m
Gate Height Base	$G_{h,b}$	24 ft	7.4 m
Gate Opening(s)			
Depth Channel ~ Sill Elevation	d	-60 ft	-18.3 m
Width Channel	Ch_w	1180 ft	360 m
Cross-Section Area Channel	A_c	70800 ft^2	6588 m^2
Sill Elevation	h_c	-60 NAVD ft	-18.3 NAVD m
Crest Level of Gates in Sunken Position	G_c	21.5 NAVD ft	6.6 NAVD m
Sill Length	S_l	16 ft	5 m
Sill Height	S_h	10 ft	3 m
Sill Width	S_w	50 ft	15 m
Artificial Island			
Number of Islands	-	-	2
Width Islands	I_{width}	500 ft	150 m
Length Outer Islands	I_{length}	3600 ft	1100 m
Length Inner Island	-	N/A	N/A

Table F.7: Geometric and structural characteristics of the Floating Sector Gates and Artificial Islands (USACE, 2021d; Ministerie van V&W, 1997).

Boundary Conditions		Imperial	Metric
Blocking Storm Surge			
Design Horizon	–	2135 (i.e. 100 years)	2135 (i.e. 100 years)
Protection Level	Ph	1/100 years	1/100 years
Design Water Level (Gulf side)	H	20 ft (NAVD+)	6 m (NAVD+)
Positive Head (Gulf > Bay)	H_p	30 ft	9.1 m
Reverse Head (Bay > Gulf)	H_r	10 ft	3 m
Design Wave Height	H_s	10 ft	3 m
Water Exchange			
Flow Regulation (Channel Flow)	V_s	6.56 ft/s	2 m/s
Flow Regulation (MLW–MHW 2017)	$MLW\text{-}MHW$	0.2–1.2 ft	0.1–0.3 m
Flow Regulation (MLW–MHW 2135)	$MLW\text{-}MHW$	2.6–3.6 ft	0.8–1.1 m
Flow Regulation (Tidal Response)	–	40% closed	72% in tide
Facilitate Navigation			
Container Vessel (MGX-24)			
Design Draft	D_c	52.5 ft	16 m
Design Width	B_c	200 ft	61 m
Design Length	L_c	1312 ft	400 m
Cross-Sectional Area	$A_{s,c}$	10,500 ft^2	976 m^2
Propeller Diameter	$PropD_c$	32 ft	9.5 m
Power of Engine	P_c	–	29,680 kW
Minimum Under Keel Clearance	$UKC_{c,\min}$	5.25 ft	1.6 m
Cruiseship			
Design Draft	D_{cruis}	30 ft	9.3 m
Minimum Under Keel Clearance	$UKC_{t,\min}$	7.55 ft	2.3 m
Houston Ship Channel (HSC)			
Design Depth HSC Project 11	d_{HSC11}	46.5 ft	14.2 m
Design Depth HSC Project 12+	d_{HSC12}	60 ft	18.3 m

Table F.8: Boundary conditions and vessel design (USACE, 2021d; Notteboom et al., 2022; Rodrigue, 2024).

Geotechnical (Foundation)	Depth [NAVD ft]	Depth [NAVD m]
Very Soft Clay	0	0
Very Soft Clay + Silty Sand	-5	-1.52
Loose to Dense Sand	-55	-16.76
Soft to Firm Clay	-60	-18.29
Laminated Firm Clay and Silt	-80	-24.38
Firm Clay	-110	-33.53
Firm to Stiff Clay	-131	-40
Very Dense Sand	-165	-50.29

Table F.9: Geotechnical conditions Bolivar Roads (Jonkman, van Ledden, et al., 2013).

Structural Design Verification

For such hydraulic structures, stability must be maintained in three directions: horizontally, vertically, and rotationally. To ensure that the sill does not displace, uplift, or rotate due to loading, the following three equilibrium conditions must be satisfied:

$$\sum H_{\text{total}} = 0, \qquad \sum V_{\text{total}} = 0, \qquad \sum M_{\text{total}} = 0 \tag{F.4}$$

where:

- $\sum H_{\text{total}}$ [kN]: the net horizontal force acting on the structure;
- $\sum V_{\text{total}}$ [kN]: the net vertical force acting on the structure;
- $\sum M_{\text{total}}$ [kNm]: the net moment about the reference point or axis.

These conditions form the basis for verifying that the sill remains stable under the most critical hydraulic loading scenario, defined in Section 6.4.3.

Hand Calculations of Forces - Fully Closed under Storm Surge
This section outlines the forces acting on the adaptable sill during the governing condition, when the barrier is fully closed under maximum hydraulic head (see Figure F.5). The forces include horizontal and vertical hydrostatic pressures, uplift under the sill, the self-weight of the sill, and the downward load of the gate structure.

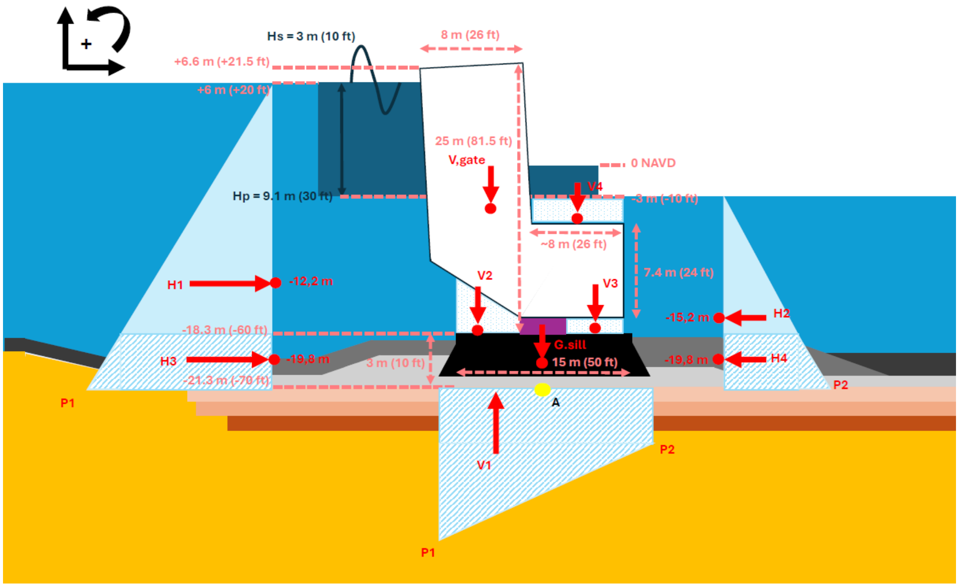


Figure F.5: Schematic Alternative 1 forces - side view.

Hydrostatic pressure arises from the water column acting on a submerged surface. The magnitude of the pressure at a depth h is determined by:

$$p = \rho \cdot g \cdot h \tag{F.5}$$

where:

- p [Pa]: pressure;
- ρ [kg/m^3]: density of saltwater (assumed as $1025\,\text{kg/m}^3$);
- g [m/s^2]: gravitational acceleration ($9.81\,\text{m/s}^2$);
- h [m]: depth from water surface to the point of interest.

The horizontal force exerted by a fluid on a surface is calculated by integrating the pressure distribution over the surface area. For a uniformly wide vertical plane, this results in:

$$F = \frac{1}{2} \cdot \rho \cdot g \cdot h^2 \cdot w \tag{F.6}$$

where:

- F [N]: total hydrostatic force;
- h [m]: height of the water column;
- w [m]: width of the structure or plane.

Based on the schematic in Figure F.5, the key hydrostatic forces acting on the structure are summarized in Table F.10. The self-weight of the concrete sill is calculated based on its volume and material density. The assumed parameters are:

- Concrete density: $\rho_c = 25\,\mathrm{kN/m^3}$;
- Cross-sectional area: $A_c = S_h \cdot S_w = 45\,\mathrm{m^2}$.

The total self-weight is calculated as:

$$G_{\text{sill}} = \rho_c \cdot A_c \cdot S_L = 5625\,\mathrm{kN} \tag{F.7}$$

This vertical stabilizing force acts through the centroid of the sill, approximately at the base elevation. The vertical load of the gate consists of its self-weight and the weight of water inside when submerged. A water-filling rate of 90% is assumed, representing the gate's submerged operational condition when it sits directly above the sill. As the precise steel self-weight of the gate could not be determined, the self-weight of one gate from the Eastern Scheldt Barrier is used as an engineering approximation. Based on the design values:

- Cross-sectional area: $A_g = 259\,\mathrm{m^2}$;
- Total gate weight (incl. water): $V_{\text{gate}} = 15663\,\mathrm{kN}$.

This load is assumed to act vertically downward, centered left above the centroid of the sill. The downward acting vertical forces V_2, V_3, V_4 are assumed much smaller as V_{gate}, and thus neglected. All forces acting on the structure under the governing condition are summarized below in Table F.10.

Symbol	Force Component	Force [kN]	PoA [NAVD m]
H1	Horizontal pressure (Gulf side)	18735	-12.2
H2	Horizontal pressure (Bay side)	4996	-15.2
H3	Lower horizontal pressure (Gulf side)	3891	-19.8
H4	Lower horizontal pressure (Bay side)	2519	-19.7
V1	Uplift pressure under sill	17157	-4.5
G_{sill}	Self-weight of concrete sill	5625	-18.3
V_{gate}	Vertical load of submerged gate	15663	-3.5

Table F.10: Summary of all acting forces and their corresponding points of action (PoA) during the governing condition.

Failure Mode Check - Horizontal Stability

The horizontal stability of the adaptable sill is verified by ensuring that the frictional resistance at the base of the structure is sufficient to counteract the total horizontal forces. For shallow foundations, horizontal loads are resisted primarily by friction between the structure and the underlying soil. To avoid sliding, the total horizontal force $\sum H$ must remain below the maximum frictional resistance, which is defined as the product of the vertical stabilizing forces $\sum V$ and a dimensionless friction coefficient f:

$$\sum H < f \cdot \sum V \tag{F.8}$$

where:

- $\sum H$ [kN]: total horizontal load acting on the sill;
- $\sum V$ [kN]: total vertical load acting on the sill, including the self-weight and uplift forces;
- f [−]: friction coefficient between the structure and the foundation soil.

A friction coefficient of $f = 0.4$ is adopted based on foundation conditions classified as "clean fine sand, silty, or clayey fine to medium sand." This value is consistent with recommendations from the USACE Technical Letters (Voorendt, 2022).

Using the force values derived in the previous section, the following results are obtained:

- Total horizontal force: $\sum H = 1373\,\mathrm{kN}$;
- Total vertical load: $\sum V = 4132\,\mathrm{kN}$;
- Available sliding resistance: $f \cdot \sum V = 1653\,\mathrm{kN}$.

Since $\sum H = 1373\,\mathrm{kN} < 1653\,\mathrm{kN}$, the criterion for horizontal stability is satisfied. The structure is deemed stable against horizontal displacement under the governing load condition.

Failure Mode Check - Rotational Stability
In addition to resisting sliding, the structure must also remain stable against rotation. For shallow foundations, it is commonly assumed that the contact stresses between the structure and the subsoil can only be compressive. This is because the soil typically cannot provide tensile resistance, especially in conditions where adhesive and cohesive strength are limited.

To ensure rotational stability, the resultant of all vertical forces acting on the structure must intersect within a central portion of the foundation base, referred to as the "core." This core is defined as the central zone covering one-third of the structure width, i.e., within $\frac{1}{6}b$ on either side of the midpoint.

The rotational stability criterion is defined by:

$$e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6}b \tag{F.9}$$

where:

- e_R [m]: eccentricity of the resultant vertical force relative to midpoint A;
- $\sum M$ [kNm]: total applied moments about midpoint A;
- $\sum V$ [kN]: total vertical stabilizing load;
- b [m]: width of the structure (sill), here $b = 15\,\mathrm{m}$.

Using the values calculated in the force and moment assessments (see Figure F.5), it is obtained:

- Total moment: $\sum M = 9871\,\mathrm{kNm}$;
- Total vertical load: $\sum V = 4132\,\mathrm{kN}$;
- Eccentricity: $e_R = 2.4\,\mathrm{m}$;
- Maximum allowable eccentricity: $2.5\,\mathrm{m}$.

Since $e_R = 2.4\,\mathrm{m} < 2.5\,\mathrm{m}$, the resultant force falls within the defined core, and the criterion for rotational stability is satisfied. This implies that all compressive contact stresses remain within the sill base and no tensile stresses are required for equilibrium, which complies with the design assumptions for shallow foundation behavior.

Failure Mode Check - Vertical Stability
Vertical stability ensures that the soil beneath the structure can safely support the applied loads without failing in bearing capacity. In shallow foundation analysis, this is assessed by comparing the maximum vertical stress acting on the soil ($\sigma_{k,\text{max}}$) to the ultimate bearing capacity of the soil (p'_{max}). To ensure safety, the condition must be met:

$$\sigma_{k,\text{max}} < p'_{\text{max}} \tag{F.10}$$

The maximum vertical stress on the foundation soil is computed as a combination of average pressure and stress increase due to eccentric moments:

$$\sigma_{k,\text{max}} = \frac{\sum V}{b \cdot \ell} + \frac{\sum M}{\left(\frac{1}{6} \cdot b^2 \cdot \ell\right)} \tag{F.11}$$

where:

- $\sum V$ [kN]: total vertical load on the foundation;
- $\sum M$ [kNm]: total acting moment about the midpoint A;
- b [m]: structure width (sill);
- ℓ [m]: structure length (sill).

For the design scenario:

- $\sum V = 4132\,\text{kN}$;
- $\sum M = 9871\,\text{kNm}$;
- $b = 15\,\text{m}, \quad \ell = 5\,\text{m}$;
- $\sigma_{k,\text{max}} = 108\,\text{kN/m}^2$.

The maximum allowable bearing capacity of the subsoil is based on the local ground conditions, classified as loose sand, silt, and clay, and estimated at:

$$p'_{\text{max}} = 96\,\text{kN/m}^2 \tag{F.12}$$

Comparing both values shows: $\sigma_{k,\text{max}} = 108\,\text{kN/m}^2 > p'_{\text{max}} = 96\,\text{kN/m}^2$. This result indicates that the vertical bearing capacity of the soil is exceeded under the assumed shallow foundation conditions. This outcome is consistent with expectations given the presence of soft subsoils in the area. Since the conceptual design already assumes a pile foundation for the final structure (as detailed in Appendix D of the Coastal Texas Study (USACE, 2021d)), no further modifications to the sill dimensions or weight are made to satisfy this check. The vertical stability will ultimately be governed by the pile foundation design, which falls outside the scope of this study.

Failure Mode Check - Internal Backward Erosion
Piping refers to internal backward erosion beneath hydraulic structures, where water seepage displaces soil particles, potentially creating channels (pipes) that undermine the structure's stability. This process is particularly critical in structures such as the sill, where the subsoil can settle while the structure remains fixed in place. This creates voids that facilitate uncontrolled seepage and erosion. To evaluate this risk, the Lane method is applied. Lane's empirical formula distinguishes between vertical and horizontal seepage paths and accounts for their different resistance to erosion. The piping check is expressed as:

$$L \geq \gamma \cdot C_L \cdot \Delta H \tag{F.13}$$

where:

- L [m]: total effective seepage length;
- $\gamma = 1.5$ [−]: safety factor;
- $C_L = 8.5$ [−]: Lane's coefficient for loose sand, silt, and clay;
- $\Delta H = 9.1$ [m]: hydraulic head difference between the Gulf and the Bay side.

For this study, the vertical seepage length is estimated $\Sigma L_{\text{vert}} = 3$ m and the horizontal seepage length is $\Sigma L_{\text{hor}} = 5$ m. Using Lane's correction for horizontal seepage paths ($\frac{1}{3}$), the total seepage length is:

$$L_{\text{available}} = \Sigma L_{\text{vert}} + \frac{1}{3} \cdot \Sigma L_{\text{hor}} = 4.67\,\text{m} \tag{F.14}$$

The required seepage length for this soil type is: $L_{\text{required}} = 116$ m. Since $L_{\text{available}} < L_{\text{required}}$, the piping check is not fulfilled. This result was anticipated due to the soft soil conditions.

Design Verification of Bed Protection Around the Sill

Bed Protection Stability Check - Current Attack
For the sill, the maximum flow velocity beneath the barrier during partial closure is identified as the governing load case (refer to Section 6.4.4). This velocity, calculated using Torricelli's law based on the maximum hydraulic head ($h = 9.1\,\text{m}$), results in $v = 13\,\text{m/s}$. To determine a more representative flow condition, an average flow velocity was estimated using the normal condition velocity at Bolivar Roads ($2\,\text{m/s}$), scaled by a storm factor of 1.5. This results in $v = 3\,\text{m/s}$ under elevated flow and $v_{\text{avg}} = 3.76\,\text{m/s}$ for depth-averaged velocity, refer to Figure F.6.

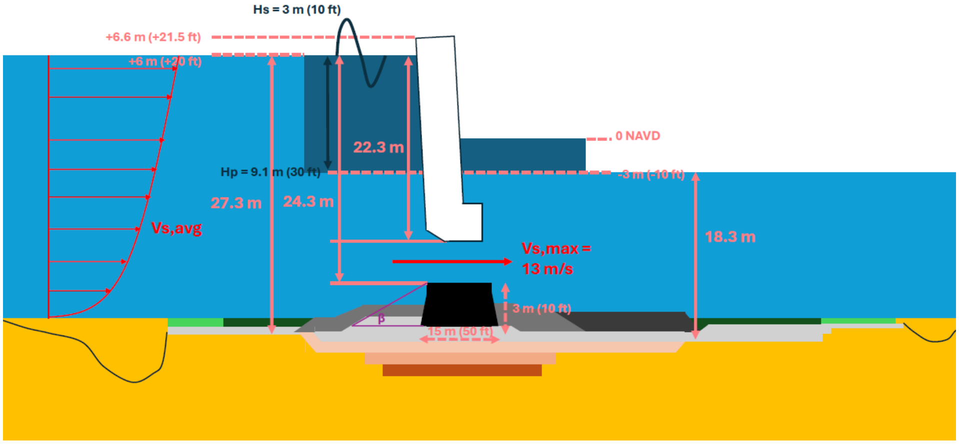


Figure F.6: Schematic Alternative 1 bed protection stability under current attack.

All formulas, theorems, parameters, and assumptions for the determination of the bed protection size due to current induced load are extracted from Chapter 5 of the Rock Manual (CIRIA et al., 2007).The required stone size for the armour layer is determined using the Pilarczyk (1998) equation.

$$D = \frac{\phi_{sc}}{\Delta\psi_{cr}} \cdot 0.035 \cdot \frac{k_h}{k_{sl}} \cdot k_t^2 \cdot \frac{U^2}{2g} \tag{F.15}$$

where:

- D [m]: required median armourstone size (D_{50}); reduced to $D_{n50} = 0.84 \cdot D_{50}$;
- ϕ_{sc} [−]: stability correction factor; 0.75 for continuous rock protection;
- Δ [−]: relative buoyant density, calculated as:

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w} = 1.59$$

- ψ_{cr} [−]: critical mobility parameter; for loose angular armourstone: $\psi_{cr} = 0.035$;
- k_h [−]: velocity profile factor; for shallow, rough flow estimated as:

$$k_h = \left(1 + \frac{h}{D_n}\right)^{-0.2} \approx 1.1$$

- k_{sl} [−]: side slope factor; slope correction for upslope or downslope flow, see below;
- k_t [−]: turbulence factor, with $r = 0.5$ (assume non-uniform flow special case), calculated as:

$$k_t = \frac{1 + 3r}{1.3} \approx 1.92$$

- U [m/s]: depth-averaged flow velocity; $U = 3.76$ m/s;
- g [m/s^2]: gravitational acceleration; $g = 9.81$ m/s^2.

The slope factor k_{sl} is applied to account for reduced stability on inclined beds. The angle of the structure slope (β) was determined from the geometry of the sill:

$$\beta = \arctan\left(\frac{G_h}{G_w}\right) =\approx 0.20 \text{ rad}$$

The internal friction angle (ϕ) is assumed to be $35°$, representative of angular stone, giving:

$$\phi = \arctan(\phi) \approx 1.54 \text{ rad}$$

Depending on the direction of flow, the slope factor is calculated as:

- Upslope flow (ψ = 0) – Soulsby (1997) full formula:

$$k_{sl,\text{up}} = \frac{\cos\psi \cdot \sin\beta + \sqrt{\cos^2\beta \cdot \tan^2\phi - \sin^2\psi \cdot \sin^2\beta}}{\tan\phi} \approx 1.18$$

- Downslope flow (ψ = 180°), simplifies to:

$$k_{sl,\text{down}} = \frac{\sin(\phi - \beta)}{\sin(\phi)} \approx 0.97$$

The resulting required sizes for the bed protection according to load under current attack are:

- Upstream of the Sill: $D_{50,\text{up}} = 1.07$ m, $D_{n50,\text{up}} = 0.90$ m, results in grading Class HMA 1000–3000 (Schiereck and Verhagen, 2019).
- Downstream of the Sill: $D_{50,\text{down}} = 1.29$ m, $D_{n50,\text{down}} = 1.09$ m, results in grading Class HMA 3000–6000 (Schiereck and Verhagen, 2019).

Bed Protection Stability Check - Wave Load
To ensure adequate protection of the bed in front of the sill during (strom) wave activity, a wave loading stability check was conducted. Unlike steady flow conditions, waves exert oscillatory forces on the bed (see Figure F.7), which can lead to the dislocation of bed material if not properly designed. In this analysis, only the upstream side of the barrier is considered to be exposed to wave action, as downstream waves are assumed negligible due to the presence of the barrier.

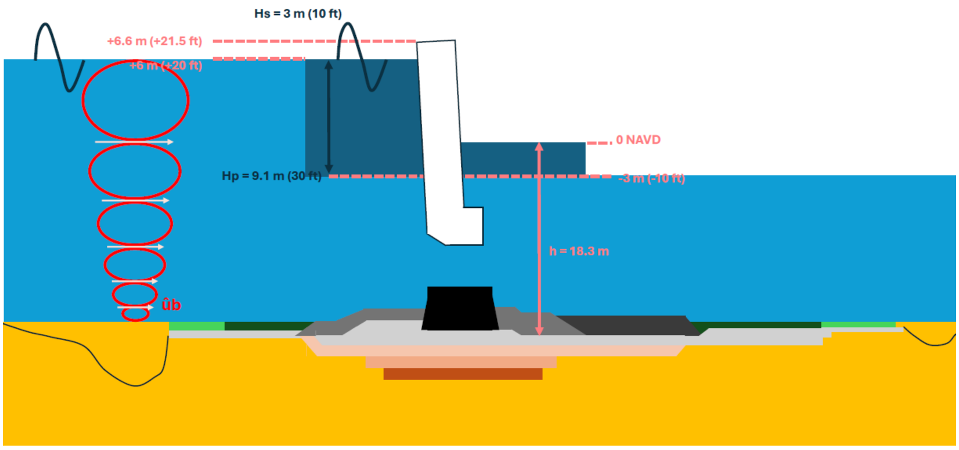


Figure F.7: Wave-induced bed loading conditions and definition of orbital motion on Floating Sector Gates.

The governing formula used to determine the required stone size under non-breaking wave conditions is derived from the work of Rance/Warren (1996), based on the modified Shields approach and experimental studies by Sleath (1978). The formulation is given as:

$$d_{n50} = 2.15 \cdot \frac{\dot{u}_b^{2.5}}{\sqrt{T}(\Delta g)^{1.5}} \tag{F.16}$$

where:

- d_{n50} [m]: required nominal diameter of the protection element;
- $\dot{u}_b$ [m/s]: maximum orbital velocity at the bed;
- T [s]: wave period;
- Δ [−]: relative buoyant density of the stone (i.e., $\Delta = \frac{\rho_{\text{rock}}}{\rho_{\text{water}}} - 1$);
- g [m/s^2]: gravitational acceleration.

For the determination of the bottom orbital velocity $\dot{u}_b$, it is assumed that the wave motion occurs in shallow water conditions, hence waves are noticeably affected by bottom topography. According to linear wave theory the velocity is depth-uniform, this means that $kh \ll 1$, or practically $h/L > 1/20$. In such conditions, the depth-uniform orbital velocity amplitude simplifies to:

$$\dot{u}_b = \sqrt{gh} \cdot \frac{H}{2h} \tag{F.17}$$

where H is the design wave height and h the water depth. This formulation eliminates the need to compute the wavelength or wavenumber k, making it a practical approach for preliminary design checks. In the current design, the design wave height was taken as $H = 6.6$ m, based on a multiplication factor of 2.2 (i.e., rule of thumb) on the significant wave height $H_s = 3.0$ m, to account for extreme storm conditions. With a local water depth of $h = 18.3$ m, the corresponding orbital velocity at the bed is calculated as $\dot{u}_b = 2.4$ m/s.

Substituting this into the stability equation, the required nominal stone size $d_{n50} = 0.10$ m is determined. Finally, using the empirical relationship $D_{50} = d_{n50}/0.84$, the upstream armourstone size in accordance with the wave induced load becomes: $D_{50,\text{up}} \approx 0.12$ m. Resulting in a light rock grading of class LMA 40 - 200 (Schiereck and Verhagen, 2019).

Bed Protection Stability Check - Ship Load

In addition to hydraulic loading from storm conditions, the bed protection must also withstand local scour effects caused by ship traffic passing over or near the sill (see Figure F.8). This is particularly relevant for the sill of the storm surge barrier during normal operational periods when vessels pass through the navigation channel. To assess the stability of the bed protection under such ship-induced loads, the primary mechanism considered is the propeller wash (also referred to as propeller jet or thruster flow), which creates significant flow velocities near the bed. Primary waves, secondary waves, and a return current will also occur when ships pass, but are consider negligible when compared to the propeller wash. All formulas, theorems, and assumptions are extracted from the PIANC Guidelines (PIANC, 2015).

The Dutch method, derived from Izbash's formulation, is applied here to determine the required median rock size D_{50} by relating the bed shear to the velocity near the bed. The following empirical equation is used (see Figure F.8):

$$\Delta D_{50} = \frac{1}{B^2_{\text{crit,Iz}}} \cdot \frac{V^2_{\text{bottom}}}{2g} \tag{F.18}$$

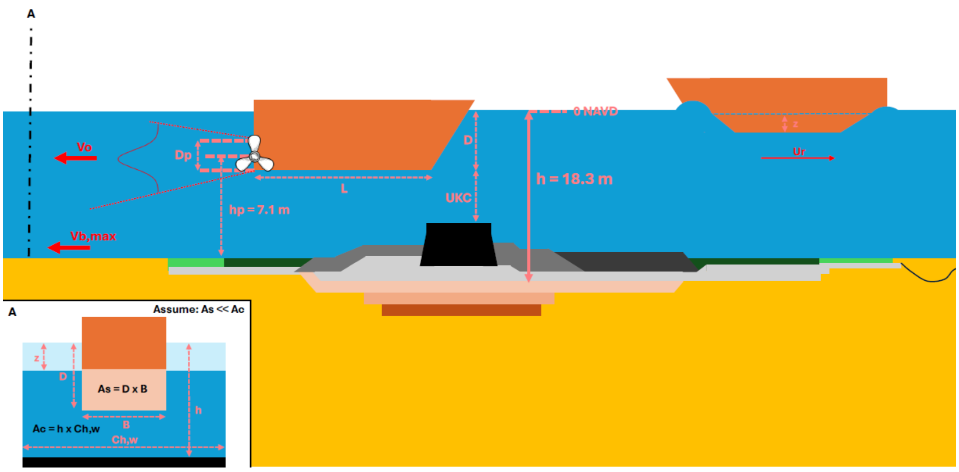


Figure F.8: Flow field induced by a passing vessel over the sill (i.e., propeller wash load case).

where:

- Δ [−]: buoyant density factor $\left(\frac{\rho_{\text{rock}}-\rho_{\text{salt}}}{\rho_{\text{salt}}}\right)$;
- $B_{\text{crit,Iz}}$ [−]: critical Izbash stability coefficient, taken as 0.8 for standard conditions;
- V_{bottom} [m/s]: maximum near-bed velocity from the propeller wash;
- g [m/s^2]: gravitational acceleration.

To determine V_{bottom}, the efflux velocity V_0 of the propeller is estimated based on the design vessel characteristics and propulsion power. For this study, the simplified empirical equation from Blaauw and van de Kaa (1978) is used for both free and deducted propeller:

$$V_0 = 1.17\left(\frac{P_D}{\rho_w D_0^2}\right)^{0.33} \tag{F.19}$$

where:

- P_D [W]: maximum installed engine power;
- D_0 [m]: effective propeller diameter;
- ρ_w [kg/m^3]: water density.

The near-bed velocity is then derived using a simplified empirical relationship:

$$V_{b,\text{max}} = (0.2 \text{ to } 0.3) \cdot V_0 \cdot \frac{D_p}{h_p} \tag{F.20}$$

where D_p is the propeller diameter and h_p is the vertical distance from the propeller to the bed. A relative turbulence intensity $r = 0.45$ is assumed based on Dutch hydraulic guidelines (RWS/DHL, 1988), to account for turbulent spreading of the jet flow.

Based on the selected container vessel (MGX-24 class) parameters and a maximum installed engine power of 29,680 kW (2x), an efflux velocity of approximately 9.88 m/s is obtained. This results in a near-bed velocity of 3.33 m/s, leading to a required rock size of $D_{50} = 0.56$ m upstream and downstream of the sill, which corresponds with grading class HMA 300 - 1000 (Schiereck and Verhagen, 2019). The corresponding nominal diameter is calculated as $D_{n50} = 0.84 \cdot D_{50}$, following the Rock Manual convention for converting median to nominal sizes.

Bed Protection Length Check
As identified from the design calculations, current-induced loads are the governing factor in determining the required rock size for bed protection at the sill. Turbulent flow conditions at the end of the protection zone can cause scour holes to form in the sandy bed, especially when sediment transport over the protection is negligible (see Figure F.9). To prevent undermining of the sill foundation, it is crucial to assess the expected scour depth and size the length of the rock armour layer accordingly.

The potential equilibrium scour depth (h_{max}) can be estimated using the simplified method based on clear-water conditions, as given by Voorendt (2022):

$$h_{\text{max}} = \frac{0.5 \cdot \alpha \cdot \bar{u} - u_{\text{cr}}}{u_{\text{cr}}} \cdot h_0 \quad \text{for} \quad 0.5 \cdot \alpha \cdot \bar{u} - u_{\text{cr}} > 0 \tag{F.21}$$

where:

- h_0 [m] $= 18.3$: local water depth at the end of the scour protection;
- $\bar{u}$ [m/s] $= 2.0$: depth-averaged velocity at the end of the scour protection (assumed as normal flow conditions);
- α [−] $= 2.0$: turbulence coefficient, based on upstream hydraulic disturbances;
- u_{cr} [m/s]: critical velocity for sediment motion initiation.

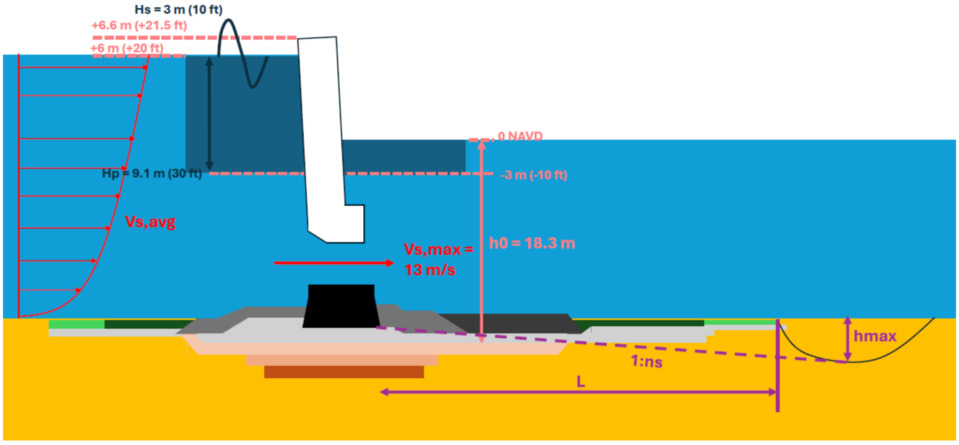


Figure F.9: Definition of scour hole slope and length of required bed protection.

The critical velocity u_{cr} is derived from the Shields equation:

$$u_{\text{cr}} = C \cdot \sqrt{\Theta_{\text{cr}} \cdot \Delta \cdot D_{50}} \tag{F.22}$$

with the following parameters:

- D_{50} [mm] $= 0.15$: median grain size; assume (silty) sand bed;
- $\Delta\,[-] = 1.59$: relative submerged density of the sediment;
- $\Theta_{\text{cr}}\,[-] = 0.045$: Shields parameter (see Figure F.10) for $D_{50} = 0.15$ mm;
- C [m$^{1/2}$/s] $= 50.8$: Chézy coefficient, computed from:

$$C = 18 \cdot \log\left(\frac{12 \cdot R}{k_r}\right)$$

- R [m] $= 17$: hydraulic radius of the flow channel, assumed equal to h_0 for wide sections;
- k_r [m] $= 0.30$: equivalent bed roughness, corresponding to rippled sandy beds.

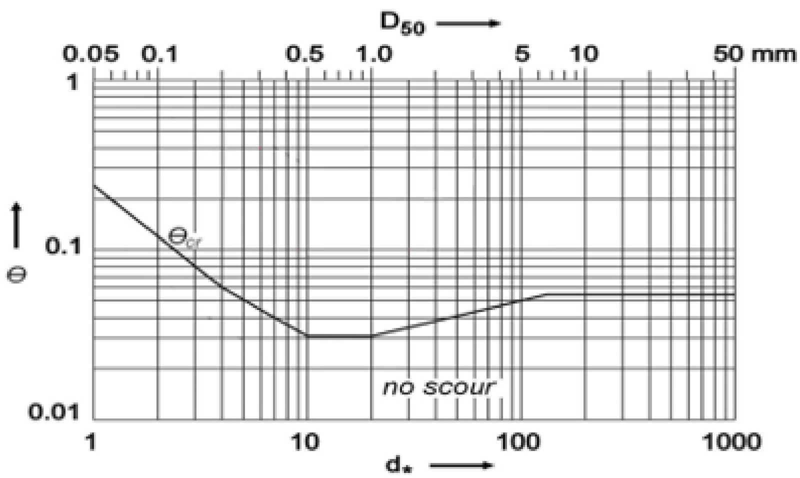


Figure F.10: Shields Curve (Voorendt, 2022).

Substituting the above parameters gives a critical velocity of $u_{\text{cr}} = 0.17$ m/s, which results in a maximum potential scour depth of $h_{\text{max}} = 11.0$ m. This calculation is visualized in Figure F.9, and emphasizes the importance of properly extending the bed protection to prevent the formation of deep scour holes adjacent to the sill.

The horizontal extent of the bed protection must be sufficient to safely accommodate the development of a potential scour hole formed under current-induced attack. If the protection is too short, the scour hole may extend beneath the structure, increasing the risk of undermining or instability. To prevent such failures, the required length L is determined based on the depth of the equilibrium scour hole $h_{\max}$ and the assumed average slope $1 : n_s$ of the failure plane, see Figure F.9.

$$L \geq \gamma \cdot n_s \cdot h_{\max} \tag{F.23}$$

where:

- L [m]: required length of the bed protection;
- $\gamma\ [-] = 1.5$: safety factor, typically > 1.0;
- $n_s\ [-] = 15$: slope factor of the failure plane; applied for loosely packed sand;
- $h_{\max}$ [m] $= 11.02$: maximum scour depth (governing).

The resulting required protection length thus becomes: $L = 248$ m. This design ensures that even in the case of maximum expected scour development, the sliding plane remains outside the structural footprint. The used slope value ($n_s = 15$) corresponds to loose material; for denser or cohesive soils, lower values (e.g., $n_s = 6$) may be applicable, potentially reducing the required length.

Design Verification of Geometrically Open Filters under the Sill

Filter Layer Design Check – Interface Top Layer and Subsoil
The purpose of this section is to evaluate whether a filter layer is required between the top layer and the existing non-cohesive subsoil. This is the first step in the design of a geometrically open granular filter system. Two independent methods are employed to validate the need for a filter:

Critical Gradient Method (CUR, 1993)
This method compares the actual hydraulic gradient i_{act} at the interface with a critical threshold value i_{cr} that marks the onset of instability of the base material. When $i_{\text{act}} > i_{\text{cr}}$, transport of base material particles may occur, indicating the necessity for a filter layer.

The critical gradient is derived from empirical design charts (Figure F.11), which relate the ratio $n_f \cdot D_{15t}/D_{85b}$ to i_{cr}, where:

- $n_f\ [-]$: porosity;
- D_{15t} [mm]: sieve size for which 15% of the top layer is finer;
- D_{85b} [mm]: sieve size for which 85% of the base layer is finer.

Based on:

$$n_f = 0.34, \quad D_{15t} = 0.928\,\text{mm}, \quad D_{85b} = 0.300\,\text{mm}, \quad \frac{n_f \cdot D_{15t}}{D_{85b}} = 1.05$$

From the chart, this corresponds to: $i_{\text{cr}} \approx 0.020$.

The actual gradient is computed using the following formula, derived from flow resistance and turbulence considerations:

$$i_{\text{act}} = \left(\frac{d\phi}{dx}\right)_{\text{subsoil}} = \frac{U^2}{RC^2} + \frac{1}{2} \cdot \frac{\beta^2 r^2 U^2}{Rg} \tag{F.24}$$

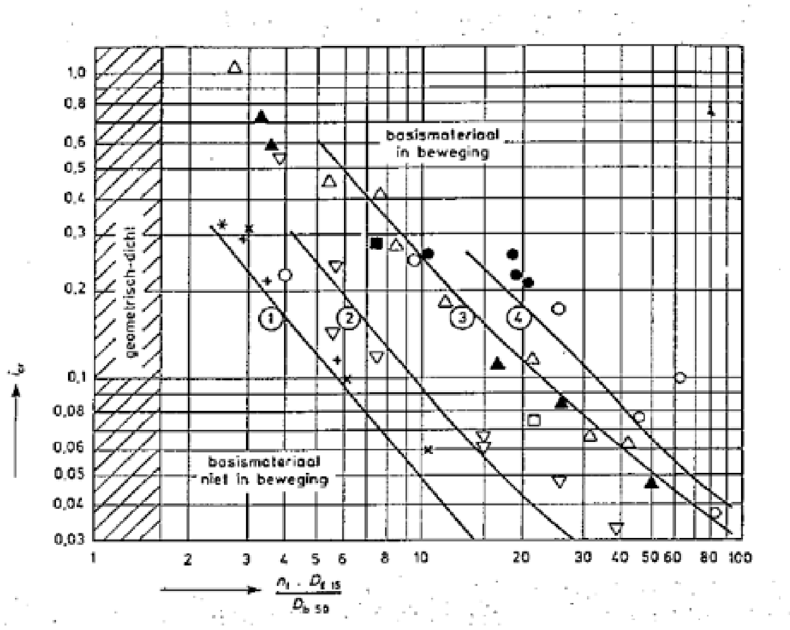


Figure F.11: Critical gradient at parallel current to top layer (CUR, 1993).

where:

- U [m/s] $= 3.8$: depth-averaged flow velocity;
- R $[-] = h = 17$: hydraulic radius (approximated by water depth);
- β $[-] = 3$: turbulence coefficient;
- r $[-] = 0.5$: relative turbulence intensity;
- g [m/s^2] $= 9.81$: gravitational acceleration;
- C [m$^{1/2}$/s]: Chézy coefficient (to be calculated below).

The Chézy coefficient accounts for resistance due to bed roughness and is calculated using the empirical formula:

$$C = 18 \cdot \log\left(\frac{6R}{D_{50t}}\right) \tag{F.25}$$

For:

- $R = 17$ m;
- $D_{50t} = 0.134$ m (characteristic grain size of top layer);
- $C \approx 33.54$ m$^{1/2}$/s.

Results in: $i_{\text{act}} = 0.033$. Hence, $i_{\text{act}} = 0.033 > i_{\text{cr}} = 0.020$. Thus, the hydraulic conditions at the interface exceed the stability threshold for the base material, and thus a filter layer is necessary to prevent transport of the subsoil. The subsequent sections will design this filter layer in accordance with geometrically open filter principles.

Bakker-Konter Method (CIRIA et al., 2007)
To verify whether a filter layer is necessary between the top layer and the base layer (non-cohesive subsoil), the Bakker-Konter method is also applied. This method offers a simplified yet effective criterion for geometrically open filters in bed protection systems and is based on the assumption that the highest hydraulic loading is linked to the top layer, and therefore, the filter must be adequately designed to prevent erosion of the subsoil beneath.

According to Bakker-Konter (1994), the filter stability criterion at the interface between the top layer and the underlying subsoil is expressed as:

$$\frac{D_{15f}}{D_{50b}} \leq \frac{15.3 \cdot R}{C_0 \cdot D_{50t}} \tag{F.26}$$

where:

- $D_{15f}[m]$, 15th percentile grain diameter of the filter layer;
- $D_{50b}[m]$, 50th percentile grain diameter of the base material (subsoil);
- $D_{50t}[m]$, 50th percentile grain diameter of the top layer;
- $R[m]$, hydraulic radius, taken equal to the flow depth h in this case;
- $C_0[-]$, correction factor, typically 30 for conservative design assumptions.

This criterion is valid for three common configurations:

- Top layer directly placed on the subsoil;
- Top layer and one filter layer on the subsoil;
- Top layer and two or more filter layers on the subsoil.

Substituting the given parameters in Equation F.26. Results in the maximum allowable ratio between D_{15f} and D_{50b}:

$$\frac{D_{15f}}{D_{50b}} \approx 4.14 \tag{F.27}$$

The actual grain sizes derived from the grading curves for the subsoil and top layer are:

- $D_{50b}[m] = 0.00018$ m (fine base layer);
- $D_{15f}[m] = 1.03$ m (from the filter material grading used under the top layer).

Hence, the actual ratio is:

$$\frac{D_{15f}}{D_{50b}} \approx 7587 \tag{F.28}$$

Since $7587 \gg 4.14$, the actual additional filter layers are required between the top layer and the subsoil to ensure proper protection and avoid material erosion or piping from the base layer. Thus, both methods (Critical Gradient and Bakker-Konter) require extra filter layers between the top layer and the subsoil to ensure popper protection. In the subsequent paragraph, these layer will be determined via the Bakker-Konter Method.

Filter Layer Design – Multi-Layered Filter System

In this section, the required filter layer system is systematically developed using the Bakker-Konter design criterion. The goal is to ensure that each interface between two adjacent layers (i.e., between top layer, filter layers, and subsoil) meets the stability conditions required to prevent internal erosion or winnowing of finer materials into coarser ones. The Bakker-Konter method is based on a hydraulic loading criterion. The key parameter in this evaluation is the ratio $\frac{D_{15f}}{D_{50b}}$, which must be less than or equal to a theoretical threshold defined by:

$$\frac{D_{15f}}{D_{50b}} \leq \frac{15.3 \cdot R}{C_0 \cdot D_{50t}} \tag{F.29}$$

In multi-layered systems, the application of Equation F.29 follows specific indexing conventions:

- t refers to the top layer;
- f to the filter layer being evaluated;
- b to the underlying layer, which may be another filter or the base (subsoil).

For example, when evaluating the interface between the top layer and the first filter layer, D_{50t} refers to the top layer, D_{15f} to the first filter layer, and D_{50b} to the same first filter layer. When assessing the filter layer against the base soil, D_{15f} still refers to the filter but D_{50b} now corresponds to the subsoil. Refer to Figure F.12.

The design procedure consists of the following steps:

1. A candidate filter layer is proposed with known grain size characteristics;
2. The filter layer is checked using the Bakker-Konter formula against the adjacent upper layer (typically coarser) and lower layer (typically finer);
3. If either of these checks does not meet the stability criterion, an intermediate filter layer must be inserted;
4. This process is repeated iteratively until all interfaces comply with the stability condition in Equation F.29.

The filter system is considered sufficient once every transition between layers meets the requirement, i.e., the actual value of $\frac{D_{15f}}{D_{50b}}$ is lower than or equal to the theoretical threshold for both the upper and lower interface. This process leads to a step-wise refinement of the gradation to ensure a stable, permeable, and constructible filter structure. The next Tables present the step-by-step construction and verification of the filter layers. Figure F.12 gives an example of the considered interfaces.

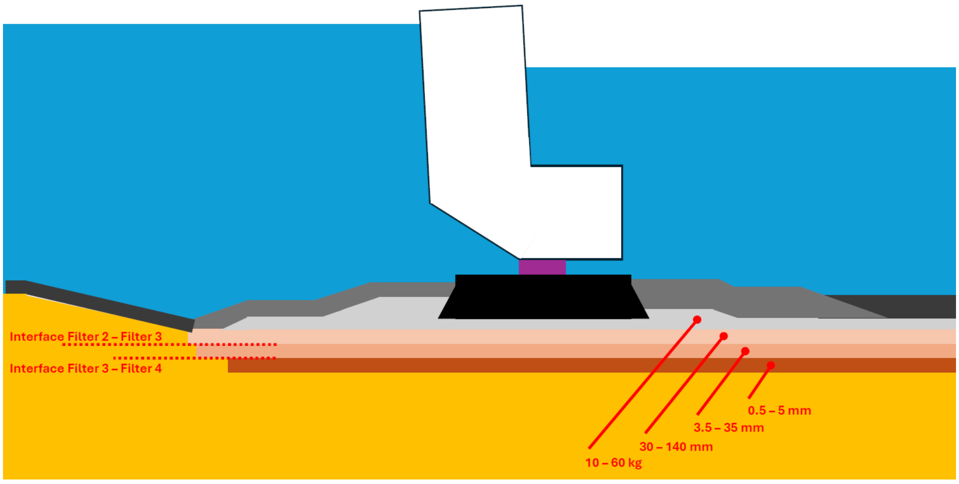


Figure F.12: Schematic of filter layer construction.

Filter Layer Design: Filter Layer 1:

Filter 1 Grading: LMA 10 – 60 (light standard grading)								
W10f1	8.5	kg	**dn10**	15	cm	**D10f1**	176	mm
W15f1	10	kg	**dn15**	16	cm	**D15f1**	185	mm
W50f1	25	kg	**dn50**	21	cm	**D50f1**	252	mm
W60f1	30	kg	**dn60**	22	cm	**D60f1**	267	mm
W85f1	48	kg	**dn85**	26	cm	**D85f1**	313	mm

Table F.11: Overview of Filter 1 Grading according to LMA 10–60 specification.

Interface Top Layer – Filter Layer 1			
γ	1.5	-	
D_{15t}	1136	mm	
D_{50t}	2048	mm	
D_{15t}/D_{50f}	4	*Theoretical*	
D_{15t}/D_{50f}	4.514	*Actual*	
Comparison	4.5	<4	Almost "sufficient"
Interface Filter Layer 1 – Subsoil			
D_{15f}	185	mm	
D_{50t}	2048	mm	
D_{50b}	0.180	mm	
D_{15f}/D_{50b}	4.14	Theoretical	
D_{15f}/D_{50b}	1030	Actual	
Comparison	1029.674	>4.14	Extra Filter Layer(s) Needed!

Table F.12: Filter Layer 1 interface checks: Top Layer–Filter Layer 1 and Filter Layer 1–Subsoil.

Filter Layer Design: Filter Layer 2:

Filter 2 Grading: 30 - 140 mm (course standard grading)		
D10f2	41	mm
D15f2	47	mm
D50f2	85	mm
D60f2	96	mm
D85f2	124	mm

Table F.13: Grain size distribution for Filter 2.

Interface Filter Layer 1 – Filter Layer 2			
D_{15f1}	185	mm	
D_{50f1}	252	mm	
D_{15f1}/D_{50f2}	33.68	Theoretical	
D_{15f1}/D_{50f2}	2.18	Actual	
Comparison	2.180	<33.67847	Sufficient
Interface Filter Layer 2 – Subsoil			
D_{15f2}	47	mm	
D_{50f1}	252	mm	
D_{50b}	0.180	mm	
D_{15f2}/D_{50b}	33.68	Theoretical	
D_{15f2}/D_{50b}	261.11	Actual	
Comparison	261.11	>33.68	Extra Filter Layer(s) Needed!

Table F.14: Filter Layer 2 interface checks: Filter Layer 1–2 and Filter Layer 2–Subsoil.

Filter Layer Design: Filter Layer 3:

Filter 3 Grading: 3.5 – 35 mm (Crushed) gravel / stone (fine aggregate standard grading)		
D10f3	6	mm
D15f3	8	mm
D50f3	19	mm
D60f3	22	mm
D85f3	30	mm

Table F.15: Grain size distribution of Filter Layer 3.

Interface Filter Layer 2 – Filter Layer 3			
D_{15f2}	47	mm	
D_{50f2}	85	mm	
D_{15f2}/D_{50f3}	99.67	Theoretical	
D_{15f2}/D_{50f3}	2.47	Actual	
Comparison	2.474	< 99.67	Sufficient
Interface Filter Layer 3 – Subsoil			
D_{15f3}	8	mm	
D_{50f2}	85	mm	
D_{50b}	0.180	mm	
D_{15f3}/D_{50b}	99.67	Theoretical	
D_{15f3}/D_{50b}	44.44	Actual	
Comparison	44.44	> 99.67	Extra Filter Layer(s) Needed!

Table F.16: Filter Layer 3 interface checks: Filter Layer 2–3 and Filter Layer 3–Subsoil.

Filter Layer Design: Filter Layer 4:

Filter 4 Grading: 0.5 – 5 mm (Crushed) gravel / stone		
D10f4	0.95	mm
D15f4	1.20	mm
D50f4	2.75	mm
D60f4	3.20	mm
D85f4	4.35	mm

Table F.17: Grain size distribution of Filter Layer 4.

Interface Filter Layer 3 – Filter Layer 4			
D_{15f3}	1	mm	
D_{50f3}	3	mm	
D_{15f3}/D_{50f4}	3080.62	*Theoretical*	
D_{15f3}/D_{50f4}	0.44	*Actual*	
Comparison	0.436	< 3080.62	Sufficient
Interface Filter Layer 4 – Subsoil			
D_{15f4}	1.20	mm	
D_{50f3}	19	mm	
D_{50b}	0.180	mm	
D_{15f4}/D_{50b}	445.88	Theoretical	
D_{15f4}/D_{50b}	6.67	Actual	
Comparison	6.67	< 445.88	Sufficient

Table F.18: Filter Layer 4 interface checks: Filter Layer 3–4 and Filter Layer 4–Subsoil.

Final Design Configuration

The final design configuration of the bed protection system is determined by the outcomes of the multi-layered filter design using the Bakker-Konter method. The governing calculations have shown that a four-layer filter system is required beneath the top layer in order to meet the hydraulic filter criteria for both particle stability and permeability.

The heaviest hydraulic loading occurs in the region directly surrounding the sill and gate foundation structure. This is due to highly turbulent flow and local current attack caused by flow constriction, pressure gradients, and propeller wash during operational conditions. As such, the heaviest classes of bed protection, up to 3–6 tons, are required only in this central area.

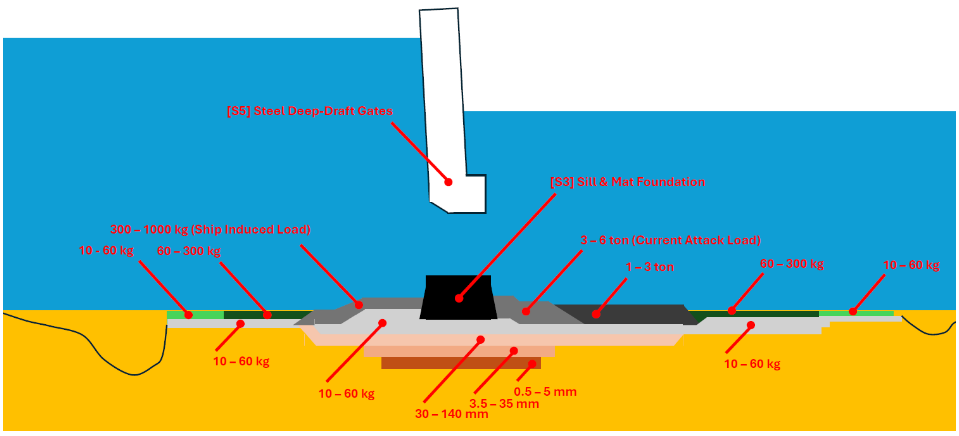


Figure F.13: Schematic of final design Alternative 1 - side view.

Further upstream and downstream from the sill, the turbulence energy and flow velocity decay substantially. In these zones, the hydraulic attack on the bed is reduced, and lighter bed protection classes (e.g., 60–300 kg and 10–60 kg) can be adopted. This tiered protection layout allows for a cost-efficient use of materials while ensuring overall system stability. The design configuration presented here is conceptually inspired by the layout applied at the Maeslant Barrier. Exact determination of the spatial extent of the zones with different bed protection weights would require detailed 2D or 3D flow modeling, which is beyond the scope of this conceptual design. Therefore, a conservative zoning estimate has been adopted based on qualitative flow behavior interpretation.

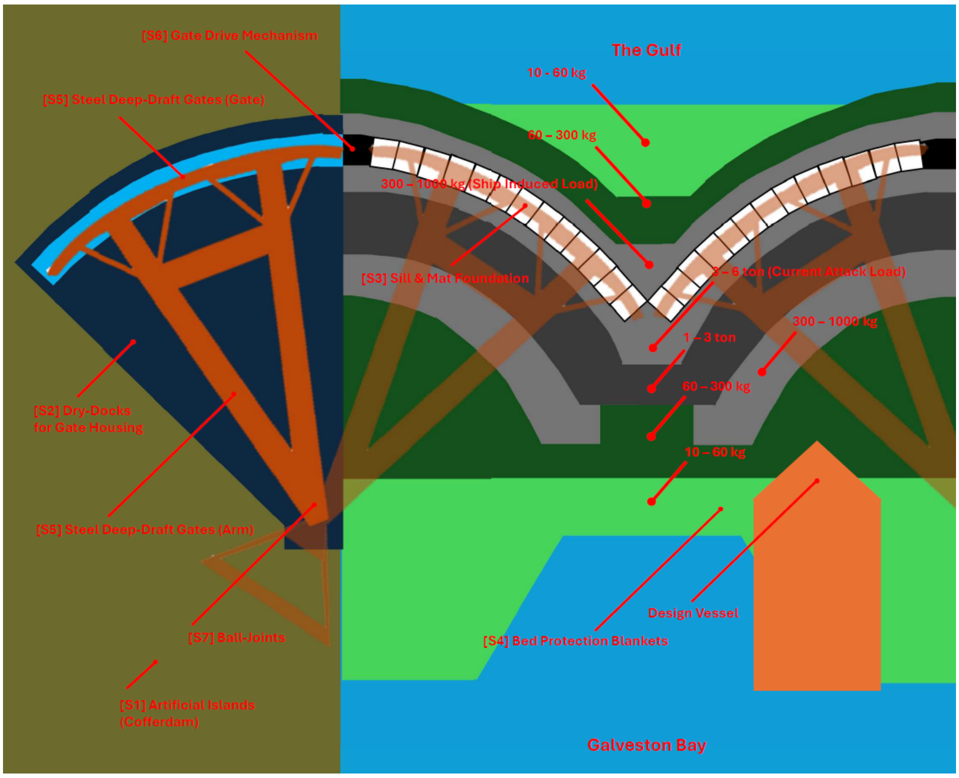


Figure F.14: Schematic of final design Alternative 1 - top view.

Figure F.13 presents a side view of the entire cross-section, showing the steel gates, sill and mat foundation, and the spatial variation of the bed protection classes. Figure F.14 shows the top view of the entire gated structure.

F.3.4. Design Verification: Alternative 2 (LEGO)

The goal of this concept development phase is to evaluate whether the modular LEGO-inspired scheme can be realized in a way that is both hydraulically effective and structurally sound, given the specific boundary conditions at Bolivar Roads. The same step-by-step design methodology used for Alternative 1 is applied here to ensure consistency in evaluation and comparison. However, to avoid redundancy, detailed derivations and formulas presented earlier will not be repeated in this section.

Structural Design Parameters and Boundary Conditions

The upcoming section introduces the main design inputs used throughout the technical assessment. These are illustrated in Figure F.15. Many of the parameters are the same as for Alternative 1, except de Design Vessel.

Structural Design Verification

To evaluate the overall stability of the adaptable sill beneath the Floating Sector Gates in Alternative 2, a set of simplifying assumptions has been applied. This analysis adopts a shallow foundation model, such as for alternative 1. This simplification allows the primary mechanisms influencing stability to be examined without the added complexity of specialized support conditions.

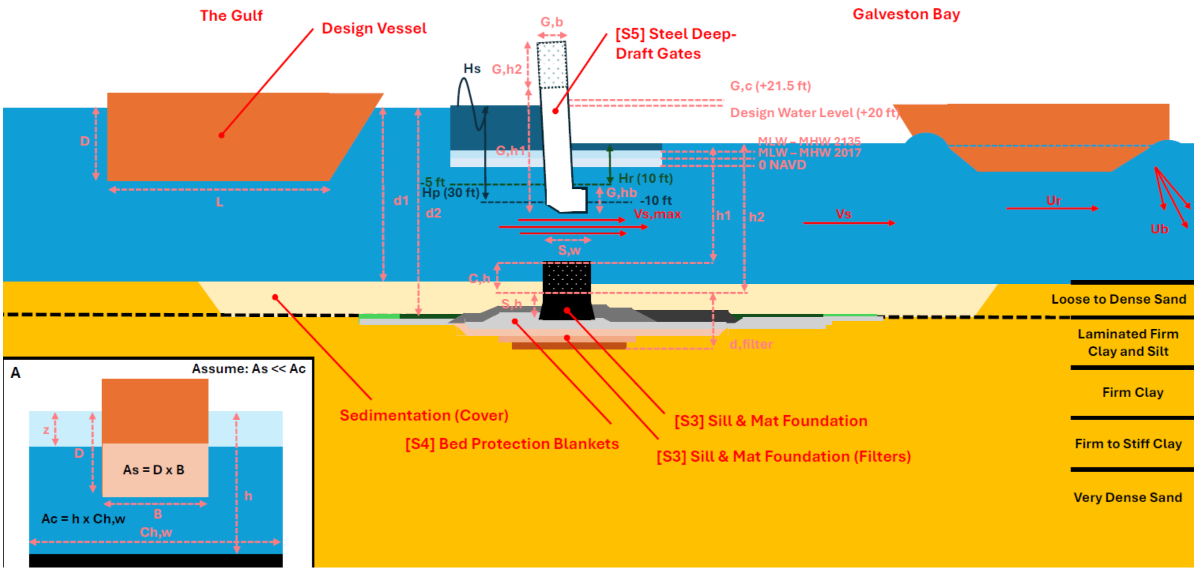


Figure F.15: Schematic of final design Alternative 2 - side view.

Sector Gate Characteristics		Imperial	Metric
Sector Gate			
Arm Length	L_{arm}	690 ft	210 m
Gate Height 1	$G_{h,1}$	81.5 ft	25 m
Gate Height 2	$G_{h,2}$	105 ft	32 m
Gate Width (z-axis)	G_b	26 ft	8 m
Gate Height Base	$G_{h,b}$	24 ft	7.4 m
Gate Opening(s)			
Depth Channel 1 – Sill Elevation	d_1	-60 NAVD ft	-18.3 NAVD m
Depth Channel 2 ~ Sill Elevation	d_2	-83.05 ft	-25.3 m
Width Channel	Ch_w	1180 ft	360 m
Cross-Section Area Channel 1	$A_{c,1}$	70800 ft^2	6588 m^2
Cross-Section Area Channel 2	$A_{c,2}$	97999 ft^2	9108 m^2
Sill Elevation 1	h_1	-60 NAVD ft	-18.3 NAVD m
Sill Elevation 2	h_2	-83.05 NAVD ft	-25.3 NAVD m
Crest Level of Gates in Sunken Position	G_c	21.5 NAVD ft	6.6 NAVD m
Sill Length	S_L	16 ft	3 m
Sill Height	$S_{h,1}$	10 ft	3 m
Caisson Height	h_c	23 ft	7 m
Sill Width	S_w	50 ft	15 m
Artificial Island			
Number of Islands	-	-	2
Width Islands	I_{width}	500 ft	150 m
Length Outer Islands	I_{length}	3600 ft	1100 m

Table F.19: Geometric and structural characteristics of the Floating Sector Gates and Artificial Islands (USACE, 2021d; Nottebom et al., 2022).

Geotechnical (Foundation)	Depth [NAVD ft]	Depth [NAVD m]
Very Soft Clay	0	0
Very Soft Clay + Silty Sand	-5	-1.52
Loose to Dense Sand	-55	-16.76
Soft to Firm Clay	-60	-18.29
Laminated Firm Clay and Silt	-80	-24.38
Firm Clay	-110	-33.53
Firm to Stiff Clay	-131	-40
Very Dense Sand	-165	-50.29

Table F.20: Geotechnical conditions Bolivar Roads (Jonkman, van Ledden, et al., 2013).

Boundary Conditions		Imperial	Metric
Blocking Storm Surge			
Design Horizon	-	2135 (i.e. 100 years)	-
Protection Level	Ph	1/100 years	-
Design Water Level (The Gulf side)	H	20 NAVD+ ft	6 NAVD+ m
(Positive) Head (Gulf > Bay)	Hp	30 ft	9.1 m
Reverse Head (Bay > Gulf)	Hr	10 ft	3 m
Design Wave Height	Hs	10 ft	3 m
Water Exchange			
Flow Regulation (Channel Flow)	Vs	6.56 ft/s	< 2 m/s
Flow Regulation (MLW - MHW 2017)	MLW-MHW	0.2–1.2 ft	0.1–0.3 m
Flow Regulation (MLW - MHW 2135)	MLW-MHW	2.6–3.6 ft	0.8–1.1 m
Flow Regulation (Tidal Response)	-	40 clsed %	72 % in Tide
Facilitate Navigation			
Design Draft Tanker (Suezmax)	Dt	75.5 ft	23 m
Design Width Tanker (Suezmax)	Bt	148 ft	45 m
Design Length Tanker (Suezmax)	Lt	935 ft	285 m
Cross-Section Area Tanker (As)	As_t	11144 ft^2	1035 m^2
Design Propeller Diameter (Suezmax)	$\text{Prop}_{t,\varnothing}$	26 ft	8 m
Power of Engine (Suezmax)	Pt	-	17117 kW
Design Draft Cruiseship	$Dcruise$	30 ft	9.13 m
Minimum Under Keel Clearance	UKC_{tmin}	7.55 ft	2.3 m
Design Depth HSC Project 11	d_{HSC11}	46.5 ft	14.2 m
Design Depth HSC Project 12+	d_{HSC12}	60 ft	18.3 m

Table F.21: Boundary conditions and vessel design (USACE, 2021d; Notteboom et al., 2022; Rodrigue, 2024).

Hand Calculations of Forces - Fully Closed under Storm Surge
For Alternative 2, the overall structural stability of the adaptable sill design is assessed in two distinct phases: (1) directly after construction, when the caisson structure is still present (refer to Figure F.16), and (2) in the future case, when the caisson is removed, resulting in a configuration comparable to Alternative 1 but with a deeper sill elevation (refer to Figure F.17). In both configurations, the governing condition is when the barrier is fully closed under storm surge, generating the highest hydraulic load on the structure (positive head from The Gulf > The Bay). Refer to Concept Development of Alternative 1 (Appendix F.3.3) for background on the determination of these forces.

The caisson configuration includes the additional self-weight of caisson. The self-weight of the caisson body including infill sand (G_{caiss}) = 5330 kN. Infill sand is assumed 80%.

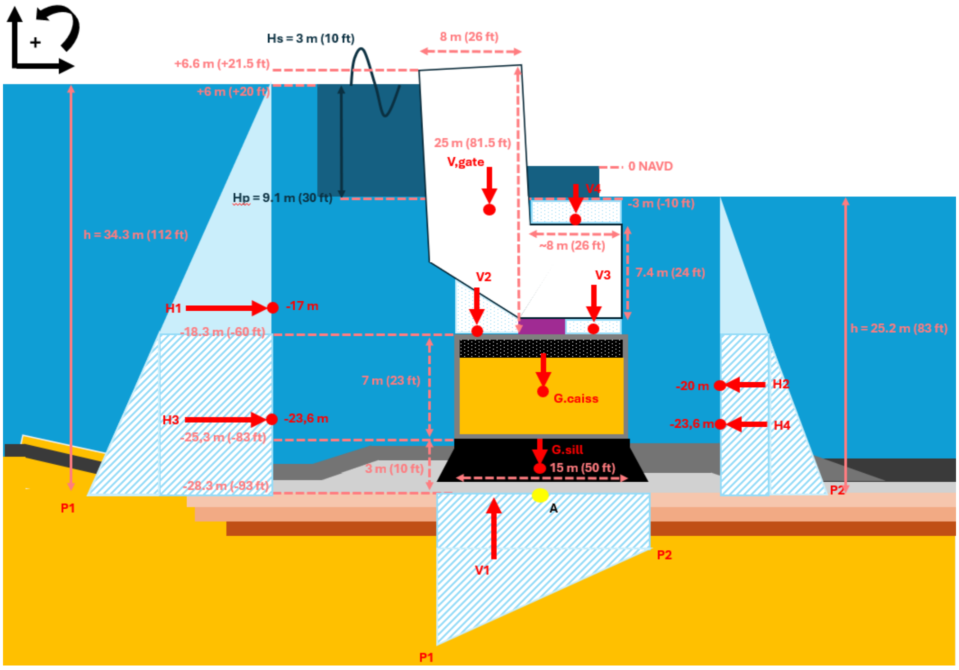


Figure F.16: Schematic forces – Alternative 2 with caisson: closed barrier (governing case).

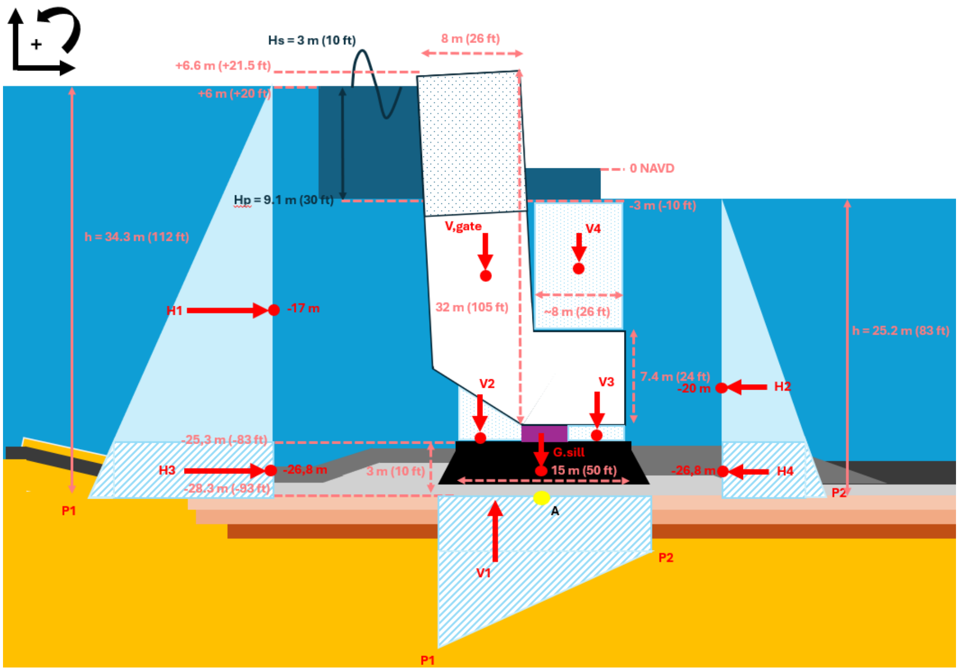


Figure F.17: Schematic forces – Alternative 2 without caisson: closed barrier (governing case).

These vertical stabilizing forces act counter to the hydrostatic uplift force under the sill (V_1), which is the primary destabilizing vertical force. The vertical forces V_2, V_3, V_4 are assumed negligible comparison with G_{caiss} and G_{gate}. Additionally, the horizontal pressures on both sides of the sill (H1, H2, H3, H4) are larger incomparrosin with alternative 1, due to the larger water depths. The horizontal and vertical forces for this case are summarized in Table F.22.

Symbol	Force Component	Force [kN]	PoA [NAVD m]
H1	Horizontal pressure (Gulf side)	29575	-17
H2	Horizontal pressure (Bay side)	15964	-20
H3	Lower horizontal pressure (Gulf side)	14731	-23.6
H4	Lower horizontal pressure (Bay side)	10156	-23.6
V1	Uplift pressure under sill	22436	-26.3
G_{sill}	Self-weight of concrete sill	5625	-18.3
G_{caiss}	Self-weight of caisson	8884	-21.8
V_{gate}	Vertical load of submerged gate	15663	-3.5

Table F.22: Summary of acting forces (with caisson) during governing condition.

In the long-term design configuration, the caisson is removed. The sill remains in place, now at a deeper elevation to accommodate structural stability through mass and geometry alone. However, the gate needs to be adjusted in this case, leading to an additional height, and thus larger vertical downward forces by the gate. Additional vertical forces V_2, V_3, are conservatively neglected due to their smaller contribution compared to the main vertical loads. However, V_4 is now considered due to the deep sunken position of the gate. These force summaries are used in subsequent sections to assess horizontal, rotational and vertical stability check for the adaptable sill design.

Symbol	Force Component	Force [kN]	PoA [NAVD m]
H1	Horizontal pressure – Gulf side	29575	-17
H2	Horizontal pressure – Bay side	15964	-20
H3	Lower horizontal pressure – Gulf side	4947	-26.8
H4	Lower horizontal pressure – Bay side	3575	-26.7
V1	Uplift pressure under sill	22436	-26.3
V4	Downlift above gate slot	2976	-4.0
G_{sill}	Self-weight of concrete sill	5625	-26.3
V_{gate}	Vertical load of submerged gate	69817	-3.5

Table F.23: Summary of acting forces (without caisson) during governing condition.

Failure Mode Check - Horizontal Stability
As elaborated in the concept development of Alternative 1 (refer to Appendix F.3.3), horizontal stability is ensured when the total horizontal hydrostatic load $\sum H$ remains smaller than the available sliding resistance, calculated as $f \cdot \sum V$, where $\sum V$ is the total vertical stabilizing force (including self-weight and gate load, minus uplift), and f is the friction coefficient.

For both cases, a representative value for laminated firm clay is adopted, reflecting the deeper embedment of the sill structure in comparison to the base alternative. A composite value of $f = 0.45$ is used, based on sub-layer characteristics between 0.2 and 0.6. Table F.24 summarizes the horizontal stability calculations for both design stages of Alternative 2. Only summarized results are presented below, as the calculation method follows the same procedure as previously described for Alternative 1 (refer to Appendix F.3.3).

Description	Case 1: With Caisson	Case 2: Without Caisson
$\sum H$ [kN]	4575	1373
$\sum V$ [kN]	-7736	-55983
f [-]	0.45	0.45
$f \cdot \sum V$ [kN]	3481	25192
Result	4575 > 3481 *Not Satisfied*	1373 < 25192 *Satisfied*

Table F.24: Horizontal stability check summary for Alternative 2: Case 1 (with caisson) and Case 2 (without caisson).

Failure Mode Check - Rotational Stability
Similar to Alternative 1, the adaptable sill must also be assessed for rotational stability under the governing condition (closed barrier, maximum positive head). The check ensures that the resultant of all vertical forces intersects within the middle third of the sill base. The stability criterion $e_R = \frac{\sum M}{\sum V} \leq \frac{1}{6}b$ is used, with $b = 15\,\mathrm{m}$. Only summarized results are presented below, as the calculation method follows the same procedure as previously described for Alternative 1 (refer to Appendix F.3.3).

Parameter	**Case 1: With Caisson**	**Case 2: Without Caisson**
$\sum M$ [kNm]	-19878	128674
$\sum V$ [kN]	-7736	-55983
$e_R = \frac{\sum M}{\sum V}$ [m]	2.6	2.3
$\frac{1}{6}b$ [m]	2.5	2.5
Result	2.6 > 2.5 *Not Satisfied*	2.3 < 2.5 *Satisfied*

Table F.25: Rotational stability check summary for Alternative 2 (Adaptable Sill): Case 1 (with caisson) and Case 2 (without caisson).

Failure Mode Check - Vertical Stability
The vertical bearing capacity of the subsoil is evaluated under the governing load condition, i.e., the fully closed barrier with maximum hydraulic head. As in the base design (Alternative 1), the vertical stability is assessed by comparing the maximum applied stress ($\sigma_{k,\max}$) with the bearing capacity of the soil ($p'_{\max}$). However, for Alternative 2 the sill is placed deeper in laminated firm clay layers, and therefore a characteristic bearing capacity of $p'_{\max} = 80\,\mathrm{kN/m^2}$ is assumed.

The governing values for both cases (with and without caisson) are summarized in Table F.26. Only summarized results are presented below, as the calculation method follows the same procedure as previously described for Alternative 1 (refer to Appendix F.3.3).

Parameter	**With Caisson**	**Without Caisson**
$\sum M$ [kNm]	-19878	128674
$\sum V$ [kN]	-7736	-55983
$\sigma_{k,\max}$ [kN/m^2]	206	57
$p'_{\max}$ [kN/m^2]	80	80
Result	206 > 80 *Not Satisfied*	57 < 80 *Satisfied*

Table F.26: Vertical stability check summary for Alternative 2 under governing load conditions.

The vertical stability condition is not satisfied for the with caisson case, indicating exceedance of bearing capacity under shallow foundation assumptions. In contrast, the without caisson case shows, satisfying the criterion. Given that a pile foundation is assumed for the final structure (USACE, 2021d), no further design adjustments are made to comply with the shallow foundation limit. Final vertical stability will depend on the pile foundation solution.

Failure Mode Check - Internal Backward Erosion
For Alternative 2, the risk of internal backward erosion (piping) is again assessed using Lane's method, under the same hydraulic head of $\Delta H = 9.1\,\mathrm{m}$. However, due to the deeper sill foundation in Alternative 2, the subsoil conditions are now classified as *firm clay*, with an adapted Lane coefficient $C_L = 1.8$. The vertical and horizontal seepage path lengths remain $\Sigma L_{\text{vert}} = 3\,\mathrm{m}$ and $\Sigma L_{\text{hor}} = 5\,\mathrm{m}$, respectively. Hence, in both stages of Alternative 2, this condition is not met. Refer for a qualitative elaboration to Concept Development of Alternative 1 (Appendix F.3.3).

Design Verification of Bed Protection Around the Adaptable Sill

Bed Protection Stability Check - Current Attack
For the adaptable sill (Alternative 2), the governing hydraulic loading scenario for bed protection occurs in the future configuration without the caisson, during a delayed barrier closure under a high head difference (see Figure F.18). In this scenario, flow accelerates under the partially closed gate, reaching a peak velocity of $v_{\text{max}} = 13\,\text{m/s}$ and depth-averaged velocity $U = 3.6\,\text{m/s}$, based on Torricelli's law.

In comparison to Alternative 1 (refer to Appendix F.3.3), the only modification is a increased flow depth (see Figure F.18), which results in a marginally lower depth-averaged flow velocity (decrease of $v_{\text{max}} = 0.2\,\text{m/s}$. All other parameters and assumptions used in the Pilarczyk (1998) equation remain unchanged. Refer to Concept Development Alternative 1 (Appendix F.3.3) and Rock Manual Chapter 5 (CIRIA et al., 2007) for an elaboration on the applied formulas, theorems, and designated parameters.

In comparison to Alternative 1, the only modification is a increased flow depth, which results in a marginally lower depth-averaged flow velocity (decrease of $v_{\text{max}} = 0.2\,\text{m/s}$. All other parameters and assumptions used in the Pilarczyk equation (Rock Manual) remain unchanged. As a result, the required rock sizes for the upstream and downstream armour layers are marginally smaller but remain within the same grading classes:

- Upstream of the Sill: $D_{50,\text{up}} = 0.95\,\text{m}$, $D_{n50,\text{up}} = 0.80\,\text{m}$, results in grading class HMA 1000–3000 (Schiereck and Verhagen, 2019),
- Downstream of the Sill: $D_{50,\text{down}} = 1.15\,\text{m}$, $D_{n50,\text{down}} = 0.97\,\text{m}$, results in grading class HMA 3000–6000 (Schiereck and Verhagen, 2019).

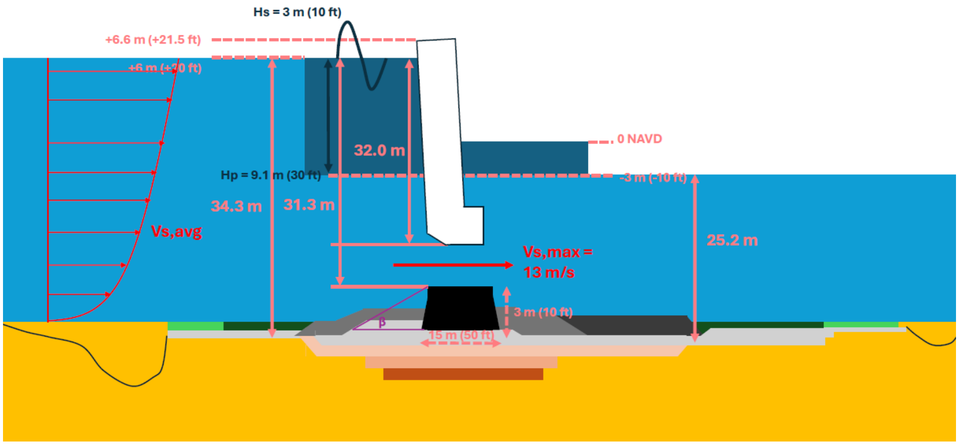


Figure F.18: Schematic Alternative 2 bed protection stability under current attack.

Bed Protection Stability Check - Wave Load
To ensure adequate protection of the bed during storm-induced wave action, a wave loading stability check is performed for the governing case: the future scenario without the caisson, where the barrier closes late under a high head difference (storm conditions). As in the base case, only the upstream side is considered exposed to wave activity (see Figure F.19). Downstream wave loading is assumed negligible due to the presence of the gate. Refer to Concept Development Alternative 1 (Appendix F.3.3) and Schiereck and Verhagen (2019) for an elaboration on the applied formulas, theorems, and designated parameters.

In comparison to Alternative 1, the only changed parameter is the local water depth, which increases due to the deeper sill elevation (see Figure F.19). This results in a slight decrease in the computed orbital velocity at the bed ($\hat{u}_b = 2.1\,\text{m/s}$), as the effect of the bottom on the the wave-induced orbital velocity decreases with increasing depth reducing the wave-induced loading on the bed.

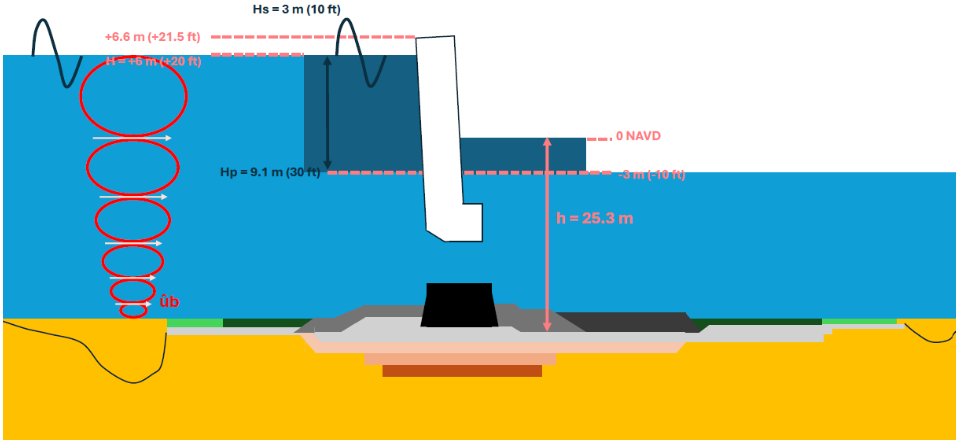


Figure F.19: Wave-induced bed loading conditions and definition of orbital motion on Floating Sector Gates.

All other parameters, such as wave height, wave period, and relative buoyant density, are maintained the same. The effect of this change is a lower required armourstone size for bed protection under wave load. The resulting required nominal stone size is $d_{n50} = 0.06\,\mathrm{m}$, giving $D_{50} = 0.08\,\mathrm{m}$. This corresponds to armourstone class CP45/180 course grading (Schiereck and Verhagen, 2019), which is a reduction compared to the original class LMA 40–200 required in the base case.

Bed Stability Check - Ship Load

In the adaptable sill design, the future scenario without the caisson represents the governing case for ship-induced loading. This scenario accommodates deeper-draft vessels, specifically a Suezmax oil tanker, compared to the MGX-24 container vessel in the base case. The Suezmax has a significantly increased design draft of 23 m (up from 16 m for MGX-24), a width of 45 m (vs. 32.3 m), and a length of 285 m (vs. 400 m), resulting in a larger effective cross-sectional propeller wash area and greater propeller proximity to the bed (i.e., reduced h_p, see Figure F.20). However, the design propeller diameter and and power of the engine are less compared to the MGX-24, refer to Table F.21. These changes impact the magnitude of the near-bed velocity from propeller jets and thus the required stability of the bed protection. Refer to Concept Development Alternative 1 (Appendix F.3.3) and PIANC (2015) for an elaboration on the applied formulas, theorems, and designated parameters.

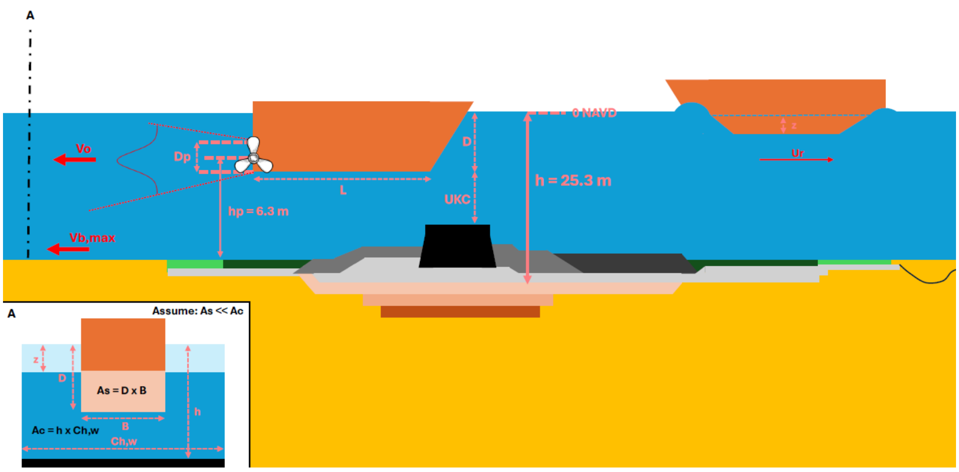


Figure F.20: Flow field induced by a passing vessel over the sill (propeller wash load case).

Using the PIANC (2015) guidelines and the updated vessel propulsion parameters (e.g., $P_D = 17{,}117$ kW, $D_p = 8$ m), the resulting propeller efflux velocity is $V_0 = 9.23\,\mathrm{m/s}$ and the maximum near-bed velocity is $V_{b,\max} = 2.93\,\mathrm{m/s}$. These inputs yield a required median rock size of:

- Upstream of the Sill: $D_{50,\mathrm{up}} = 0.42$ m, $D_{n50,\mathrm{up}} = 0.35$ m,
- Downstream of the Sill: $D_{50,\mathrm{down}} = 0.42$ m, $D_{n50,\mathrm{down}} = 0.35$ m.

This corresponds to armourstone grading class LMA 60–300 (Schiereck and Verhagen, 2019), which is a lighter grading than the class HMA 300–1000 used in the base design. The decrease in rock size requirement is attributed to the reduced propeller loading intensity relative to bed contact.

Bed Protection Length Check
In the adaptable sill design, the future scenario without the caisson again governs the design for scour protection length. However, applying the same design methodology as used for the base case leads to an unrealistic result (Refer to Concept Development Alternative 1 (Appendix F.3.3) and Voorendt (2022) for an elaboration on the applied formulas, theorems, and designated parameters). Due to the increased water depth ($h_0 = 25.3$ m), the scour depth calculation yields a value of $h_{\max} = 19.73$ m, which is physically implausible and not observed in comparable real-world conditions. This depth translates into a required protection length of $L = 444$ m, an excessively large extent that is deemed unfeasible both from a construction and cost perspective.

The simplified equilibrium scour method is based on shallow-to-intermediate flow regimes and may become invalid when the hydraulic radius and flow depth substantially increase. In such deepwater conditions, the assumptions embedded in the Shields parameter and Chézy roughness formulation no longer reliably capture the mechanics of sediment behavior and scour development, leading to overestimation of the scour hole dimensions.

For these reasons, the bed protection length as calculated for the base case (Alternative 1), i.e., $L = 248$ m, is retained as the design basis for the adaptable sill. This provides a conservative and practically justifiable approach while recognizing the method's limitations in deeper water scenarios. If needed, a more advanced scour analysis could be performed using CFD or physical model testing in future design phases.

Design Verification of Geometrically Open Filters under the Sill
In the future scenario of the adaptable sill without caisson, the filter layer system is reassessed under the governing hydraulic condition: ships with increased draft (e.g., a Suezmax tanker) and corresponding changes in flow velocity and hydraulic radius. Refer to Concept Development Alternative 1 (Appendix F.3.3), CUR Report 161 (CUR, 1993) and the Rock Manual Chapter 5 (CIRIA et al., 2007) for an elaboration on the applied formulas, theorems, and designated parameters.

However, the governing load for determining the armourstone size remains the current-induced attack, resulting in a required armour class of HMA 3000–6000 for the top layer (which is the same at Alternative 1). No change is assumed in the subsoil composition (fine silty sand or clayey fines). The only updated design parameter is an increase in hydraulic radius from $R = 17$ m to $R = 22$ m. This could, in principle, influence the required filter dimensions due to changes in critical gradient and hydraulic load. However, re-evaluation of the filter design shows that the filter configuration previously determined for Alternative 1 remains fully sufficient under these new conditions.

Both the Critical Gradient Method (CUR, 1993) and Bakker-Konter (CIRIA et al., 2007) interface checks, when re-applied using the updated R value and existing layer gradations, confirm that the required stability and hydraulic permeability are still met. As the grain size of the subsoil and the top layer armourstone remain unchanged, and given the absence of significant changes to other hydraulic boundary conditions, no adjustment to the filter layer construction is necessary. Therefore, the same multi-layered geometrically open filter system, developed and validated in the Appendix F.3.3 for the base case, can be adopted for the future adaptable sill configuration.

F.3.5. The Construction and Use Sequence of the Adaptable Sill

The caisson-based adaptable sill offers a simple yet proven constructability strategy (Voorendt et al., 2020). Its modular nature allows for a phased construction process using standard marine equipment, while also enabling future reconfiguration with minimal disruption. This construction concept unfolds in two phases. The Initial Construction Phase builds a fully functional sill configuration using prefabricated caisson modules filled with sand, placed atop a reinforced filter and foundation system. Later, in the Future Construction Phase, the flexibility is activated. The caissons can be easily emptied, floated, and removed to restore full channel depth. This two-step approach minimizes upfront costs while preserving adaptability. The following steps gives a simplification of this construction method. Stated equipment is extracted from Chapter 13 of Schiereck and Verhagen (2019). The caisson construction method is based on Voorendt et al. (2020).

Initial Construction Phase (build-in flexibility)

(a) Step 1: Installation of pile foundation.

(b) Step 2: Dredging to final filter layer depth.

Figure F.21: Construction sequence for Alternative 2 – Initial foundation preparation.

Step 1: Installation of Pile Foundation (Figure F.21a)
The process begins with the placement of a foundation using prefabricated steel piles. A floating pile-driving rig or barge-mounted crane is used to vertically drive the piles into the bed, reaching into stable soil layers. The piles act as long-term structural supports for the sill foundation.

Step 2: Dredging to Final Depth (Figure F.21b)
A trailing suction hopper dredger or cutter suction dredger is mobilized to excavate to the final depth required for the sill configuration. Split barges may be used to transport and dispose of the dredged material. GPS-guided dredging ensures level excavation to avoid over-dredging or bed disturbance.

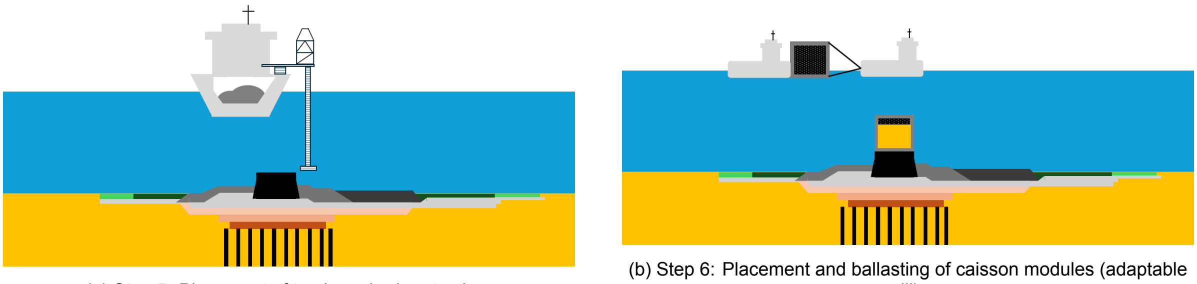
Step 3: Placement of Filter Layers (Figure F.22a)
Using waterborne equipment such as side stone dumping vessels, pontoons with excavators, or fall-pipe vessels (for precision), a multi-layer granular filter is placed. Grading transitions from fine crushed sand (0.5–5 mm) to light rock (10 - 60 kg), ensuring permeability and preventing piping or winnowing.

(a) Step 3: Placement of multi-layer filter system.

(b) Step 4: Placement of sill modules.

Figure F.22: Construction sequence for Alternative 2 – Filter and sill installation.

Step 4: Placement of Concrete Sill Modules (Figure F.22b)
Precast concrete modules forming the permanent sill are placed atop the filter system using floating crane barges. Precision is ensured using winch-controlled lowering and slack tide conditions to reduce current forces. The sill is aligned with underwater markers and a gravel bedding.



(a) Step 5: Placement of top layer bed protection.

(b) Step 6: Placement and ballasting of caisson modules (adaptable sill).

Figure F.23: Construction sequence for Alternative 2 – Final sill and bed protection works.

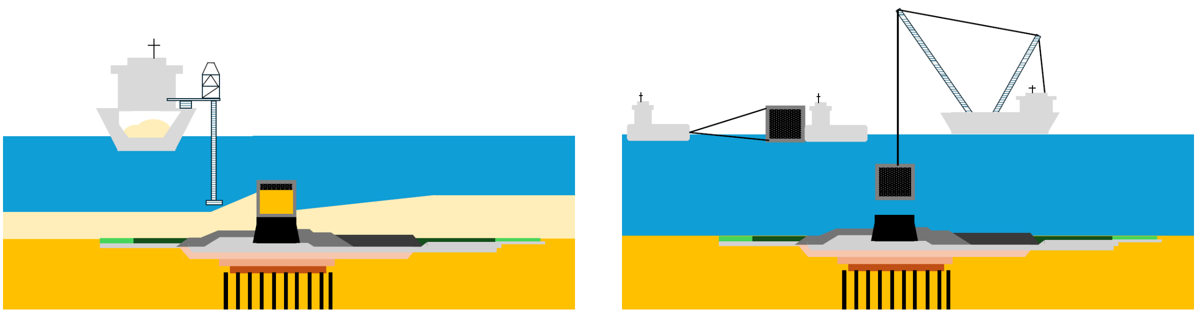
Step 5: Placement of Heavy Armour (Top Layer Protection) (Figure F.23a)
Heavy armour rock is applied using stone placement vessels. The heaviest gradings (3–6 tons) are placed in central zones, while 10–60 kg and 60–300 kg stones are used further out. A fall-pipe vessel is used where precision is critical.

Step 6: Placement of Caissons (Figure F.23b)
Prefabricated caissons are towed from a construction dock using tugboats and immersed using ballasting techniques. Water ballast tanks are filled to control descent. Positioning is done during slack tide using winches and anchors. Once submerged, the caissons are filled with sand via split barges or bottom dump vessels, forming a raised sill.

Future Construction Phase (leveraging flexibility)

Step 1: Dredging Sedimentation Cover (Figure F.24a)
Over time, sediment may accumulate over the sill. Before caisson removal, this sedimentation cover is dredged to expose the original armour layer. Dredging is done using suction dredgers or clamshell grabs, avoiding damage to filter layers.

Step 2: Removal of Caissons (Figure F.24b)
The sand inside the caissons is removed via pumping or grab excavation. As ballast is removed, the caisson becomes buoyant and floats. Winch cranes and tugs remove the modules, restoring the sill to its original low-profile configuration.



(a) Step 1: Dredging of sedimentation layer to expose caisson.

(b) Step 2: Floatation and removal of caisson modules.

Figure F.24: Removal sequence for Alternative 2 – Caisson exposure and retrieval.

G

Transcripts Semi-Structured Interviews

The resulting research findings of Phase 1, 2 and 3 were discussed and validated through semi-structured interviews with experts and main stakeholders. The interviews offer tacit information about the nature, the meaning, and an understanding of the Coastal Texas Study, and storm surge barrier (SSB)s in general. Furthermore it helps to explain, describe, and evaluate the research findings. Semi-structured interviews provide the opportunity to discuss the research findings with a number of questions, and explore beyond these questions. Relative to other interview types a semi-structured interview is relatively simple, gives reduced bias, and increased credibility, reliability and validity.

G.1 Interviewee Selection

For the interviews conducted, judgment sampling was employed to select a targeted group of respondents. This approach allows for a focus on experts with specialized knowledge in SSBs, particularly those familiar with the Bolivar Roads Gate System. Participants were chosen from key institutions and stakeholders, including I-STORM, Rijkswaterstaat, Texas A&M, Houston Pilots, the Texas General Land Office, and the Gulf Coast Protection District.

G.2 Interview Protocol

The interview protocol was developed following the Literature Review, refer to Table G.1. As part of the preparation for conducting the semi-structured interviews in this research, a Data Management Plan (DMP) was developed in accordance with TU Delft's guidelines. Using the TU Delft DMP template (2025) and reviewed by the faculty Data Steward on 10 February 2025. Alongside the DMP, the Human Research Ethics Checklist (i.e., HREC Checklist) was completed and submitted, outlining the methodology, data handling procedures, and ethical safeguards for working with human participants. The research protocol, including informed consent procedures, interview structure, and risk mitigation strategies, was reviewed and subsequently approved by the Human Research Ethics Committee (HREC) of TU Delft on 23 February 2025. These steps ensured that all interviews were conducted with full ethical compliance and aligned with data protection standards. Documentation regarding the approved DMP, the completed HREC Checklist, and the official letter of approval from the HREC Committee are retrievable from the responsible researcher.

G.3 Applied Method: Thematic Analysis

A thematic analysis was performed (i.e., identify common themes). The procedure followed three steps:

Step 1: Identifying Common Themes

Open coding was used to break down the transcripts into discrete, meaningful statements or phrases that pointed to dependencies relevant to the SSB system. These included both technical and socio-economical factors such as: increasing vessel size and funding delays. Mentions were counted and categorized when they appeared multiple times or were emphasized by the interviewee.

Section	Details
Introduction	• Welcome the respondent and provide interview purpose; • Explain the consent form;
Main Topics Phase 1	• Understanding of baseline design concept; • Design feasibility and considerations; • Technical and functional aspects; • Operational functionality and maintenance; • Stakeholder needs and concerns, focus on asset management; • Overall assessment and recommendations;
Main Topics Phase 2	• Identifying uncertain system drivers, and prior probability; • Historical trends of system drivers; • Possible future scenarios;
Main Topics Phase 3	• Dependent relationships between system drivers and SSB elements;
Conclusion	• Thank respondent for their time; • Reconfirm confidentiality.

Table G.1: Interview Protocol.

Step 2: Grouping into Themes
The identified themes were then clustered into broader themes, aligned with elements of the ESM (i.e., Phase 3). This step served to structure the analysis around drivers and elements of the system. The clustering was based on both the meaning of the themes and their contextual role in the system.

Step 3: Assigning Dependencies
In the final stage, selective coding was used to explicitly assign dependency strengths between drivers and system elements using the following qualitative scale:

- *Strong*: the driver was discussed with high frequency or described as having a direct and critical impact on the system element;
- *Moderate*: the connection was discussed clearly but with less emphasis or indirect influence;
- *Weak*: mentioned only briefly or inferred with minor emphasis;
- *Not Mentioned*: no direct link was drawn in the interview.

G.4 Summary Transcript - Interview A

Major Sources of Uncertainty Affecting the Future Performance of a Storm Surge Barrier

Physical System Drivers

- *Morphological and Hydrodynamic Changes:*
  - The construction of the storm surge barrier will disrupt the fragile equilibrium of Galveston Bay. The bay is a low-energy system with fine sediments, meaning even small disturbances can lead to large, unintended changes in sediment transport and hydrodynamics.
  - Changes in sedimentation and water flow patterns could affect navigability, ecosystem balance, and structural stability over time.
  - Example: changes in wind patterns alone have led to substantial variations in local water levels, independent of tidal effects. Similar shifts could have large, unforeseen consequences on the bay's dynamics once the barrier is in place.
- *Relative Sea Level Rise & Land Subsidence:*
  - Relative sea level rise consists of both rising water levels and land subsidence. While sea level rise follows a predictable trajectory based on climate models, land subsidence is more variable and site-specific. The foundation and elevation of the barrier must be resilient to these long-term trends.
- *Extreme Weather Events (Hurricanes, Storm Surges, and Wind Fields):*
  - The unpredictability of hurricanes poses significant challenges. Each hurricane has unique characteristics, including intensity, trajectory, and duration.
  - A storm surge barrier must function effectively under these extreme conditions, but the evolving nature of hurricanes due to climate change introduces new uncertainties.
  - Examples:
    - Hurricane Harvey (2017): produced catastrophic flooding due to excessive rainfall, not storm surge.
    - Hurricane Ike (2008): a classic storm surge event that caused widespread inundation.
    - Hurricane Beryl (2024): primarily a high-wind event, knocking out power grids.
  - A single storm surge barrier cannot address all hurricane-related risks, but it is critical for mitigating surge-induced flooding.

Socio-Economic System Drivers

- *Maritime Industry and Vessel Traffic Growth:*
  - The Gulf region is experiencing increasing maritime trade, with ever-larger vessels requiring deeper and wider shipping channels.
  - The barrier could become a bottleneck for economic activity, necessitating potential future modifications.
  - Example: Ports along the Gulf Coast are in constant competition for deeper channels to accommodate the latest generation of cargo and oil tankers.
- *Stakeholder Uncertainty & Governance Challenges:*
  - Multiple entities are involved in the storm surge barrier's construction, operation, and maintenance.
  - The U.S. Army Corps of Engineers is leading construction, but long-term operational responsibility remains uncertain.
  - Political and organizational instability may affect funding, maintenance schedules, and decision-making.
  - The barrier's function is intertwined with global economic conditions. Changes in trade routes, sanctions, or geopolitical events could alter shipping patterns unexpectedly. (Example) a U.S.-China trade war, a pandemic, or an energy crisis could significantly impact shipping volumes, influencing how the barrier is used.

Main Objectives

- *Primary function:* to prevent storm surges from raising water levels in Galveston Bay, protecting Houston and surrounding economic areas.
- *Secondary functions:* allowing navigation under normal conditions and minimizing ecological disruption.

Main Stakeholders

- Residents & Businesses (e.g., flood protection, economic security).
- Army Corps of Engineers & Texas Authorities (e.g., construction and governance).
- Maritime Industry (e.g., ensuring minimal disruption to trade).
- Environmental Groups (e.g., ecosystem preservation).

Main Operation & Maintenance Concerns

- *Traffic Congestion & Collision Risk:* The barrier introduces a bottleneck in a region known for frequent maritime accidents. (Example) a recent tanker collision in Houston disrupted shipping for days.
- *Severe Corrosion & Biofouling:* (Example) research equipment left in Galveston Bay for just two weeks accumulates barnacles and algae.
- *High Maintenance Demands:* (Example) similar projects in New Orleans require constant upkeep due to extreme weathering.

Does the Level/Quantity of [System Driver X] Significantly Affect the Design of the Storm Surge Barrier?

Some drivers have a direct and significant impact on the barrier's design, while others may be more relevant for operational considerations.

- *Relative Sea Level Rise (Strong Impact on Design):*
  - Requires higher foundation elevation and potential for future adaptability.
- *Maritime Traffic Growth & Vessel Size (Strong Impact on Design):*
  - Impacts the required width, depth, and operational procedures of the barrier. *Example:* The Port of Houston has already undergone multiple expansion projects, demonstrating a trend toward ever-larger vessels.
- *Short-Term Economic Shifts (Minimal Impact on Design):*
  - Fluctuations in trade do not immediately necessitate design changes.
- *Climate Change Effects Beyond Sea Level Rise (Minimal Impact on Design):*
  - While temperature and drought may impact broader infrastructure, they do not significantly influence the barrier's core function.

Interview A: Thematic Analysis

Theme	Category	# Mentions
Vessel size growth / channel depth	Economic Growth	5
Maritime trade competition	Economic Growth	2
Traffic congestion / collisions	Economic Growth / O&M	3
Sea level rise	Relative Sea Level Rise	4
Land subsidence	Relative Sea Level Rise	3
Extreme weather / hurricanes	Relative Sea Level Rise	4
Maintenance / corrosion / biofouling	Asset Management	4
Governance uncertainty	Asset Management	2
Structural stability	Structural Integrity	2
Foundation elevation / dredging	Sill/Foundation	3

Table G.2: Identify and Grouping Common Themes - Summary Transcript Interview A.

Driver	ESM	# of Mentions	Dependency
S1	F2	6	Strong
S1	S3	3	Strong
S1	S1	2	Moderate
S1	O&M2	3	Moderate
S1	S5	1	Low
S2	F1	4	Strong
S2	S3	4	Strong
S2	S5	2	Moderate
S2	O&M2	2	Moderate
S2	F5	2	Moderate
S2	O&M1	1	Weak

Table G.3: Assigning Relational Dependencies - Summary Transcript Interview A.

G.5 Summary Transcript - Interview B

Major Sources of Uncertainty Affecting the Future Performance of a Storm Surge Barrier

Physical System Drivers

- *Sea Level Rise:* One of the most critical uncertainties affecting storm surge barriers. If sea level rise exceeds projections, existing barriers may become ineffective or require significant modifications.
- *Increased Storm Intensity and Frequency:* More frequent and stronger storm surges put higher stress on the barrier's structure, requiring more robust designs.
- *Seiches (Standing Waves):* Initially overlooked in the Maeslantkering, seiches were later identified as a significant risk. Their unpredictable nature makes it harder to design a barrier that can effectively handle extreme water level fluctuations.
- *Sedimentation and Morphological Changes:* Over time, shifting seabeds and sedimentation patterns may alter the effectiveness of the barrier, requiring dredging or design modifications.
- *Protected Species and Legal Constraints:* (Example) Seagulls nesting in structural components of the Maeslantkering led to maintenance delays because regulations prohibit disturbing nests during the breeding season (April-September).
- *Water Exchange and Ecosystem Impact:* Ensuring the movement of water to maintain ecological balance is a challenge. A poorly designed barrier could disrupt fish migration, water salinity levels, and overall biodiversity.
- *Aging Infrastructure and Material Fatigue:* Components such as the bolscharnier (large gate hinge) in the Maeslantkering have shown signs of wear, raising concerns about long-term durability.
- *Lack of Redundant Components:* (Example) The dock doors in storm surge barriers often lack backup systems, creating vulnerability in case of failure.

Socio-Economic System Drivers

- *Government Reorganizations & Budget Cuts:* (Example) Rijkswaterstaat's restructuring led to a loss of specialized knowledge, impacting maintenance quality and decision-making. Funding cuts have also led to cost-saving measures, such as replacing hardware-based solutions with software-based control systems in the Maeslantkering, which later resulted in issues.
- *Unforeseen Maintenance Costs:* Barriers require ongoing investments, and when funds are delayed, maintenance backlogs accumulate.
- *Flood Protection vs. Economic Development:* The primary function of the barrier is flood protection, but stakeholders like shipping companies, fisheries, and environmental organizations have competing interests.
- *Conflicts Between Maintenance Needs and Legal Restrictions:* (Example) Dutch ARBO (health and safety regulations) and cybersecurity concerns were not initially considered but later became major constraints.

Impact of System Drivers on Barrier Design

- *Rising Sea Levels & Storm Intensities:* Require higher barriers, stronger foundations, and more adaptable gates to handle extreme water levels.
- *Environmental Regulations & Protected Species:* Design needs to prevent birds from nesting in structural components to avoid maintenance delays. The use of artificial nesting sites or barriers to prevent access can be considered.
- *Financial Constraints Leading to Suboptimal Designs:* (Example) The Maeslantkering's floodgate ballast system was originally designed with mechanical ballast tanks, but cost-saving measures led to their removal, resulting in increased reliance on software-controlled systems.
- *Increased Software Dependency:* While digital automation improves efficiency, it also creates challenges related to long-term software maintenance, vendor dependence, and cybersecurity.

Physical Components Affected by Changing System Drivers

- *Structural Integrity Elements:*
  - *Bolscharnier (Large Gate Hinge):* Critical wear point in barriers like Maeslantkering, vulnerable to material fatigue.
  - *Dock Doors:* Lack of backup units means a failure could result in operational shutdowns.
- *Water Exchange Systems:* Changes in sediment accumulation and water salinity require adaptable flow control mechanisms.
- *Mechanical & Operational Systems:* Hydraulic systems, pumps, and motors must be designed to handle long-term wear while ensuring reliability.

Main Objective of a Storm Surge Barrier

- *Primary Goal - Flood Protection:* Preventing catastrophic flooding to safeguard human lives, economic assets, and infrastructure.
- *Secondary Objectives:*
  - Maintaining ecological balance.
  - Ensuring shipping and navigation functionality.
  - Supporting economic activities (ports, fisheries).

Main Stakeholders

- Government Authorities (e.g., Rijkswaterstaat in the Netherlands).
- Asset Management Organizations (handling long-term maintenance).
- Shipping & Port Authorities.
- Environmental Agencies.
- Local Communities & Economic Sectors.

Operation/Organization Concerns

- *Knowledge Retention & Organizational Structure:* (Example) Rijkswaterstaat's fragmentation of responsibilities led to gaps in barrier oversight.
- *Reliability & Safety Considerations:* Need for continuous monitoring and predictive maintenance.
- *Cost of Ownership & Long-Term Financial Planning:* Case studies like MOSE barrier and Rampsol barrier highlight the importance of full life-cycle cost analysis.

Maintenance Concerns

- *Adapting to Future Conditions:* Extending maintenance life beyond initial projections.
- *Ensuring Accessibility for Repairs:* (Example) Maeslantkering was not designed with easy maintenance access, creating logistical issues.
- *Impact of Budget Cuts:* Deferred maintenance increases future costs exponentially.
- *Unintended Consequences:* (Example) Bird nesting restrictions delaying critical maintenance work.
- *Software & Automation Dependencies:* Aging software infrastructure causing system reliability concerns.

Interview B: Thematic Analysis

Theme	Category	# Mentions
Sea level rise	Relative Sea Level Rise	4
Increased storm intensity	Relative Sea Level Rise	3
Sedimentation / Seiches	Hydrodynamic / Morphology	3
Protected species / maintenance delay	Legal Constraints	2
Ecosystem impact / water exchange	Water Exchange	3
Aging infrastructure / fatigue	Structural Integrity	3
Lack of redundancy	Structural Integrity	2
Software dependency	Automation	3
Budget cuts / maintenance backlog	Asset Management	3
Knowledge loss / fragmentation	Asset Management	2
Flood protection function	Flood Protection	3
Navigation / shipping	Navigation	2

Table G.4: Identify and Grouping Common Themes - Summary Transcript Interview B.

Driver	ESM	# of Mentions	Dependency
S2	F1	3	Strong
S2	F2	2	Moderate
S2	F3	3	Strong
S2	F5	5	Strong
S2	S3	4	Strong
S2	S5	2	Moderate
S2	O&M1	3	Moderate
S2	O&M3	3	Moderate

Table G.5: Assigning Relational Dependencies - Summary Transcript Interview B.

G.6 Summary Transcript - Interview C

Major Sources of Uncertainty Affecting the Future Performance of a Storm Surge Barrier

Physical System Drivers

- *Relative Sea Level Change:*
  - As global sea levels continue to rise, the structural integrity and effectiveness of the storm surge barrier may be compromised. If sea level rise exceeds current projections, the barrier may require significant modifications.
- *Hurricanes & Storm Surges:*
  - With climate change increasing the frequency and intensity of storms, the ability of the barrier to withstand extreme weather events remains uncertain.
- *Engineering Uncertainties:*
  - The barrier is expected to last at least 100 years, raising concerns about long-term durability, maintenance, and adaptability.

Socio-Economic System Drivers

- *Maritime Traffic & Vessel Size:*
  - The increasing size of commercial vessels necessitates the construction of wider and deeper navigation channels, which could impact the barrier's design and operation.
- *Political & Financial Uncertainty:*
  - The most unpredictable factor in the project is political will. (Example) Unlike in the Netherlands, where long-term infrastructure projects receive strong governmental support, the U.S. political system is highly volatile. Decision-making is often influenced by short-term political agendas, partisan conflicts, and changing administrations.

  - The total estimated cost of the project has escalated from $8–12 billion for gates to a $34 billion bundled project, raising concerns over whether it will ever be fully funded.
  - In the U.S., projects are frequently delayed or derailed by lawsuits, particularly from environmental groups. The legal system allows minor stakeholders to challenge large-scale infrastructure projects, often leading to prolonged litigation.
  - (Example) In New Orleans, after Hurricane Katrina, a $20–25 billion flood protection system was implemented within five years due to immediate political urgency. In contrast, Houston, despite its greater economic importance, has struggled for decades to secure funding for similar protection.

Main Objective of the Storm Surge Barrier

- *Prevent Flooding in Galveston Bay and Houston Ship Channel.*
- *Safeguard Critical Infrastructure:*
  - Protects oil refineries, chemical plants, and military supply chains, which are vital to the U.S. economy.
  - Despite Houston's economic and strategic importance, political and financial roadblocks have delayed the construction of a storm surge protection system. The delay increases the risk of catastrophic loss with every passing hurricane season.

Main Stakeholders

- USACE & Gulf Coast Protection District (GCPD) (Government Agencies)
- Port Authorities (Houston, Galveston)
- Environmental Advocacy Groups (Likely opponents, as lawsuits could be filed over wildlife, wetlands, or endangered species protections).

Main Operation & Maintenance Concerns

- The Gulf Coast Protection District has no technical expertise, raising concerns about its ability to manage operations and maintenance. (Example) GCPD lacks sufficient workforce.
- Political shifts could change funding availability or operational control.
- *U.S. Infrastructure Maintenance Culture is Weak:* Unlike in the Netherlands, where maintenance is built into long-term planning, U.S. projects often ignore maintenance costs until failure occurs.
- *Funding Uncertainty:* (Example) Annual maintenance cost estimated at $500M+.
- *Risk of Neglect:* New Orleans' flood defenses are already struggling with maintenance due to lack of funding.

Interview C: Thematic Analysis

Theme	Category	# Mentions
Relative sea level change	Relative Sea Level Rise	4
Hurricanes	Relative Sea Level Rise	2
Life-cycle	Structural Integrity	3
Maritime traffic & vessel size	Economic Growth	3
Political & financial uncertainty	Asset Management	4
Environmental lawsuits	Ecosystem Impact	2
Weak U.S. maintenance culture	Asset Management	2
Lack of technical expertise (GCPD)	Asset Management	2
Maintenance costs	Asset Management	2
Sector gates	Structural Integrity	2
Sill elevation	Structural Integrity	2

Table G.6: Identify and Grouping Common Themes - Summary Transcript Interview C.

Driver	ESM	# of Mentions	Dependency
S1	F2	2	Strong
S1	S3	2	Moderate
S1	S5	1	Moderate
S2	F1	3	Strong
S2	F5	2	Moderate
S2	S3	2	Strong
S2	O&M2	2	Moderate
O&M	O&M1	4	Strong
O&M	O&M2	2	Moderate

Table G.7: Assigning Relational Dependencies - Summary Transcript Interview C.

G.7 Summary Transcript - Interview D

Major Sources of Uncertainty Affecting the Future Performance of a Storm Surge Barrier

Physical System Drivers

- *Morphological and Hydrodynamic Changes:*
  - A key source of uncertainty stems from how the local hydrodynamic and morphological systems around Bolivar Roads might respond once a storm surge barrier is introduced. Similar to the Eastern Scheldt barrier in the Netherlands, there is concern that changing the equilibrium conditions of water flow and sediment transport can lead to scour formation and altered tidal dynamics.
- *How Hurricanes Manifest:*
  - Hurricanes can manifest in vastly different ways. (Example) Hurricane Harvey brought an unprecedented amount of rainfall rather than a massive storm surge, yet still resulted in severe flooding. Other hurricanes may have different characteristics, stronger winds, higher surge, or varied landfall locations, leading to a range of outcomes for Galveston Bay.

Socio-Economic System Drivers

- *Port Industry and Vessel Traffic Growth:*
  - Uncertainties revolve around the barrier's impact on critical economic interests, especially the Port of Houston, which is one of the nation's busiest ports. Any impediment to navigation (e.g., shipping delays, channel restrictions) can have broad economic repercussions.
- *Stakeholder Uncertainty (Ecology):*
  - Ecological concerns, particularly for fisheries in Galveston Bay, could influence public perception and stakeholder support over time.

Main Operation & Maintenance Concerns

- *Funding and Governance:* Since there is no federal sponsor for O&M, the financial burden rests on the GLO and local authorities (e.g., GCPD) through state funding or property taxes. This raises the question of sustained public support, especially during years with no major storm events.
- *Sustained Public and Political Support:* A wide range of stakeholders, community members, port authorities, and ecological groups must remain informed and supportive. If the barrier is not frequently used, the public may question continued high O&M costs. Since O&M relies on local funding and tax revenues, maintaining long-term buy-in is crucial to finance necessary repairs, inspections, and modernization.

Does the Level/Quantity of [System Driver X]

- Changes in the intensity or frequency of certain factors, such as hurricane surge levels, tides, sediment transport patterns, or shipping volumes, can drive modifications to the barrier's design. For instance:
  - If storm intensity is projected to increase due to climate change, design specifications may need to accommodate higher surge loads.
  - If channel usage increases, designers might need to provide larger or more frequently operated navigation gates to ensure minimal disruption to shipping traffic.

Interview D: Thematic Analysis

Theme	Category	# Mentions
Hydrodynamic change	Hydrodynamics & Morphology	3
Hurricane variability	Climate	2
Vessel traffic growth / port concerns	Economic Growth	3
Ecological stakeholder conflict	Water Exchange	2
Funding and governance	Asset Management	3
Political/public support	Asset Management	2
Local funding mechanisms	Asset Management	2
Gate design flexibility	Asset Management	2

Table G.8: Identify and Grouping Common Themes - Summary Transcript Interview D.

Driver	ESM	# Mentions	Dependency
S1	F2	3	Strong
S1	S5	2	Moderate
S1	F3	1	Weak
S2	F1	2	Moderate
S2	F3	2	Moderate
S2	S5	1	Moderate
O&M	O&M1	3	Strong
O&M	O&M2	2	Moderate

Table G.9: Assigning Relational Dependencies - Summary Transcript Interview D.

G.8 Summary Transcript - Interview E

Major Sources of Uncertainty Affecting the Future Performance of a Storm Surge Barrier

Socio-Economic System Drivers

- *Political and Funding Processes:*
  - The project experiences bureaucratic hurdles and slow political processes, delaying approvals and construction timelines.
  - The Gulf Coast Protection District (GCPD) primarily depends on non-federal sources, state appropriations, or local taxes to operate and maintain the barrier. This funding is not guaranteed, making future performance and necessary updates uncertain.
  - Dependence on state-level decisions and voter referendums for funding (such as property taxes or bond measures) injects uncertainty into the project's future. (Example) If voter approval is required to generate funds through property taxes, unforeseen political or public opposition could alter or slow down the barrier's completion. Moreover, heightened stakeholder demands increase administrative complexities, potentially influencing the barrier's scope and operational protocols.
  - Despite the urgency of coastal protection, slow-moving political and funding mechanisms create organizational bottlenecks. Accelerating these processes requires innovative funding tools and more streamlined governance frameworks.

Main Operation & Maintenance Concerns

- *Responsibility Transition:* After construction by the U.S. Army Corps of Engineers (USACE), operational responsibility will shift to the Gulf Coast Protection District (GCPD). This "handover of the keys" transfers long-term risk, accountability, and daily operational tasks to an entity that relies heavily on non-federal resources.
- *Long-Term Funding Reliability:* Maintenance demands stable, predictable funding over the barrier's lifespan. If the tax base or state funding fluctuates, critical repairs or upgrades might be deferred, compromising the barrier's effectiveness. (Example) Political changes could reduce allocations from state budgets, leaving GCPD with inadequate resources to address normal wear-and-tear or damage after extreme weather events.

- *Complex Stakeholder Environment:* Because GCPD is dependent on taxes, bond measures, and potential voter approval, multiple stakeholders become involved (e.g., local communities, state representatives, voters, environmental groups). The broader the stakeholder base, the more complex the governance. Balancing different interests (environmental vs. economic, local vs. regional, private vs. public) can lead to organizational friction and delays.
- *Organizational Capacity:* Proper maintenance depends on sufficient personnel, technical expertise, and clear protocols. A newly established oversight organization like GCPD may need time and resources to develop robust maintenance routines, specialized staff, and reliable response systems. (Example) Without trained teams or established operational guidelines, routine inspections could fall behind, leading to structural vulnerabilities.

Does the Level/Quantity of [System Driver X] Significantly Affect the Design of the Storm Surge Barrier?

- *Impact of Funding on Design:*[noitemsep,topsep=0pt]
  - The level of available funding can significantly shape the barrier's design choices. Higher budgets may allow for more advanced gate systems, auxiliary flood protection measures, or redundant safety features. Conversely, insufficient or uncertain funding may force scaled-back designs, slower construction, or phased implementation.

Interview E: Thematic Analysis

Theme	Category	# Mentions
Political delays / bureaucracy	Project Management	4
Unreliable funding (taxes, bonds)	Asset Management	4
Complex stakeholder landscape	Project Management	2
Responsibility transition to GCPD	Asset Management	2
Lack of long-term maintenance funds	Asset Management	2
Organizational capacity & staffing	Asset Management	2

Table G.10: Identify and Grouping Common Themes - Summary Transcript Interview E.

Driver	ESM	# of Mentions	Dependency
Political / Funding Process	O&M1	10	Strong
	O&M2	6	Strong

Table G.11: Assigning Relational Dependencies - Summary Transcript Interview E.

G.9 Summary Transcript - Interview F

Major Sources of Uncertainty Affecting the Future Performance of Houston Shipping Channel
Physical System Drivers

- *Extreme Weather Events:*
  - Severe weather (e.g., storms, fog, and hurricanes) can disrupt ship traffic, causing economic losses. (Example) Even minor fog events force temporary closures, leading to fluctuations in national gasoline prices. A hurricane poses a far greater challenge, as the channel must be cleared before impact.
  - Recent hurricanes have been forming more rapidly within the Gulf rather than over the Atlantic, reducing the available response time for shipping companies and port authorities.
  - The Houston area is prone to storm surges, which the barrier aims to mitigate. However, a static barrier may introduce rigid operational constraints, making it difficult to decide when to close it, potentially leading to unnecessary disruptions or failures to act in time.

- *Changing Hydrodynamics and Sedimentation:*
  - The HSC is naturally maintained by currents that keep sediment from accumulating. However, a storm surge barrier will alter these currents, potentially leading to sedimentation or erosion in unintended areas.
  - If sedimentation occurs, parts of the channel may become shallower, reducing draft depth and limiting the size of vessels that can pass through.
- *Ship Size and Navigation Constraints:*
  - Over the last 10–15 years, the number of ships using the channel has remained steady, but the size of individual vessels has increased significantly.
  - Larger ships require wider and deeper channels, increasing the challenge of maneuvering in tight spaces.
  - The maximum tanker size allowed is a Suezmax vessel, and VLCC (Very Large Crude Carriers) cannot access the channel due to draft limitations. If global shipping trends demand larger vessels, the HSC must be modified to accommodate them.

Socio-Economic System Drivers

- *Economic Shifts in Trade and Energy Markets:*
  - Historically, Houston refined oil from Mexico, Venezuela, and Saudi Arabia.
  - With the rise of Texas fracking, much of the oil now being produced is lighter crude, which Houston's refineries are not fully equipped to handle. As a result, Houston now exports much of its crude oil instead of importing it, reversing traditional shipping flows. This shift means that outbound loaded ships are now common, requiring adjustments to the channel's traffic management and anchorage logistics.
- *Competitive Pressures from Other Ports:*
  - Houston is the only major container port in Texas, but it competes with ports in New Orleans, Mobile, and the East Coast. Other ports are investing in deeper and wider channels, allowing them to accommodate larger ships. If Houston does not keep pace with these expansions, it risks losing business to competitors.
  - The HSC undergoes continuous expansion projects, with Project 11 completed and Project 12 anticipated in the next decade. Infrastructure expansion must balance the economic benefits of growth with the engineering challenges of maintaining safe navigation.

Main Operation & Maintenance Concerns

- *Traffic Management During Construction:* The barrier is expected to take 10 years to build, disrupting normal operations throughout this period. There is no clear strategy for how ships will be rerouted or managed.
- *Emergency Protocols for Storms:* Ships prefer to wait until the last minute before evacuating, but the barrier may force earlier closures, causing disputes. Current protocols require closure 12–24 hours before a storm, but if storms form rapidly, adjustments are needed.
- *Maintenance and Unexpected Closures:* Regular maintenance will require closing one or both gates. Simulations show that two-way traffic cannot be maintained through a single gate, meaning any closure will be a major disruption.

Does the Level/Quantity of [System Driver X] Significantly Affect the HSC/Storm Surge Barrier?
Some drivers have a direct and significant impact on the barrier's design, while others may be more relevant for operational considerations.

- *Ship Size Increase:*
  - Requires a wider and deeper channel, which conflicts with a fixed storm surge barrier.
  - Larger vessels have a harder time maneuvering, especially in high winds and currents.
  - A narrow passage through the barrier increases the risk of collisions, especially when visibility is poor.
- *Storms and Extreme Weather:*
  - Early closure of the barrier for storm surge protection could disrupt shipping operations unnecessarily, leading to economic losses.
  - If storms form quickly in the Gulf, ships may not have enough time to leave the port before the barrier closes.
  - Emergency protocols must be revised to ensure a balance between storm protection and economic activity.

- *Hydrodynamic and Morphological Changes:*
  - The static nature of the barrier could create unexpected sedimentation patterns, requiring extensive dredging to maintain channel depth. This could lead to additional costs and delays, reducing the efficiency of the port.

Further Key Insights (Politics, Bureaucracy, and Stakeholder Management)

- *Rapid Approval of Project 11 Due to Industry Influence:* The oil and gas industry and container shipping industry worked together to fast-track Project 11. This highlights how political and industry support can accelerate major projects.
- *Stakeholder Engagement:* Initial decisions about channel width and barrier placement were made without sufficient input from navigational experts.

Interview F: Thematic Analysis

Theme	Category	# Mentions
Extreme weather & hurricane formation	Climate	3
Hydrodynamics & sedimentation	Hydrodynamics & Morphology	2
Vessel size & maneuvering risk	Economic Growth	3
Shipping direction change (exports now)	Navigation	1
Port competition & capacity expansion	Economic Growth	2
Barrier closure disrupts port ops	Navigation	2
Project approvals shaped by industry	Project Management	1
Maintenance during construction	Project Management	1
Anchorage concerns	Project Management	1
Collision risk in narrow passage	Structural Integrity	1
Storm protocols & economic balance	Flood Protection	2

Table G.12: Identify and Grouping Common Themes - Summary Transcript Interview F.

Driver	ESM	# of Mentions	Dependency
S1	F2	2	Strong
S1	S3	2	Strong
S1	F4	1	Moderate
S2	F1	2	Moderate
S2	F5	1	Moderate
S2	S3	1	Moderate
O&M	O&M1	1	Moderate
O&M	O&M2	1	Moderate

Table G.13: Assigning Relational Dependencies - Summary Transcript Interview F.