Gate Design For Large, High Head Locks
"The development of an innovative lock gate"

Current Technologies: Area of Aplication

Field of Innovation

Panama Canal Expansion:

- ◆ Mitre Gate
- ☐ Rolling Gate
- △ Vertical Lift Gate
- ⊙ Sector Gate

Maximum Head [m] / Lock Width [m]

Master Thesis Report

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Master Thesis
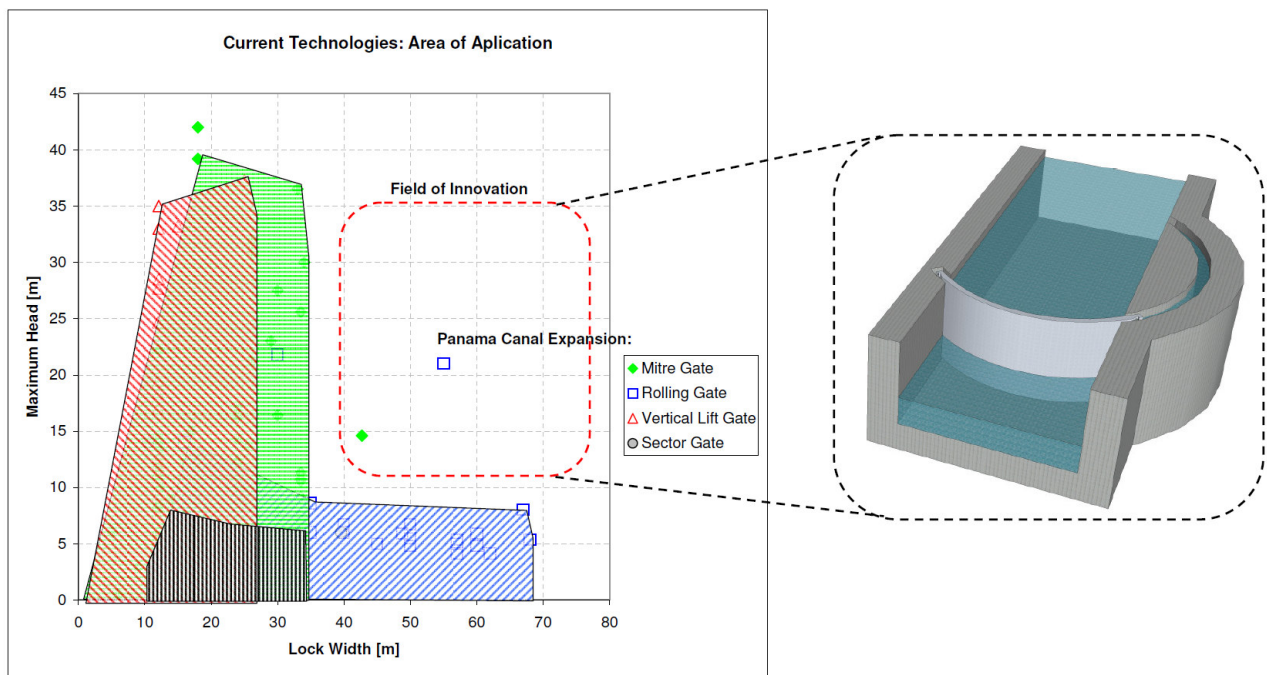
Gate Design For Large, High Head Locks
"The development of an innovative lock gate"

Master Thesis Report

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PREFACE

This Master Thesis Project presents the development of a new and innovative lock gate: *'The Sliding Arch Gate'*. A lock gate design specially attuned for large and high head locks, taking into account requirements that will be highlighted. The design of the gate, presented in chapter 12, has been worked out as a very slender arched structure and the hydrostatic forces are transferred in tension to the lock head structure. The gate which moves in a circular path in and out of the lock profile, limits the water usage of the lock chamber allowing significantly faster lockage. In addition there are no 'sensitive' moving parts below the water line and it is expected that the gate will out perform conventional lock gate technologies at this scale (large and high head locks).

The Thesis has been written as a final testimony to my educational life, hereby accomplishing my Masters Degree in Civil Engineering at the Technical University of Delft. I hope that the results of my research will lead to further research & development of the Sliding Arch Gate and that I may inspire others (who have the time) to let go of conservative thinking and to search for truly innovative and optimized solutions in stead of scaling up conventional technologies, ignoring the potential of innovation.

The initiation of this one year long project started in 2008, when I was writing my Bachelor Thesis on the design of an emergency gate for the new Panama Canal. I was surprised how the lock gates from IJmuiden and Antwerp where just being scaled up to fit the dimensions of the Panama Canal, without a search for new approach. The Panama Canal Project is of a whole different order of magnitude, not only dimension wise, but also considering operational requirements. My mentor ir. H. v. Stralen, who was also intrigued by the possibilities of new lock gate technologies, toke the initiative to investigate new and innovative lock gates, which lead to the initiation of this Master Thesis research project in assignment of the engineering firm DHV.

Delft,

02 – 02 – 2012

Jan Wiebe Doeksen

SUMMARY

The increasing dimensions of ships and the world wide development of new navigation infrastructure result in increasing dimensions of locks. Therefore also lock gate dimensions are increasing and conventional technologies are being scaled up, to meet the new dimensions and demands emplaced by the infrastructure system. However it is questionable if up-scaling conventional technologies will provide optimal solutions and the objective of this master thesis is therefore: To research the need and possibilities of innovative lock gate design for future large, high head locks. Finally developing an innovative gate design, that is geared towards diminishing the drawbacks of extrapolated technologies, and meets the future requirements emplaced by the navigation infrastructure system.

This master thesis project is divided up into three distinct phases. Phase 1; 'Field of innovation', investigates current lock gate technologies, and the future development considering the navigation infrastructure system. A historic research and a data analysis have been preformed, analyzing over 220 of the worlds largest locks throughout history. In total over 20 different types of lock gate have been found from which 4 main lock gate types have been defined; Rolling Gates, Mitre Gates, Vertical Lift Gates and Sector Gates. Each of these has a specific application area, where performance can be assumed to be optimal and specific drawbacks limiting optimum performance, when being applied at larger scale.

The future developments of the navigation infrastructure have been investigated and it appeared that a number of future projects require lock gates far beyond the scale of conventional technologies. One of the most well known of these projects is the Panama Canal 3rd lane, which is currently under construction. The lock gates must span the 55 m wide lock and retain over 20 m of water during normal operation. This combination of a wide <u>and</u> high head lock causes it to fall far outside of the application area of conventional technology. Therefore it has been concluded that for these future dimensions, conventional technologies are considered 'unproven technology' and research to new / innovative concepts is required, as conventional technologies may not provide optimum solutions. The current and future development of the infrastructure system will also highlight a number of requirements concerning future lock gate design. Geared towards reducing whole life cycle costs and the economic risks of the navigation infrastructure system, the most important of these requirements have been listed below:

- <u>Reliability;</u> low rate of break down, low maintenance interruption, high redundancy and adequate provision against flood events
- <u>Safety</u>; resistance to unusual loads, stability, reliability of safe operation.
- <u>Accessibility</u>; the influence of the lock gate design on the <u>capacity</u> of the lock considering, restricted dimensions (head clearance), gate operation time, effects on filling and emptying times.
- <u>Water consumption;</u> Volume of lost water every lock cycle due to inefficient use of the chamber area by the lock gate(s).

In the Phase 2 'Concept Development', new and innovative techniques have been explored, focusing on the demarcated field of innovation and performance considering the future requirements. Concepts have been developed according to three distinct design principles, each taking into account one of the major conflicts that occur when up scaling current technology:

1. <u>Eliminate mechanical interaction and friction:</u> Thus no wear and tear will occur, and no moving parts are required maximizing the reliability of operation and minimizing maintenance.
2. <u>Minimize the weight of the barrier</u>: Reducing the forces on the operating equipment and thus minimizing wear and tear. The gate should be easily accessible and in combination the minimal weight and slender dimensions the gate is easy to repair, maintain and install.
3. <u>Eliminate/minimize the loss of water and use of space:</u> Maximizing the effective lock area, thus shortening the lock cycle time due to filling and emptying and minimizing water consumption from the upper reach and the use of space.

The concept designs have been worked out and are evaluated according to their performance considering the future requirements. From this evaluation the most 'promising' and 'technically challenging' was: 'the Sliding (tension) Arch Gate'. A new/innovative gate design that transfers the hydrostatic loads through arch action (tension) to the lock head structure, resulting in a slender gate design, limiting water consumption by a strongly decreased recess area. The gate slides in and out of the lock profile, using hydrofeet to eliminate friction and wear, by separation between the gate and the sliding surface through a thin fluid film. This alternative was presumed to possess major benefits considering water consumption, reliability, accessibility and use of space.

And in order to reach consensus on the validity of these presumptions was chosen for further research and design. Hence, these presumptions also imply that, given more time for working out other alternatives, may be even better gate design can be found.

In the third and final phase 'Design and Validation' the design of the sliding arch gate has been worked out to an operational design level in order to evaluate its potential performance and to make comparison with conventional technologies. To do so, the Panama Canal Expansion Project (PCEP) has been used to supply realistic boundary conditions and design criteria. As mentioned before the PCEP requires lock gates that fall far outside the application area of conventional lock gate technologies and it fits the area of innovation. However, for the current design of the lock gates, only conventional technologies have been considered (Rolling and Mitre Gates) by the canal authorities ACP who is employer of this mega project. Thereby, the PCEP also supplies a reference design to which comparison can be made.

The design process of the sliding arch gate posted some serious design challenges, mainly due to the fact the gate is arched and is moved in tangential direction, in which it also must be supported. The saying; 'the devil is in the details' was surely in its place. However the design problems have been tackled, resulting in a number of innovative design aspects of which the high lights are given below:
- Pin support: A support system developed to allow movement of the gate in the same direction it is supported. By locking the gate in place with a number of pins inserted through the gate at both ends, also eliminating local bending moments in the gate and concrete structure.
- Modular design The diameter of circumference much large then lock width, therefore the gate cannot be simply removed from its recess and floated away. In order to allow lifting and transportation of the structure, especially considering possible application at even larger scales, the gate design is modular.
- No moving / mechanical equipment below water, all mechanical equipment can be replaced without the entire gate have to be removed and be out of operation for significant time.
- The hydraulic friction drive mechanism eliminates the use of carriages, rails, cables pulleys etc.

Finally the Sliding Arch gate is evaluated in comparison to conventional technologies and the following conclusions have been drawn:
- The Sliding Arch Gate appears to be slightly more expensive then Rolling Gates, considering construction costs for the PCEP.
- The Sliding Arch Gate outperforms conventional technologies considering; water consumption, accessibility and use of space.
- The economic consequences of reduced water consumption appear to be very significant. Especially when considering the effects on the filling and emptying times, which become shorter due to the reduced wet area of the lock. This can shorten the total lock cycle time and thus increase the locks capacity. This reduction becomes stronger when considering high head locks because filling and emptying times become more dominant. The application of the Sliding Arch Gate, compared to the current Rolling Gates, can increase the capacity with 7.5 operation days annually. Therefore saving up to $110 mln. in investment costs, or resulting in approximately $1983 mln of added revenues during the commercial life time of the gate. More then compensating the extra investment costs of the Sliding Arch gate.

It has therefore been concluded that scaling-up conventional lock gate technologies will not lead to optimum solutions, especially considering water consumption, which can significantly impact the locks capacity. New/Innovative concepts like the Sliding Arch Gate can out perform up scaled conventional technologies and earn back their initial investments by low/simplified maintenance and increased lockage capacity.

However, due to the limited time and the number of innovative aspects of the gate, there are some uncertainties considering the gates performance and further research should be preformed considering:
- Other alternatives lock gate concepts
- General detailed design and optimization
- The economic feasibility of modular gate structure design
- The Pin Support System as support for arched gates
- The gates performance considering reliability of operation and safety

However further research into new and innovative concepts like the Sliding Arch Gate is recommended. As is proper research on the economic consequences of the water consumption of lock gates, also taking into account the environmental picture. Other alternative measures to enhance water saving and capacity increase may also become interesting for further research.

SHORT REFERENCE, SYMBOLS AND UNITS

SHORT REFERENCE:

ACP	: Autoridad Canal de Panama
BRIC	: Up and coming developing countries (Brazil, Russia, India, China)
CESedupack	: Software Database for material properties
CH(1,2,3…)	: Lock Chamber, definition (with indication number), of the Panama Canal Pacific Lock Complex, see paragraph 10.2.2
DHV	: Abbreviation for the name of a Dutch engineering firm, initiator of this project
EC2	: Euro Code 2, design code for concrete structures
EC3	: Euro Code 3, design code for steel structures
EMP	: Electro Magnetic Propulsion
EPDM	: Ethylene Propylene Diene Terpolymer rubber, (rubber often used for sealing)
F&E System	: Filling and Emptying System
IFR	: Ideal Final Result
LC (1,2,3…)	: Load Case (with indication number), see paragraph 11.4
LH(1,2,3…)	: Lock Head, definition (with indication number), of the Panama Canal Pacific Lock Complex, see paragraph 10.2.2
MatWeb	: Online database for material properties
OP (1,2,3…)	: Operation Phase, definition for gate operation, see Figure 46
PA 6.6	: Nylon, (Polyamide) type 6.6
PCEP	: Panama Canal Expansion Project
PCUM ton	: Panama Canal Universal Measurement System, equivalent to approximately 100 cubic feet of cargo space
PE	: Poly Ethylene (general plastic family name)
PIANC	: The World Association of Waterborne Transport Infrastructure
PLD	: Panama Level Datum
TRIZ	: Theory Of Inventive Problem Solving (translation from Russian)
TEU	: Twenty-foot Equivalent Unit, is the term employed to identify a 20-feet maritime container or its equivalent.
UC	: Unity check, safety check according to the Euro Code, UC < 1.0
UHMWPE	: Ultra High Molecular Weight Poly Ethylene
USACE	: US Army Corps of Engineers
WLC	: Whole Lifecycle Costing

SYMBOLS:

A	: Area [m²]
a	: Acceleration [m/s²]
B	: Lock width [m]
B_{sup}	: Effective span of the gate (distance between supports) [m]
C_d	: Constriction Coefficient [-]
d	: Diameter [m]
d_i	: Interference depth, lining thickness [m]
E	: Elasticity modulus [n/mm²,GPa]
e	: Eccentricity, subscripts as defined [m]
EI	: Bending stiffness [kN×m²]
F	: Force, subscripts as defined [kN]
f	: Friction Coefficient [-]
G	: Weight, subscripts as defined [kN, ton]
g	: Gravitational acceleration [9.81 m/s²]
h	: General dimensional measure, subscripts as defined [m]
I	: Second moment of area [m⁴]
k	: Wear Coefficient [-]
k_{st}	: Spring coefficient of the support. [kN/m]
L	: Length, subscripts as defined [m]
M	: Bending Moment, subscripts as defined [kNm]
	: Mass, subscripts as defined [kg, ton]
N	: Normal Force, subscripts as defined [kN]
	: Number, Number of cycles (fatigue, wear phenomena), subscripts as defined
n	: Wave number [1/rad]
P,p	: Pressure, subscripts as defined [MPa, Pa]
Q	: Flow, subscripts as defined [m/s³]
q	: Distributed load, subscripts as defined [kN/m]
R	: Radius, subscripts as defined [m]
S	: Indication for compression struts, subscripts as defined [-]
t	: Thickness measure for structural steel elements, subscripts as defined [m]
T	: Indication for tension ties, subscripts as defined [-]
V	: Shear Force, subscripts as defined [kN]
V	: Volume, subscripts as defined [m³]
v	: Local coordinate definition, for displacements along normal axis [m]
v	: Velocity, [m/s]
w	: Local coordinate definition, for displacements perpendicularly to normal axis [m]
W_{el}	: Section modulus (elastic region) [m³]
x,y,z	: Global coordinates definition, as defined [m]
α	: Stiffness coefficient [-]
β	: Support angle [rad]
β	: Dimensionless pressure ratio [-]
γ	: Dimensionless radius ratio [-]
δ	: Deflection [m]
η	: Viscosity of the fluid [N/m² × s, Pa×s]
θ	: Angle, polar coordinate definition [rad]
λ_{loss}	: Relative water loss (percentage of total lock area) [%]
ρ	: Density, subscripts as defined [kg/m³]
σ	: Stress, subscripts as defined [n/mm², MPa]
$\varnothing$	: Diameter [m]

UNITS:

Angel:
rad : Radian

Force:
N : Newton
kN : Kilonewton [10^3 N]

Length:
m : Meter
mm : Millimeter [10^{-3} m]

Mass:
kg : Kilogram
ton : Metric ton (10^3 kg)

Pressure:
Pa : Pascal (1 N/m²)
MPa : Megapascal (10^6 Pa, 1 N/mm²)
bar : Pressure (0.1 MPa, 0.1N/mm²)

Time:
s : Second
yr : Year

Other:
Hz : Hertz, frequency (cycles per second) [1/s]
kW : Kilowatt, Power [J/s]
MJ : Megajoule, Energy [10^6 J]
Pcs : Pieces [-]

CONTENTS   PAGE

APPENDIXES

FIGURES   PAGE

TABLES   PAGE

1 INTRODUCTION

1.1 Background

In modern day navigation, the increasing waterborne transportation and the ever increasing dimensions of ships create challenges to adapt existing and to create new navigation infrastructure. The complex logistical commodity chains demand effective and reliable functioning of the navigation infrastructure system, while the economies of scale push the capacity use of this infrastructure to a maximum. Locks, which are often bottle necks in this system, are gradually being scaled up to meet these tough requirements. The lock dimensions are becoming larger and therefore also their water, time & energy consumption. With the increasing lock dimensions, lock gates are also being scaled up. The lock gates are essential elements in the lock system and the reliability of operation is a big issue. Efficiently scaling up traditional gate designs is finite and new/innovative concepts could possibly prove to be better suited for large high head locks.

The senior structural engineer; ir. H. van Stralen (DHV), who has been involved in the development of a number of large lock and storm surge barrier projects such as the Panama Canal 3rd lane and the st. Petersburg Barrier, has taken initiative to investigate alternative and innovative technologies for lock operation. The reason for this was the design of the lock gates for the future Panama Canal, where traditional Rolling Gates are applied with a span of 55m and an extreme water head of max. 21m. Doubts rose if applying traditional technology at such extreme dimensions would be the most effective solution and if new & innovative concepts designed especially for these circumstance may prove to be better suited. He has therefore requested a graduation student to do research on innovative lock gate design. This master thesis project will investigate the limitations presented by up-scaling current technology and to develop a conceptual design of an innovative lock gate that is geared towards diminishing these limitations for future lock design.

"Do not be afraid by innovation. Promote innovation.
Innovation is required to reach highly reliable infrastructures, to reduce cost (construction mode), fullfil new requirements (fast locking non standard dimension)"
PIANC WG29, CONFERENCE BEIJING 2008 [1]

1.2 Problem definition and objective

Problem:
Lock dimensions are increasing together with their water, time and energy consumption. Until now limited research has successfully pioneered new & innovative lock gates while traditional gate designs are being scaled up.
Hypothesis**:**

Hypothesis:
Lock dimensions are increasing [1], efficiently scaling up traditional gate designs is finite [2] and new/innovative concepts could prove to outperform up-scaled conventional technologies [3].

Goal:
Research the need and possibilities of innovative lock gate design for future large, high head locks. And develop an innovative gate design that is geared towards diminishing the drawbacks of up-scaled conventional technologies, and meets the future requirements emplaced by the navigation infrastructure system.

1.3 Project Strategy

This master thesis project; "Gate design for large, high head locks" investigates the limitations presented by up-scaling current lock gate technology and the application of new / innovative technologies for future lock design. The project has been split-up in three phases which are shortly described below:
      Phase 1: Technology Analysis
      Phase 2: Concept Development
      Phase 3: Detailed Design and Validation

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[1] PIANC WG29, (2008), Lock Innovations Presentation, Keynote speech ,Conference Beijing, Retrieved from PIANC 2009 Locks report DVD

Phase 1 Technology Analysis:
In this phase the field of innovation will be defined. This field of innovation forms the boundaries wherein innovation should take place and enables to come to an optimum solution effectively and to prevent an overflow of concept designs. These boundaries consist of quantitative (dimensional) and qualitative (functional) objectives and requirements. The field of innovation is defined by analyzing:
- The operation and functionality of locks and lock gates
- The past and future development of current lock gate technologies and the future demands and requirements stemming from the macro system.
- The application and limitations of current lock gate technologies.

Results: The results from Phase 1, will form the most important input for Phase 2; general knowledge on locks and lock gates and innovation objectives and requirements. Also the reference project for which detailed design will be worked out in phase 3 is defined from the analysis of future projects.
In Phase 1 a conclusion will be drawn on part [1] and [2] of the hypothesis

Phase 2 Concept Generation
In this phase the effects of implementing the objectives defined in phase one will be analyzed resulting in a number of problems / contradictions to be solved by innovation. This is the fuel for the idea generation and brainstorms. The generated ideas and solutions will be presented in a morphological matrix, to which they will be combined to form concept designs. After evaluating the concept designs the most promising is chosen through a multi criteria analysis.

Results:
A concept design that will be worked out into a detailed design in Phase 3

Phase 3 Detailed Design and Validation
In this phase the chosen conceptual design (form Phase 2) will be worked out to a detailed design using a reference project (from Phase 1) to provide specific design criteria and boundary conditions. Also a cost estimate will be made, considering the life cycle costs. According to this detailed design and costs, the new concept will be validated by comparing it with existing technologies, originally designed for the reference project.

Results: A detailed design of the lock gate, which is presented in chapter 12 and a validation of the design compared to the existing technology applied. A conclusion on the justness of part [3] of the hypothesis will be drawn.

1.4   Structure of the report

The structure of the Master Thesis Report follows the Project Strategy as described above. In Figure 1 on the following page structure of the report is presented within the frame of the Project Strategy. The chapters and their interaction are presented and for every chapter the main content is short- listed.

Chapter 1
Introduction
- Backgrounds
- Problemdefinition
- Project strategy

PHASE 1
TECHNOLOGY ANALYSIS

Chapter 2
Locks in a Nutshell:
General terminology and operation of locks

Chapter 3
Historic Overview of Lock Gates:
Overview of historic development of lock gate technology

Chapter 4
Past and Future Development of Lock Gates:

Data Analysis:
Determining past development and current aplication of lock gate technologies

Future Developments:
-Analyzing past development of lock gate technology
-Defining demand for future development of lock gate technology

Chapter 5
Analysis of Main Lock Gate Types
- Description of main lock gate technologies (Vertical lift, Mitre, Hor. Trasl & Vert. axis radial gates.)
- Analyzing limitations of main lock gate technologies

Current Tech.
Water Head
Need
Width

Chapter 6
Field of innovation
- Determining objectives and boundary conditions for Phase 2
- Determining reference project for Phase 3

PHASE 2
VARIATION & SELECTION

Chapter 7
Idea Generation

Methodology
Explaining methodology used during Idea Generation
(TRIZ, Brainstorm, Morphological Matrix)

Effect Tree Analysis
- Analysing the effects of implementing the objectives difined in chapter 7
- Defining problems / contradiction to be solved

Morphological Matrix
Appendix 2
- Visual representation of ideas and solutions
- Combine ideas and solutions into concepts

Chapter 8
Concept Designs:
Presentation of conceptual design based on simple calculations

Chapter 9
Concept Design Selection
Selection of conceptual disign for validation phase (3), using multi criteria analysis

PHASE 3
DETAILED DESIGN AND VALIDATION

Chapter 10
Reference Project The Panama Canal 3rd Lane
- Description of reference project
- Lock gate technologies sugested for the Panama Canal
- Determinig specific Design Criteria for detailed design stage

Chapter 11
Basis of Design
Boundary conditions and requirements

Chapter 12
Design and Operation of the Sliding Arch Gate
Design Presentation
Detailed illustrations and explanation

Chapter 13-17
Working out the specfic design elements:
13: Structural Modeling of Gate Structure
14: Design of the Support Stystem
15: Gate Structure Design
16: Lock head structure
17: Operation equipment

Chapter 18
Costs & Validation
- Determining costs of lock gate
- Comparing new gate type, to traditional gate types, designed for Panama Canal

Chapter 19
Conclusion and Recomendations

Figure 1: Contents of the report

PHASE 1: TECHNOLOGY ANALYSIS

2   LOCKS IN A NUTSHELL

Locks make navigation possible between two waters (reaches) with differing water levels and play a crucial role in large scale water systems, transportation, energy production and (global) economic development. They are essential for developing navigation in canals and natural rivers where water levels are regulated to enable navigation and to prevent flooding. For harbours in tidal areas, they account for strategic port infrastructure to guarantee a certain water level/depth inside the harbour, mitigating costly downtime and allowing large ships to berth. In low lying areas like the Netherlands and New Orleans locks form an important role in the flood defense system, as they form a passage through dikes, also allowing passage from marine (saline) environment to fresh water environment limiting salt water intrusion. This chapter will give a basic description of the general lock lay-out and operation, defining terminology used through the report and supplying the reader (without civil engineering background) of essential knowledge on locks.

2.1   General lock lay-out and operation

In essence a lock consists of a *lock chamber* in which the water level can be adjusted via the *filling and emptying system*, enclosed by two *lock heads* with movable barriers (*lock gates*). Ships enter the lock when; the water level in the reach and in the *lock chamber* are equal and the lock gate is open. When the ships are inside the lock the gate is closed and the water level inside the chamber adjusted to match the water level of the other reach. Once equal, the lock gates are opened and the ships leave the lock.
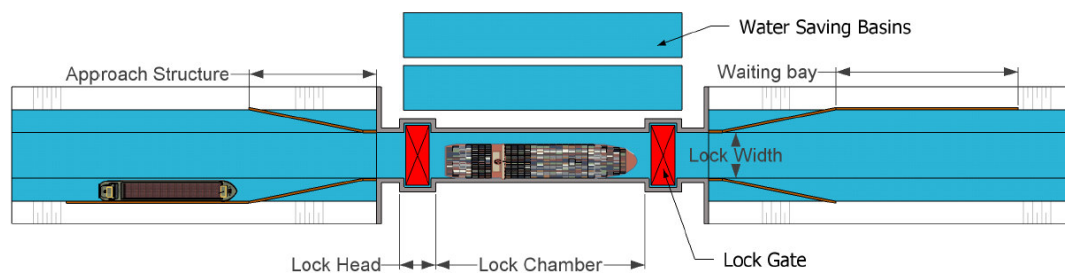
Figure 2: General lock lay-out, top view

Before the ships enter the lock chamber, they may have to wait until a previous ship has been transferred. During the waiting time, the ship can temporarily berth in *the waiting bay* where *berthing structures* can facilitate one or more ships. When approaching the lock, the ship is guided by the *approach structures*, which form a visual barrier and a funnel to align and safely guide the ships into the lock, preventing a head on collision between the ship and the lock structure.
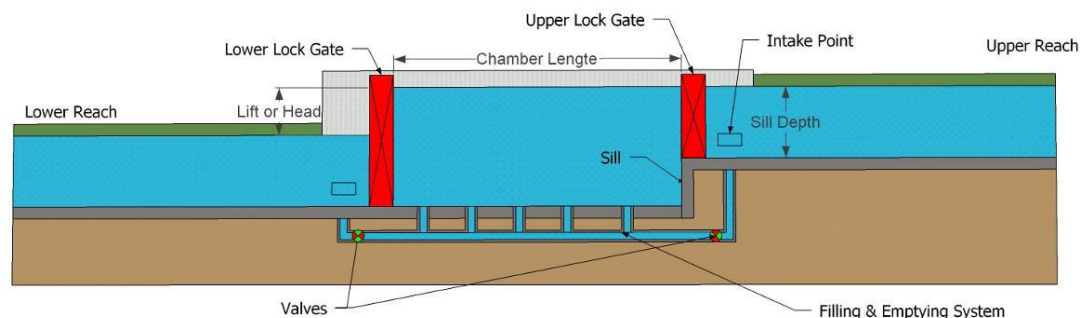
Figure 3: General lock lay-out, side view

2.2 Lock Gates

Lock gates are movable structures, which form a 'water tight' enclosure of the lock chamber when closed and allow passage of ships to an from the chamber when opened. For this Master Thesis Project the lock gate is regarded as a technological system consisting of a number of subsystems all working together to full fill the functions of the lock gate:

The *barrier system* (gate structure), is a movable barrier and closes off the lock chamber in closed position. It retains water and transfers the hydrostatic forces to the *lock head system* which in its turn transfers the forces to the foundation. In order to allow ships to pass through the system, in and out of the lock chamber, the Barrier is moved by the *actuation system* and the movement is controlled by the g*uidance system* which can also supply stability. In opened position the barrier is stored in the *lock head system*, i.e. in a recess or tower. No water level difference is present in the water and thus ships can navigate through the system.

Many different lock gate designs exist, an overview of which can be found in the next chapter. The choice of a specific lock gate type, and the design of its sub-systems is very project dependent. Where, the most economical design is sought to fit the specific boundary conditions and requirements. Some of the most important aspects are listed below:
  – Required span, sill depth and retaining head (main dimensions and hydraulic loads)
  – Project specific boundary conditions and requirements (geology, frequency of operation, speed, etc.)
  – Secondary functions (traffic crossing, use as an emergency gate, integration into F&E system)
  – Available space (limited available space for lock gate)
  – Environmental issues. (water scarcity, salt water intrusion, durability etc.)
  – Specific load conditions (waves, currents, seismic, ship impact etc.)

2.3 Filling and Empting System:

The water level inside the lock chamber is adjusted through the Filling& Emptying (F&E) system. The lock is filled by transferring water by gravity from the upper reach into the lock chamber. When emptying the water is also transferred by gravity from the lock chamber into the lower reach. The amount of water transferred is approximately equal to the lock camber area times the lift of the lock. In Figure 3, a system is shown with separate intakes and a culvert system, which can run under or around the chamber controlled by valves. Depending on the specific lock project different alternative types of systems are possible, filling and emptying the lock chamber can be done by means of: culverts in the wall, floor, though the gate, or even by controlled opening the lock gates. When selecting and designing a filling and emptying system, the indirect costs of longer lock cycle times must be weighed against the capital cost of the system.

Water usage
The volume of water used during a normal lockage, is equal to the lock chamber area, including the gate recesses times the lift of the lock. In waterways where water supply is limited; artificial canals, port areas or river systems with limited discharge, the water usage, can cause a lowering of the upstream water level. This could limit the navigability of the waterway, or accessibility and functionality of a harbour; it could also limit the water supply for irrigational, industrial and drinking water usage. It is therefore of utmost importance that in case of water scarcity water saving measures are considered. In addition the increased wet area of the lock results in longer filling and emptying times and can cause a decrease of the locks capacity, regarding the daily number of transits with significant economic consequences, see chapter 18. The investments required must be weighed up against the economic consequences of water los; congestion costs due to a limitation of lock cycles and environmental compensation. In order to limit the water usage the following measures are commonly applied.
  – Multiple Lift Lock, see Figure 4a
  – Water saving basins, see Figure 4b
  – Maximizing effective lock area, see next page
  – Pumping back water to the upstream reach, generally considered as desperate and unacceptable measure, as it is expensive, non durable and maintenance intensive.

a. The functioning of the water saving basins. In this particular scheme 60% of the water is saved

b. A triple lift lock only uses 1/3 of the water compared to a single lift lock
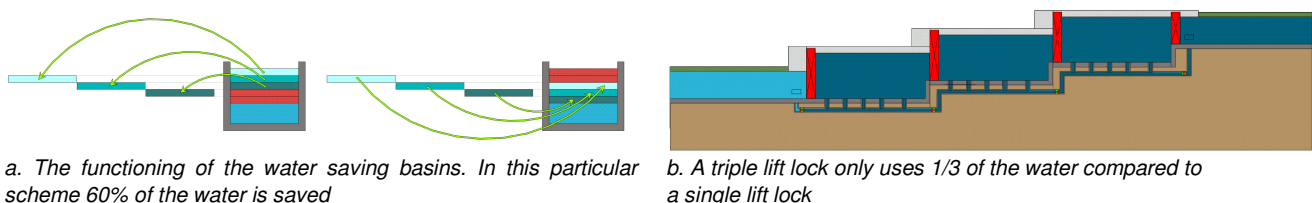
Figure 4: Water saving basins, red part is lost water during lock cycle

Water usage of lock gates, the effective lock area

The effective lock area is equal to the area which is effectively used for the lockage of ships. All other 'wet' area of the chamber causes extra water usage, and thus, unnecessary loss water from the upper reach and increased filling and emptying times of the lock. The effective lock area has therefore been illustrated in the figure below.
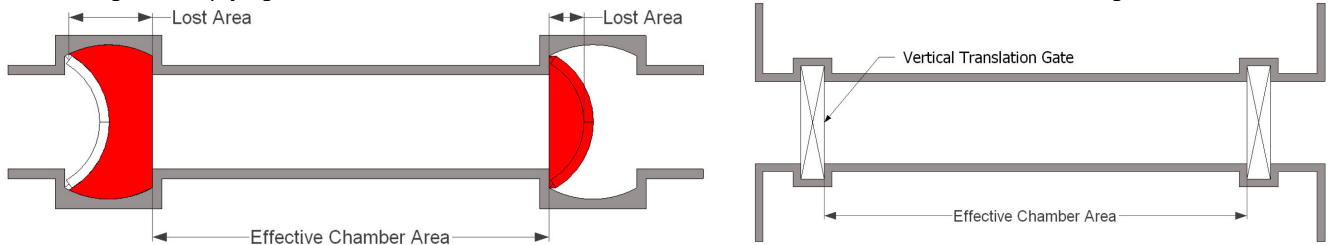
Figure 5: Effective Lock Area

2.4 Maritime and Inland Navigation Locks

In civil engineering terminology, a distinction is made between Maritime and Inland Navigation Locks of which a generalization is given below:

Maritime Navigation locks are often used as strategic port infrastructure, used for maintaining a 'constant' required water level inside the ports basin, eliminating tidal and wave influences. Allowing large ships to enter and berth in the harbour and reduce down time. The head during normal operation is generally relatively low (<10m) and the lock gates have to be able to retain water in both directions. The design of Maritime Navigation Locks is accessibility based, designed to transfer the largest possible ships into the harbour (which may only happen a few times per year). This is in contradiction to *Inland Navigation Locks*, for which the chamber dimensions are generally optimized to transfer the largest amount of cargo, in the shortest time and at the lowest cost. In inland navigation, ship dimensions are often standardized and significantly smaller than maritime ships and locks are often designed to transfer multiple ships. Also the retaining head is generally much higher and sometimes alternative lock layouts are used as multiple lift locks, shaft locks and Lock & Dam complexes. An other significant difference is the geologic and hydraulic boundary conditions. Where *Maritime Navigation Locks* are often built in sandy clayish area's with relatively large waves and tides. *Inland Navigation Locks* are often built in swamp areas with peat, or in mountainous area's in rock, and waves are generally not governing in the design however they are more exposed to flooding.

This master thesis project will not necessarily focus on especially one of these two, as large high head locks can fall in both categories and the technology developed could prove to work for both. The Panama Canal Expansion Project, which is used as reference project, later on in this report, is more or less a crossover between a maritime and Inland Navigation Lock as it combines some important design aspects from both categories: Large maritime ships, capacity driven design, water scarcity issues, multiple lift lock with high heads.
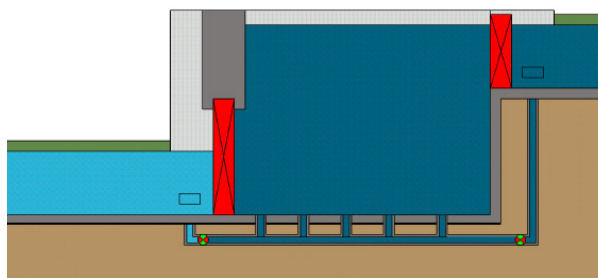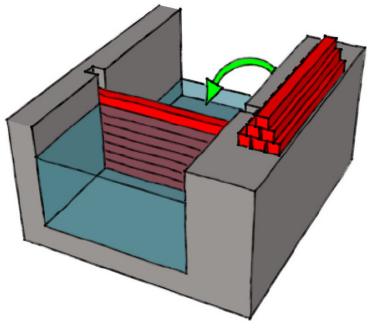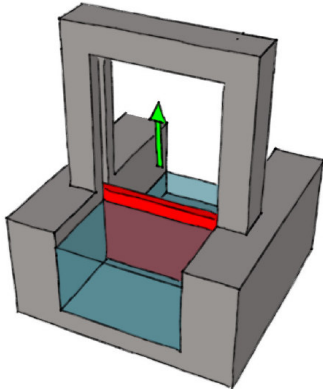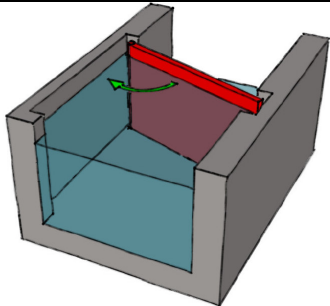
a. Shaft Lock   *b. Lock & Dam Complex [USA]*

Figure 6: Alternative lock lay-outs

3   HISTORIC OVERVIEW OF LOCK GATES
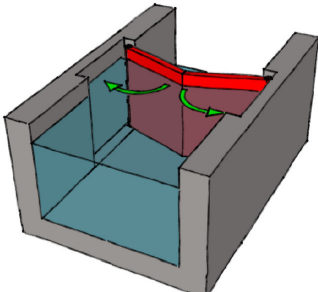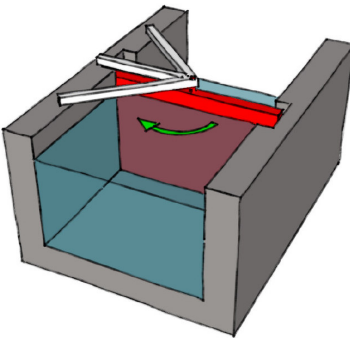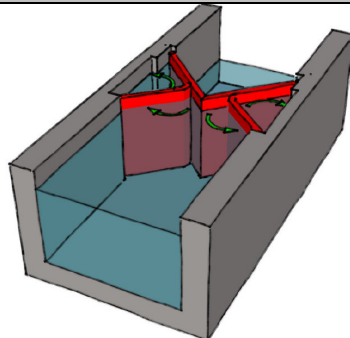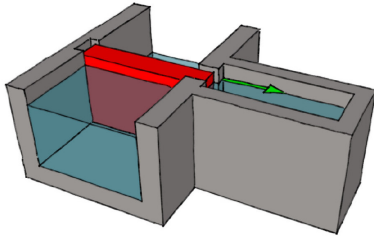
Throughout the history of navigation lock design many lock gate types have been invented. Some found limited application and some where reinvented in a few centuries later due to improved construction materials and methods. To be aware of the different technologies that have been applied in the past, the lessons learnt and inspiration that can be found in all these different designs, an investigation has been done into the historic development of lock gates. Over 20 different types of gates have been found, some of which where quite similar. The most fundamental of these have been shortly described below. Further detailed description and structural analysis of the main gate types used for modern lock design can be found in Chapter 5

Historic overview of lock gate types		
1	**Stop Logs**	**10th Century**
		The most basic gate type, where wooden logs or steel/concrete beams are lowered in a recess. Was only used as operative lock gate in the very early ages of navigation locks. Currently they often service as emergency or maintenance closure of a lock. For regular lock operation in modern day locks this method is too time consuming. Presumably stop logs where used for the first locks in china (986 AD)[2][3].
2	**Vertical Lift Gate [4]**	**13th Century**
		Used, presumably for the early European locks. The Vertical Lift Gate evolved from Stop Logs. They consisted of a wooden frame work that was hoisted manually with a lifting structure. Dimensions where limited due to the friction and the weight of the gate structure. After the industrial revolution the Vertical Lift Gate made a break through in inland navigation lock design. With rollers and mechanical operation equipment, the Vertical Lift Gate was able to fit modern day lock dimensions. Engine powered ships weren't presented with the disadvantage of lowering masts to pass under the gate. It became a common technology for modern day inland navigation locks, as ships generally have limited dimensions for which unrestricted clearance is not required. They are hardly ever used for maritime locks, as these do require unrestricted clearance. For detailed description see paragraph
3	**Single Leaf Gate[4]**	**13th Century**
		The first rotating lock gate, that also gave unlimited clearance and easy operation. Common for mid-evil lock design and later for small locks. They have clear structural disadvantages compared to other similar gate types, but due to their simplicity they can still be found in operation in numerous small locks today. The span of the gate was limited due to the forces on the hinges and the long gate recess and thus lengthy chamber made it relatively expensive for wider span locks.

[2] ICOMOS, *The International Canal Monuments List, Individual Structures*, Retrived from www.icomos.org/studies/canals2a.htm
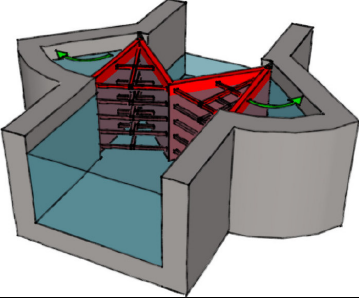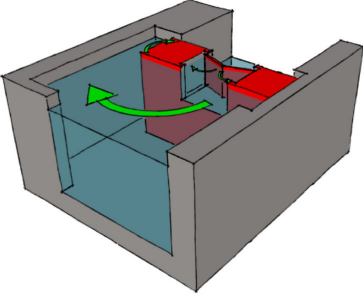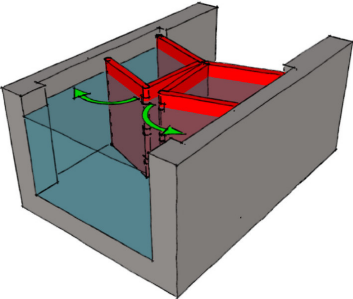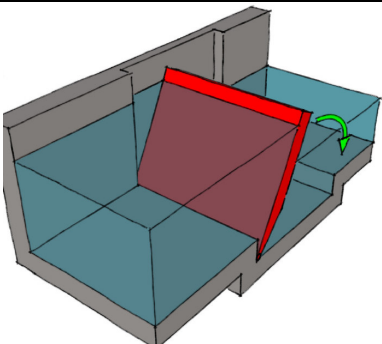
[3] ERBISTI P.C.F, (2004), *Design of Hydraulic Gates*, A.A. Balkema Publishers, Lisse

[4] ARENDS G.J., (1994), *Sluizen en Stuwen, Bouwtechniek in Nederland 5*, Delftse Universitaire Pers, Delft
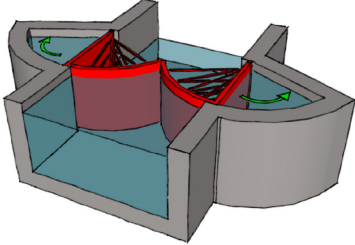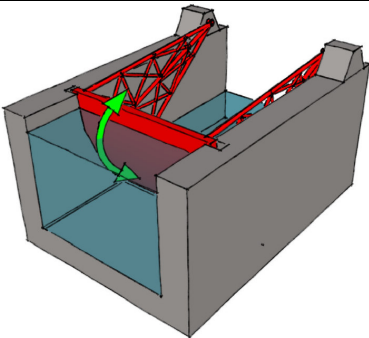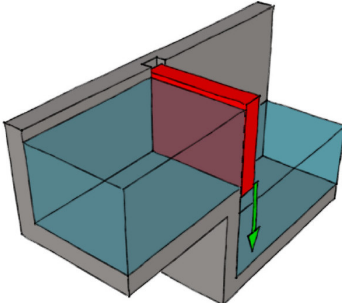
Historic overview of lock gate types		
4	**Mitre Gates[4]**	**15th Century**
		Mitre Gates evolved from Single Leaf Gates, being able to close a larger span, due to the arch action and limited forces on the hinges. The gates where relatively light weight and easy to operate. Though they could (in early days) only retain water in one direction. Nowadays Mitre Gates are the most commonly applied lock gates from; small wooden gates to the largest high head gates in the world. They can only retain a limited reverse head and can't be operated under a head difference or in flowing water. For detailed description see paragraph 5.2
5	**Toll Gate[4]**	**15th Century**
		A typically Dutch lock gate, first used in 1500. It was able to retain water in two directions and to open under a head difference. The gate turns around a vertical axis in the center of the gate, balancing out the hydrostatic forces on both sides. Hence the moments around the axis, when operating under a head difference are approx. zero. Later the design was adapted to provide unlimited clearance, making it a popular gate type in the golden era (1568 – 16 48) due to its unique advantages. Nowadays this gate type can hardly be found. It no longer has unique advantages and the use of space is very inefficient. The delta gate (7) evolved from the Toll Gate and was a much more effective alternative.
6	**Cross Gate[4]**	**16th -17th Century**
		Also a typical Dutch lock gate from the golden era (end 16th century). It was able to retain water in two directions and open under a head difference. It was fully hydraulically operated (by opening and closing valves) and gave unlimited head clearance for ships to pass. Though its construction was very complex and only found limited application.
7	**Horizontal Translation Gate**	**16th -17th Century**
		Horizontal Translation Gates where first applied in the Netherlands around 1600. The wooden gate was moved along bronze rollers situated in a recess on the bottom of the lock. The early applications weren't very successful. The Horizontal Translation Gate didn't make a breakthrough until the 19th century, when the gate was supported by a carriage rolling on rail tracks[4]. Nowadays rolling doors are commonly applied and the widest locks on earth are equipped with these doors (Berendrecht lock: 68m wide)[5]. The horizontal translation can commence in the following ways: – Rolling: wheels on rail tracks[6] – Sliding: hydro-foot[6] – Hanging: on rails or crane type structure above water[4] – Floating: rolling along rails above water[4]. For detailed description see paragraph 5.3

[5] PIANC, (1986), Final Report of the International Commission For the Study of Locks, List of Locks , PIANC, Brussels

[6] LEUSEN B., (2007), *Duikers en sluizen,* Noordhoff Uitgevers B.V., Houten

Historic overview of lock gate types		
8	**Delta Gate**[4]	**18th Century**
		Also a Dutch invention, first designed in 1777. The delta, mostly applied in pairs (see picture), consisted of two retaining doors sturdily connected to form a triangle. The delta gate (after some modifications) had evolved from the Toll Gate. The gate could be fully (or partially) hydraulically operated by altering the water level in the gate recess. The door could be operated in flowing water and retain water in two directions. Though complex and costly, they where very popular and replaced the Toll Gate being more rigid and easy to operate. Modern sector and Segment Gates replaced the Delta Gate, though some are still operative in the Netherlands.
9	**Ship Gate**[4]	**18th -19th Century**
		A ship door is a caisson like structure sometimes with an integrated Mitre Gate. They can be used for large locks and are reliable. Their operation is very time consuming and are only used when operation is required sporadically. The integrated gate can provide smaller vessels regular (fast) passage, but due to the time consuming operation they are only used for ship docks.
10	**Coupled Gate**[4]	**19th Century**
		Presented as 'cheaper' alternative for the delta gate in 1823. It consists of two hinged wooden 'water tight' parallelograms that meet each other in the middle of the lock when in operation. Operation is fully hydraulic, by altering the water level in the parallelogram via conduits and valves. They have the same operative advantages as the delta gate, but never became very popular, presumable due to their complexity, large weight and maintenance problems.
11	**Flap Gate**[4]	**20th**
		Flap gates with a top hinge are the oldest known gate types, used in the roman era. They where used for discharge sluices and ducts. Flap gates can be bottom hinged or top hinged depending on their application. Not until the 19th century where Flap gates also used for navigation locks and shipping docks (bottom hinged). Flap gates are mostly used for weirs and movable barriers. Maintenance and inspection of the bottom hinge requires closure of the lock and sedimentation can cause frequent problems. Therefore they are hardly applied for navigation locks [7]

Historic overview of lock gate types		
12	**Radial Gate: Sector Gate**	**20th**
		A Sector Gate, is like the delta gate but with a curved front skin plate. It is more or less the modern version of it. The inside leaf is also closed with a skin plate, so the gate can be operated fully hydraulically by altering the water level in the gate recess. Sector Gates can be applied with a vertical and horizontal axis. Both also applied for navigation locks. They are especially suitable for limited- head locks where operation in flowing water is essential, or where the filling and emptying must commence through the doors[7]. For detailed description see paragraph 5.4
13	**Radial Gate: Segment Gate**	**20th**
		Invented in the 20th century by the German professor H. Krey. It is quite similar to the Segment Gate <u>but only has one closed plane</u>, namely the front curved plane. Operation is by electro mechanical of oil hydraulic equipment, making them suitable for higher heads then the Sector Gate. They are especially popular for use as movable weir or storm surge barrier and have been used for extremely large spans or high heads[8]. But also find application in navigation lock design, where the gate must be able to operate in flowing water or under a head difference. They are especially suitable for limited head locks where operation in flowing water is essential, or where the filling and emptying must commence through the doors. For detailed description see paragraph 5.4
14	**Submersible gate**	**20th**
		Submersible gates have vertical translation like the Vertical Lift Gate, accept they translate in downward direction when opening. They can operate with a head difference and close in flowing water. Often find application as upstream gate in very high head lock[5], where the sill of the lock is so high and the gate does not need a recess in the bottom lock chamber (See picture). Under normal circumstances, the gates would require major excavation, limiting their application for larger locks. Also sediment and maintenance issues contribute in their limited application.

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[7] JITTA J.P.J., (1947), Sluizen en Andere Waterbouwkundige Kunstwerken, De Erven F. Bohn

[8] PIANC INCOM WG26, (2005), Design of Movable Weirs and Strom Surge Barriers, PIANC, Brussels

4   PAST AND FUTURE DEVELOPMENT OF LOCK GATES

In this chapter the past and (possible) future developments of lock gate technology is analyzed and the justness of part [1] of the assumed hypothesis is justified. The hypothesis presented in Chapter 1 assumes that lock dimensions are increasing [1], efficiently scaling up traditional gate designs is finite [2] and new/innovative concepts could prove to outperform up-scaled conventional technologies [3]. This is a rather deterministic view on technology and it is therefore required to understand the technological development of lock gates in order to check if this assumption is correct. Knowledge of this development process and the different relevant factors in it may give better insight in the possibilities of influencing the development in the future. This can help an engineer better understand his own position. It can also be useful when we want to steer a certain course in developing technology, enabling us to reach certain specific goals or to avoid negative effects.[9]

A data analysis has been preformed analyzing over 220 historic, operational and future locks. The results of this data analysis are presented in paragraph 4.1 and further in depth analysis on these results and on the future developments will be given in paragraph 4.2. Together with the results from chapter 5, (the limitations of current technologies) the field of innovation is defined in chapter 6. Also the justness of part [2] of the hypothesis is discussed in Chapter 6.

4.1   Past development of lock gates; lock gate data analysis

4.1.1 Methodology data analysis

The data analysis conceived over 220 locks and mainly focused on large locks of widths between 12 – 68m. As it is difficult and time consuming to obtain detailed information on a lock, let alone many locks, the analysis was preformed on basic lock data, sufficient to fulfill the goal of the analysis:
   –   Chamber Length
   –   Minimum width (width at lock head)
   –   Sill depth
   –   Max head over gate (lift)
   –   Gate type upstream head
   –   Gate type downstream head
   –   Gate dimensions (if available)
   –   Year of construction

Reliability of the data
Most of the data was obtained from the PIANC [10][11](World Association of Waterborne Transportation) and AMSCE (American Society of Civil Engineers) database, two of the most significant institutions in the field of navigation infrastructure. Also other sources have been used such as historical data from: *ESTRIBI* [3],*ARENDS* [4] *JITTA* [7], and *ICOMOS* [2]. The most significant locks have been incorporated in the data, though some significant locks may have been overseen due to the limited available resources and time. It has been attempted to get data of all the largest locks throughout history per gate type. The data has been processed and sorted to produce the results presented in the following paragraph a list of all the locks can be found in Appendix 1 of this report.

4.1.2 Results

Data contents
In total 10 different gate types where found in the data analysis. The gate types and the number of appearances in the data have been presented in the figure below. It can be seen that some gate types are only applied as upstream gates. This can be explained with the following reasons:
   –   The upper gate has to able to open/close in flowing water, emphasizing significantly different design conditions for the upstream and down stream gate.

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[9] MULDER K.F. et al., (2009), Philosophy, Technology Assessment and Ethics for Civil Engineering, Course Syllabus WM0312CT, TU Delft, Delft, 135 - 140

[10] PIANC, (1986), Final Report of the International Commission For the Study of Locks, List of Locks , PIANC, Brussels

[11] PIANC WG106, (2009), Innovation in Lock Design, Report no 106., Annex III List of locks, PIANC, Brussels

– The sill depth (d) is much smaller than the lift (H) of the lock d/H<<1. The head over the upstream gate is therefore much smaller than for the downstream gate, resulting into significantly different design parameters and making it possible to apply a submersible gate types without extra major excavations.
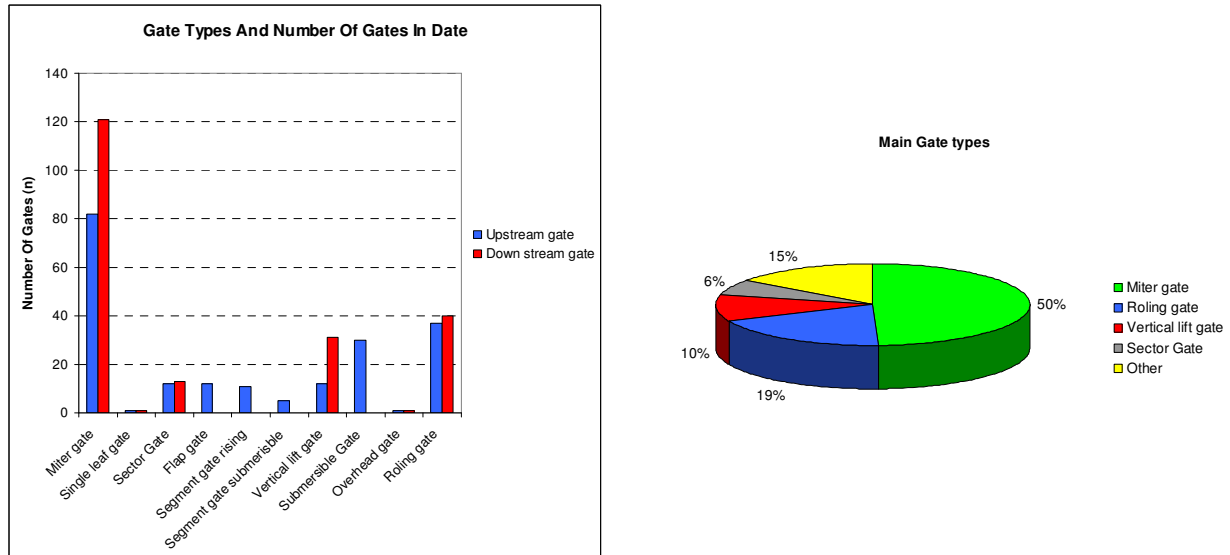
Figure 7: Contents of the data; lock gate types and number of gates

The above figure also shows that there are only 4 main types of lock gates that are regularly used for both upstream and downstream gates; Mitre Gates, Rolling Gates, Vertical Lift Gate and Sector Gates. This is also illustrated in the above figure which shows the percentage of the data represented by a certain type of gate:

Development of dimensions in time

Lock gates have become considerably larger since the invention of the lock. The first locks, built in china were only a few meters wide, using stop logs made from wood as a gate structure. These logs where placed and removed manually. The last 150 years the lock widths have increased significantly, see figure below. The reasons for this will be discussed in chapter 7. A line has been drawn through the maxima as performance parameter for the width of lock gates. It would be hard to define a mean value and as this research considers 'Large' and 'High head' locks a maximum value is therefore more appropriate.
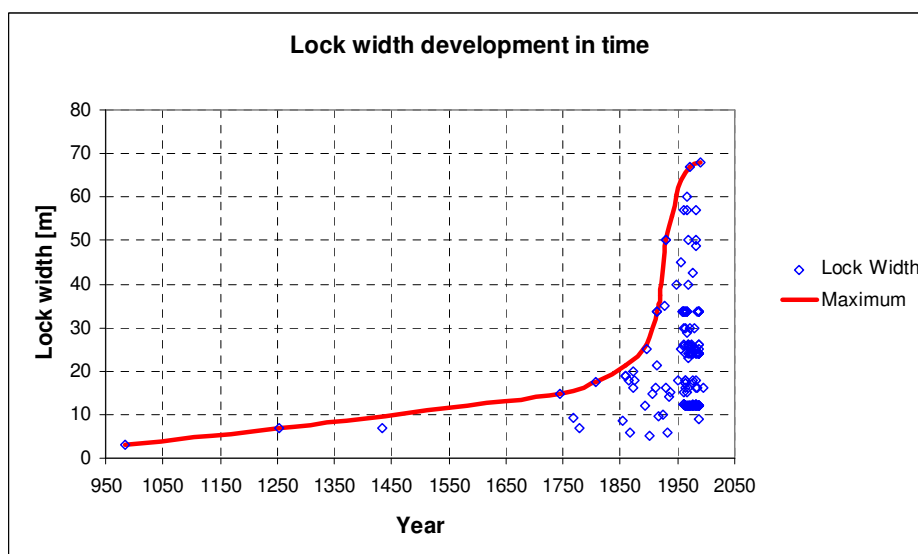
Figure 8: Lock width development in time

Because the scale in the above figure is so small its, the most significant period in lock gate development (last 150 years) is rather unclear. Therefore the development over the last 150 years has been plotted in the figure below. When only looking at the past 150 years; the graph presents a significantly different impression, with stagnation in the growth of the lock width in the last few decades.
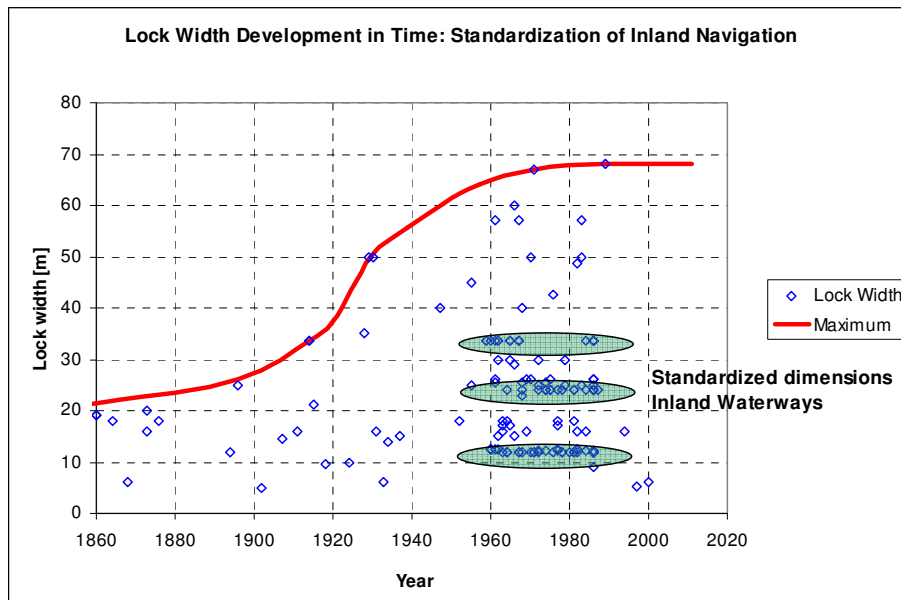
Figure 9: Lock width development in time, 1860-2010

When one plots the development of the maximum water head over a single gate in time, one gets a quite similar image. Though the maximum values peak out more, due to the fact that the head over the gate is more project specific (geological and hydraulic conditions) and the width is more system specific (ship size, waterway limitation), see chapter 7. Therefore a more representative secondary maximum line has been drawn.
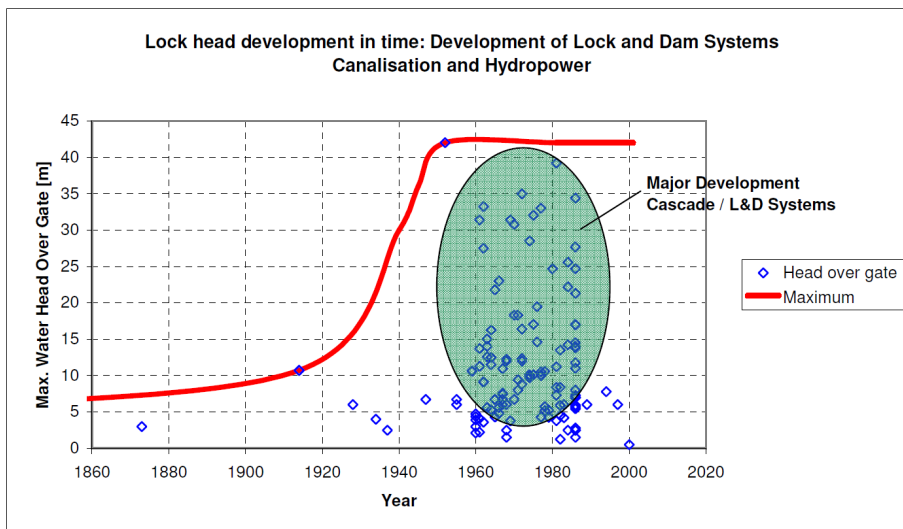
Figure 10: Development in time of the maximum head over a single gate

A significant increase in lock dimensions has been observed over the past 150 years for both the width and the maximum head over the gate, though the growth has stagnated over the last few decades, producing a typical S-curve, for more detailed analysis and for trends and future developments see paragraph 4.2.

4.1.3 Application of gate types

To investigate in which dimensional ranges certain lock gates are applied and to determine where the limitations of certain technologies lay, the four main gate types have been plotted in width/maximum head relation. This relation has been chosen as width and the head difference over the gate are the most important design parameters for a lock gate. In the scatter plot below, also the most significant locks per lock gate type have been named.
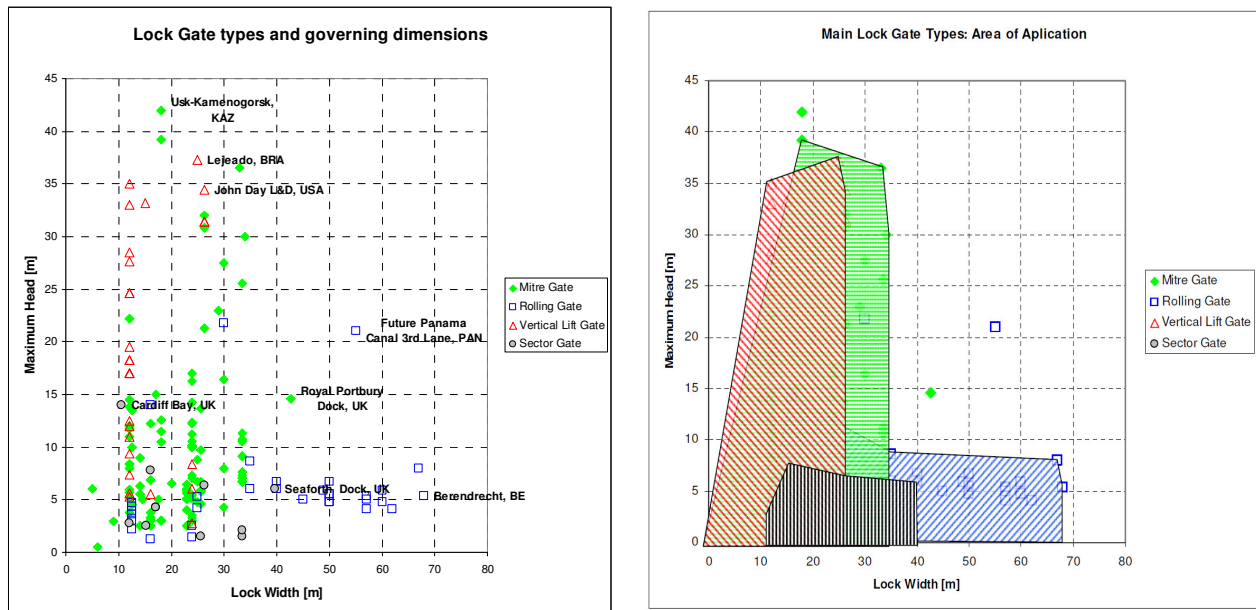
a. data scatter, main lock gate types

b. Aplication area per lock gate type

Figure 11: Area of application of main lock gate types

To get a clearer impression of the application area of each lock gate type, the area of application has been highlighted in the following figure. The maximum values per gate type have been left out in order to get a representative picture, leaving out the peaks. It can be clearly seen that the future Panama Canal lock gates which will be constructed for the 3rd lane of the canal are well outside the area in which current technologies have successfully been applied. The application of Rolling Gate at these dimensions could be possible but should be seen as 'unproven technology'.

- Vertical Lift Gates find application in a similar area as Mitre Gates but the limited head clearance makes them less applicable for large locks. See paragraph 5.1
- Mitre Gates have the largest field of application, being regularly applied with widths up to 33.5m and the highest head lock gates are also Mitre Gates 42.7m. This is due to the structural benefits due to arch action in closed position, See paragraph 5.2.
- Rolling Gates are applied for the widest locks on earth, up to 68m. but generally the head over the gate is limited approx. 10m. The simple translation movement makes them suited for wide locks as they do not rotate around a (heavily loaded) hinge. They are popular for marine application due to easy maintenance in the gate recesses (corrosion) and that in case of double door application they don't require very long lock heads. But with a increasing head the gates become very heavy thick and less easy to operate, causing operational and maintenance problems with the wheel burrows and tracks. See paragraph 5.3.
- Sector Gates only find specific application as they are very expensive; they are only applied when operation in flowing water is required for flow regulation of a river, increase overflow capacity of a dam or ice and debris control. See paragraph 5.4

4.2   Future Developments

Nowadays the major capital investments needed to scale up the current infrastructure system restrict explosive development, which was observed in the majority of the 20th century (Figure 9). The complex supply chains and distribution networks have caused increasing logistical complexity of intermodal transportation systems (combinations of road, rail, air and water way transport with intermediate distribution centers). On-time delivery and availability of products is therefore essential for the logistical chain. Increasing traffic, congestion and waterway capacity are going to be even more important issues in the future than they are now and will influence price and costs. This will highlight factors such as reliability and accessibility.[12]

However, parts of the system and some subsystems are reaching their maximum capacity and/or are at the end of their life-span, making renewal, expansion and up-scaling feasible in the near future. This could also cause a synchronized development in maritime technology leading to increased (standardized) ship dimensions and better maneuverability of large vessels, triggering a gradual up scaling of the entire system. It is very hard to even guess how the scale of the infrastructure system will develop and thus how exactly lock dimension will increase in the future. The complexity of the current system, required investments, the unclear future economic development and the effects of climate change contribute to this vague view on the future. Though increasing scale/dimensions can be expected. A few examples of (possible) future projects are shown in the figure below and are shortly discussed after. These projects have been integrated into the graph which shows the application of current technology, Figure 11, a result of the data analysis. As can be seen the scale of lock gates will increase three trends can be identified:

Trend 1. New extreme high head locks
Trend 2. New extremely large maritime locks
Trend 3. New large, high head locks

Until what extent, however, is unclear. But the scale of future lock gates is far beyond the scale at which current technology is applied. <u>Therefore the assumption in first part of the hypothesis; "Lock gate dimensions are increasing", is justified.</u>
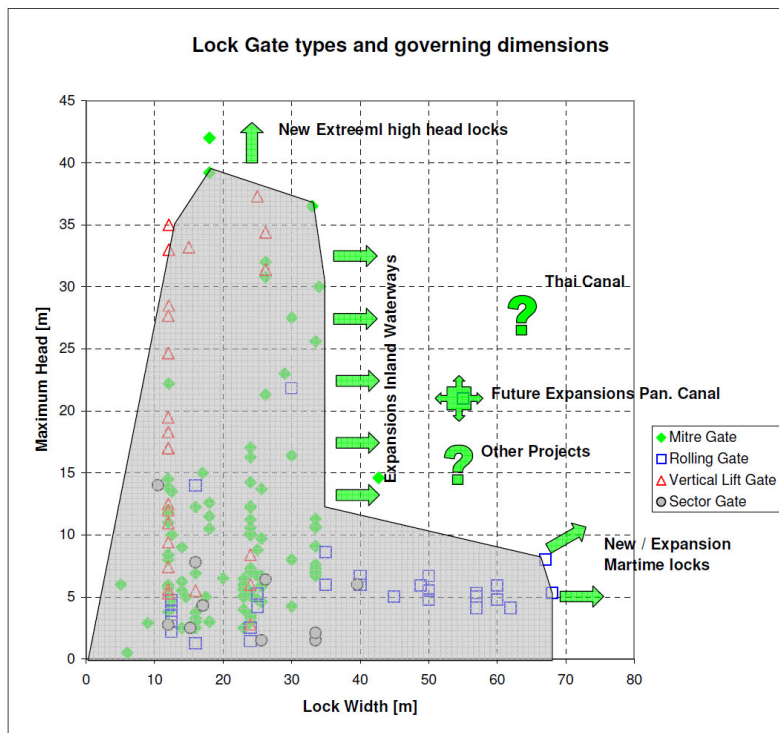
Figure 12: Possible future projects and the application of current lock gate technology

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[12] PIANC WG21, (2005), Economic Aspects of Inland Waterways, PIANC, Brussels

Trend 1: New High extreme high head locks (inland navigation)

The current global shift of economic powers is sparking new developments considering infrastructure and energy production in the so called BRIC countries (Brazil, Russia, India and China). Of which specifically Brazil and China are developing new hydropower projects in combination with navigation infrastructure. This will presumably involve the development of new extremely high head locks, like the Three Gorges Dam (Table 2) and the Lejeado and Tucurui Dams (Table 1), which are recent examples of these developments.

Trend 2: New extremely large maritime locks[13]

Many of the world's large harbours are situated in low lying deltas (Antwerp, Rotterdam, Amsterdam) and estuarine areas (Liverpool, Le havre) where large tidal variations occur. These mostly traditional harbours often stem from times when ship dimensions where not as large and to keep the accessibility of the harbours up to competitive level the harbour entrances or docks are often closed of by locks, in order to maintain the water levels inside the harbours and guarantee sufficient depth. To allow the modern (extremely large) vessels into their docks, a number of these harbours are planning the construction of new, extremely large locks (>65m wide); Ijmuiden (Port of Amsterdam) and Berendrecht (Port of Antwerp)

Trend 3: New large, high head locks

Future Expansions of the Panama Canal

The current Panama Canal will be expanded with a 3rd lane of locks; the new locks will be 55m wide 427m long and 18.3m deep. During operation the maximum head over one lock gate is 21m. The project is currently under construction and is expected to be completed in 2014. Also a 4th lane expansion has been proposed by the Authorities of the Panama Canal (ACP) and this has been taken in to consideration in the design of the current expansion[14]. The future 4th lane may even become wider then the 55 meters of the current expansion. This project can also trigger expansions of waterways elsewhere and result in the construction of new large locks. The Panama Canal expansion, has already triggered new large lock projects around the Gulf of Mexico[15], where expansions are being planned for the Kentucky waterways, including a new 33.5 (110)×400 m (1200) (ft) lock with a 23m lift[16].

Thai Canal

China plans on investing approximately 20-25 billion U.S. Dollars on a canal through the Kra Isthmus, of Thailand to shorten shipping routes and relieve the extremely busy Malaka straight.
The length on land of a proposed Thai Canal could be anywhere between 50 and 100 km depending on the route chosen The height of the interior mountain chain is 75 m above sea level. At a depth of 25 m (82 ft) below sea level the width of the Kra Isthmus is about 200 km. [17]

The Strait of Malacca, just under 1,000 kilometers long, is narrow, less than 2.5 kilometers at the narrowest and just 25 meters deep at its shallowest point. It is heavily used by oil tankers[18] and bulk carriers. Some 80 percent of Japan's oil supplies pass through the Straits. Any planned canal in Thailand would mean that large ships could travel through the region from India and on to China and Japan without passing through the pirate-infested Strait of Malacca.

If the canal is built it will probably be of comparable or even greater scale then the Panama Canal. Though there is no detailed information on the design or dimensions of the canal, it will probably be built for very large or ultra large bulk carriers and tankers, probably exceeding new Panamax Dimensions.

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[13] HIJDRA A., VRIJBURCHT A.; (2006) : *Port of Amsterdam, Alternatives for the Projected Sea Lock*, PIANC'06 Congress, Estoril, Paper 059

[14] AUTORIDAD CANAL DE PANAMA, (2006), *Proposal for the Expansions of the Panama Canal, Third set of locks project*, Retrieved from

http://www.pancanal.com/eng/plan/documentos/propuesta/acp-expansion-proposal.pdf

[15] WEST KENTUCKY REGIONAL CHAMBER ALLIANCE, *Priority Project 2 :Inland Waterways*, Retrieved from:

http://www.wkrca.org/lock_dam.html

[16] USACE NASHVILLE DISTRICT, *Kentucky Lock Addition, webpage with project description,* Retrieved from

http://www.lrn.usace.army.mil/pao/kylock/Default.htm

[17] WIKIPEDIA, *Thai Canal,* Retrieved from: http://en.wikipedia.org/wiki/Thai_Canal

[18] SCHURMANN F., (2003), *China's Demand for OIL May Make Thailand Canal a Reality,* New America Media, Retrieved from:

http://infowire.newamericamedia.org/news

Expansion of inland waterways:

Some inland waterways allow navigation of relatively large vessels. Particularly in the USA, where 15 barge tows with a length of 349 m and max. beam of 32 m and navigate the large river and canal systems[19]. In the lower open Mississippi there are even +35 barge tows (fully loaded) [20] with dimensions of approx. 471 × 53.3 m depending on the configuration of barges.

Almost ocean going like ships (309 × 32 m) navigate the great lakes, which are inter connected through canals and locks. According to the PIANC[21] a large number of the Lock & Dam complexes and other hydraulic structures that make up these infrastructure networks are reaching the end of their economical lifetime making expansion of the system economically feasible. The American Congress has already planned for a number of new large locks and harbour expansion in the great lakes system[22].

Together with an urge to inject economic development[15] and possible developments in maritime technology this could lead to future up-scaling of ship sizes in whole reaches or part of the system. The standard lock width of the above waterway systems is already 33.5m (3 barges wide) and almost all of these locks are equipped with Mitre Gates. Renewal of these locks and possible up-scaling (for example too 4 barge width = 42.7 m) could require new large lock gates, presenting possibilities for further developing or applying new lock gate technologies.

Figure 13: Ships of the Grate Lakes, and a 15 barge tow [USA]

[19] USACE, (2009), *Inland waterway navigation value to the nation*, USACE, Retrieved from:

www.spn.usace.army.mil/value_to_the_nation/InlandNavigation.pdf

[20] USACE, (1997), Engineering and Design- Monograph Prepared by M. Petersen on Inland Navigation and Canalization, USACE, Retrived from USACE publications: http://140.194.76.129/publications

[21] BROLSMA J.U., (2010), *the World Association for Waterborne Transport Infrastructure*, *an association in a changing world, 1885-2010*, PIANC, Brussels

[22] USACE, (2009) *Great Lakes Navigation-Economic Strength of the nation*, AMSCE, Retrieved from:

http://www.lre.usace.army.mil/greatlakes/navigation/

5   ANALYSIS OF MAIN LOCK GATE TYPES

In this chapter a more in depth analysis is presented of the main lock gate types, which where also briefly described in Chapter 4. The main goal of this chapter is to analyze the limitations of the main lock gate types that occur when up-scaling the gate dimensions. With these limitations is meant, the problems which occur when applying the technology at extremely large dimensions, and the effects of these problems on reliable/effective operation of the gate. These limitations are not persé due to structural issues but can also stem from water usage, operation speed, limited access of the lock etc. The main gate types (Figure 11) considered in this chapter are:
  − Vertical Lift Gates, paragraph 5.1
  − Mitre Gates, paragraph 5.2
  − Horizontal Translation Gates, paragraph 5.3
  − Vertical axis Radial Gates, paragraph 5.4
For each gate type a general description and analysis of the gate's operation and structure is presented and the limitations when up-scaling are given. Finally a shortlist is presented of the most significant projects where these gate haven been applied.

5.1   Vertical Lift Gate

A Vertical Lift Gate is a gate which is lifted vertically out of the chamber profile allowing ships to pass under it. They mainly find application in relatively small and moderately to extremely high head locks. They are most often applied for inland navigation locks, where the limited head clearance for ships is not an issue and the width of the lock is limited. In case of shaft locks, the (down stream) gate can simply be hung in the lock walls and no super structure is required. However, they are also used to rise vertically above the lock, requiring lifting towers as shown in the figure below:
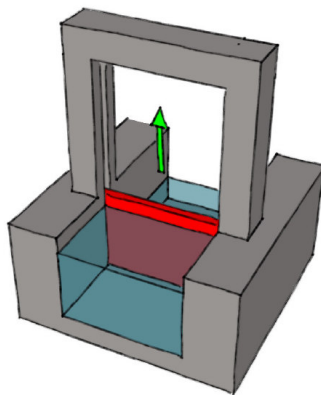
Figure 14: Illustration of a Vertical Lift Gate and Vertical Lift Gates at the Prins Bernhard Sluis [NLD]

5.1.1 Analysis, Vertical Lift Gate

a. Flow of forces, Vert. Lift gate in retaining position. Top view of typical lay-out.

b. Flow of forces, of an arched Vertical Lifting Gate, like

c. The forces in the superstructure are dependent on the operation equipment.

d. Side view, top heavy structure, excitation during an earthquake
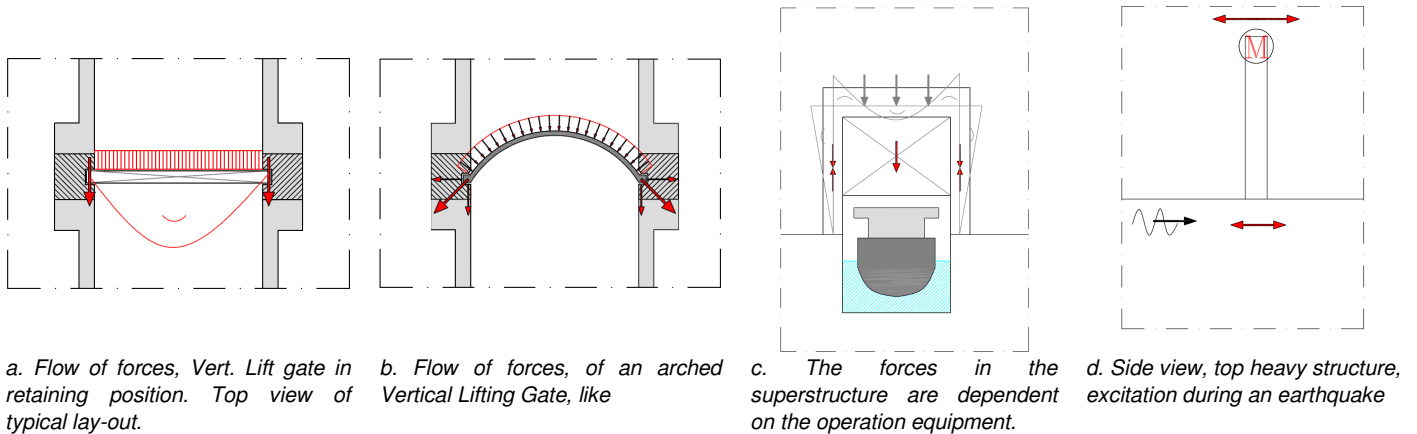
Figure 15: Gate analysis, Vertical Lift Gate

Structural:
- A typical vertical lifting gate has a rectangular gate plane (a), transferring the hydrostatic force through bending to the lock head structure. This will result in a relatively heavy gate structure, which needs to be lifted in and out of the gate profile every lock cycle, requiring heavy lifting equipment or a counter weight mechanism. However the loads on the lock head are in the direction of the lock axis, which allows a compact and 'light' lock head structure.
- A Vertical Lift Gate can also be constructed as an arch (b), transferring the hydrostatic loads by normal force to the lock head (arch action). This results in a lighter gate, though the thrust forces, perpendicular to the lock axis, cause significant bending moments in the lock head structure, which therefore becomes heavier, less compact and generally more expensive.
- When in opened position, the gate is stored above the lock (c), limiting the clearance of the ships passing through the lock. The super structure supports the gate and transfers the vertical load to the foundation via normal force through the pillars to the foundation. The gate structure is often supported by a locking mechanism, which supports directly in the pillar limiting the bending moments in the super structure.
- Often a horizontal member (c) is situated between the pillars; this can be solely for bracing the superstructure, providing extra stability. Or to aid the lifting mechanism of the gate, if there are hoisting points in the 'middle' of the gate.
- The superstructure is sensitive to seismic and wind loading (d), especially when the gate is in opened position. The large mass at the top of the (stiff) super structure will create large bending moments and shear forces when subjected to horizontal accelerations. And the large gate plane can result in considerable loads due wind pressures, and associated dynamic phenomena. Note: when integrated into a hydro dam structure or shaft lock, these drawbacks do not apply in comparison to other gate structures.

Operational:
- The restricted clearance of ships limits the application of Vertical Lift Gates to inland navigation locks, or small maritime locks where unrestricted clearance is not required. Though, it could be considered to provide sufficient clearance for larger ships by making the superstructure very high. But in most cases the choice for this design then becomes irrational, especially when considering wind , seismic loads and cost of the super structure.
- Vertical Lift Gates are often operated with winches and cables, with rollers or sliding shoes attached to the gate to provide horizontal guidance and support during operation. Therefore no mechanical parts are permanently submerged. And maintenance can be executed in the dry when the gate is in opened position.
- The gate can be fully supported in horizontal direction while being operated. Therefore the gate can be operated with a head difference and in flowing water, though rollers may be required to limit friction.

General
- – A typical vertical lifting gate (a), minimizes the use of space (area) and maximizes the effective lock area, resulting in minimal water consumption of the lock.
- – The high superstructure will be clearly visible on the horizon causing landscape pollution.

Application at larger scales:
Although the use of space and water consumption can be considered optimum, the application of vertical lifting gates will be constricted due to the limited head clearance, or the extremely high super structure. High head locks considered for this master thesis project are assumed to be ocean going vessels or vessels alike (great lake ships etc.).

List of gates:
The most significant applications of Vertical Lift Gates have been listed in the table below:

Table 1: List of Vertical Lift Gates

Lock	Width [m]	Draft [m]	Head [m]	Remark
Lejeado, Bra	25		37.3	Highest head Vertical Lift Gate
Tucurui, Bra	33		36.5	Widest Vertical Lift Gate, under construction
John Day L&D	26.2	4.6	34.4	
Spaarndam, NLD	7			Presumably the first European ship lock, 1253 AD

5.2   Mitre Gates

Mitre Gates consist of two rotating leafs, symmetrical with regard to the centre line of the lock, which rotate around the vertical axes and are usually supported at two points (hinges) They evolved from Single Leaf Gates, being able to close a larger span, due to the arch action. In closed position the leaves meet at the centre of the lock, supporting each other on the free ends, like a bishop's mitre, hence the name. Mitre Gates find application from low to extremely high head locks with small to moderate spans and are commonly used for both maritime and inland navigation locks.
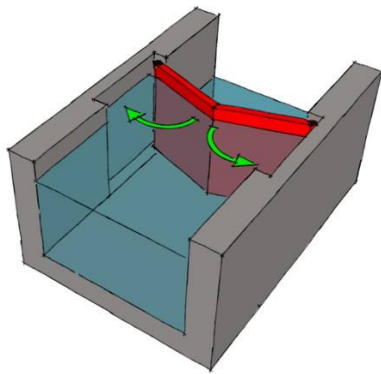
Figure 16: Right: Illustration of a Mitre Gate, Left: Arched Mitre Gates of the Dallas L&D, [USA]

5.2.1 Analysis, Mitre Gate

a. Flow of forces, top view	b. Ineffective lock area due to gate design	c. Forces during operation, top view	d. Forces during operation, side view, of gate plane
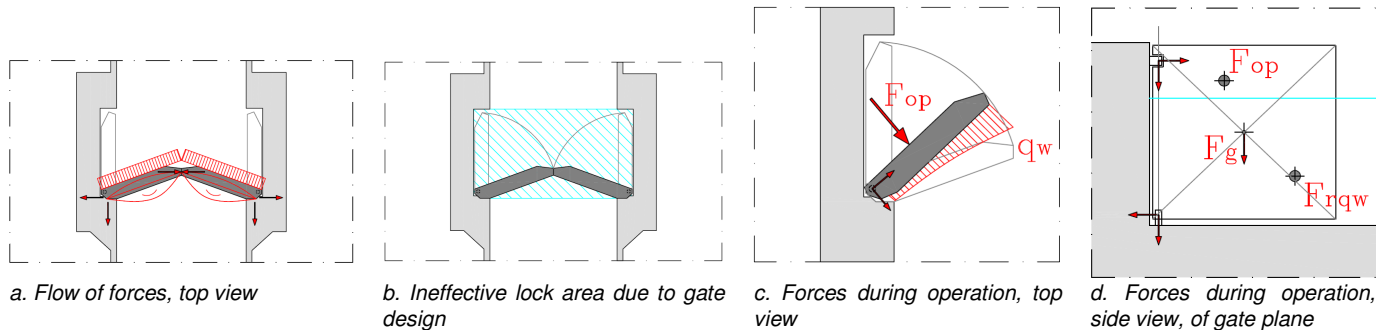
Figure 17: Gate Analysis: Mitre Gate

Structural:

- Mitre Gate leaves transfer the hydrostatic loads efficiently to the lock head structure making use of (partial) arch action (a). The gate structure is therefore relatively light weight and slender. However the thrust forces load the lock head structure in a less favorable manner, in out-ward direction. This causes significant bending moments in the lock head structure which therefore becomes heavier, less compact and generally more expensive, especially when soil conditions are not favorable.
- In order to prevent excessive loading of the hinges and wearing of the seals, Mitre Gates are often designed with eccentric hinges such that the gate structure supports directly on the lock head structure when in closed position. A wooden (Azobé) or elastomer bearing surface prevents damage to the gate structure.
- The Mitre Gates will only support on each other when loaded in compression. Therefore retaining a negative head is generally not possible. Though if holding the leaves in place, or when locking the leaves together with a pin retaining a limited negative head is possible.
- The angle of most Mitre Gates vary between 18-34 degrees with A being L/3 or L/6.[3]
- Numerous shapes of the leaves are possible and are presented in the figure below.
  - A. Straight leaves, traditional shape, often applied when construction small wooden Mitre Gates.
  - B. Fully arched leaves, transfer in full arch action and only normal forces will be present in subjected to evenly distributed loads. Often used in case of extremely high head locks.
  - C. Partially arched leaves, eccentric contact points create counter acting bending moment in the gate.
  - D. Trapezoid arched leaves, simpler in construction then the rounded shapes. Though still has increased load transfer efficiency due to eccentric contact points.
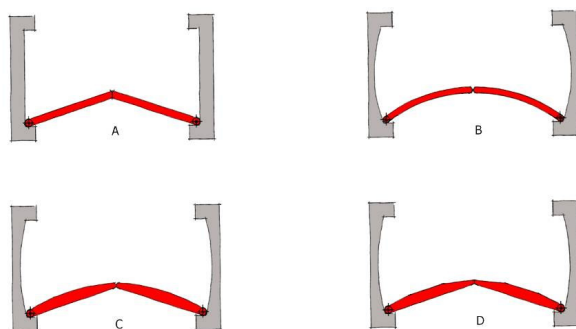
Figure 18: Leaf shapes of Mitre Gates

Operational:

- In order to open and close the Mitre Gate, the leaves must be rotated through the water. In case of large gates, this causes large water displacements and in order to operate the gate in limited time, large operation forces will also be required (Figure 17 c). These operation forces increase linearly when considering the height of the gate but up to the 3th power when considering the length of the gate[23]. The resultant of the operation force, applied at the top of the gate, and the resultant force of the hydraulic pressures are not in the same location and therefore can cause significant moments in the gate (Figure 17 d). As a result the hinges are not only loaded in vertical direction but also in horizontal direction, to compensate for the moment. This bi-axial loading causes significant stress concentrations in the bearings and can lead to excessive wear of the difficult to access bearings[24], especially considering large (span) gates.
- In addition the weight of the gate also contributes to the horizontal (bi-axial) loading of the hinges, as the center of gravity is eccentric from the hinges. Though this can be largely compensated by using buoyancy chambers or a vertical support (wheel) at the leafs end.
- In succession of the above, operating Mitre Gates with a head difference or in flowing water will be limited or may not even be possible in case of larger gates, as the hydraulic pressures on the gate plane increase considerable.
- Nowadays (large) Mitre Gates are operated by means of hydraulic cylinders situated above water, allowing for high reliability and low maintenance.

General:

- The gate is stored in the walls of the lock head structure and therefore supplies unrestricted height of the ships passing through.
- The lock structure is significantly lengthened by the Mitre Gates, as the required length to store the gate is approximately 2/3 of the span of the gate. This also causes a large ineffective area of lock, (see Figure 16 b) and there for also large water consumption.
- The gate is vulnerable to contact with ships in opened, as the recess hardly forms any protection from passing ships.

Application at larger scales, (large and high head locks):

The area of application of Mitre Gates, as can be seen in Figure 11 is limited to moderately wide gates, and application over 33m spans is uncommon. Though, due to the efficient load transfer Mitre Gates are used for extremely high head locks. In fact the gate that retains the highest head (45.2m) is designed as Mitre Gate. However the large operation forces and bi-axial loading of the hinges, may limit optimum application for wider locks. Another limiting factor for applying Mitre Gates at larger scale is the great amount of water consumption, related to the gates design. High head locks, are often part of a canal or impoundment system, where water can be scarce, additionally the larger wet surface of the lock will cause longer filling and emptying times. Only being able to retain a significant head in one direction will probably not be limiting as high head locks are generally not subjected to negative retaining heads.

List of gates:

The most significant applications of Mitre Gates have been listed in the table below:

Table 2: List of Mitre Gates

Lock	Width [m]	Draft [m]	Head [m]	Remark
Bristol, UK	42.7	8.0	14.6	Largest Span Mitre Gates
Three Gorges Dam, Ch	34	5.0	45.2*	Largest overall Mitre Gates
John Day, USA	26.2	4.6	34.4	Highest head Mitre Gate, without upper-sill
Ust Kamenogorsk, KAZ	18		42	Highest head lock gate, lower gate is a round Mitre Gate.(also supports on upper traverse wall)
Kattendijk Sluis, BE	23.75	9.0	2-3	Largest wooden Mitre Gate
Golby Gate, FR	5	2.2	6	Composite Mitre Gate
Spieringsluis	6	4	0.5	Composite Mitre Gate

* Maximum lift is 22.6m (5 lift lock scheme)

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[23] VRIJBURCHT A. et al, (2000) Ontwerp van Schutsluizen, Deel 2, Bouwdienst Rijkswaterstaat, Utrecht

[24] RYSZART D.A., DEMBICKI E., (2006) Contact Problems In Lock Gate In View Of Investigation And Field Experience, PIANC Magazine no. 125, October

5.3   Horizontal Translation Gate (Rolling Gate)

Horizontal Translation Gates, move in and out of the lock profile perpendicular to the locks axis. These gates most commonly use rollers, or carriages to support vertically and minimize friction, hence the name; Rolling Gates. However there are also other types of Horizontal Translation Gates, mentioned in chapter 3 but these hardly find application. Rolling Gates mostly applied in moderate to extremely large locks, with limited head difference and are often used for maritime locks due to their unrestricted clearance and capabilities of retaining a reverse head, and span the largest lock in the world (see figure below).

Figure 19: Left: Illustration of a Horizontal Translation Gate, Right: Berendrecht locks, [BEL]

5.3.1 Analysis, Rolling Gate

a. Flow of forces, top view   *b. Ineffective lock area due to gate design*   *c. Forces during operation, front view*
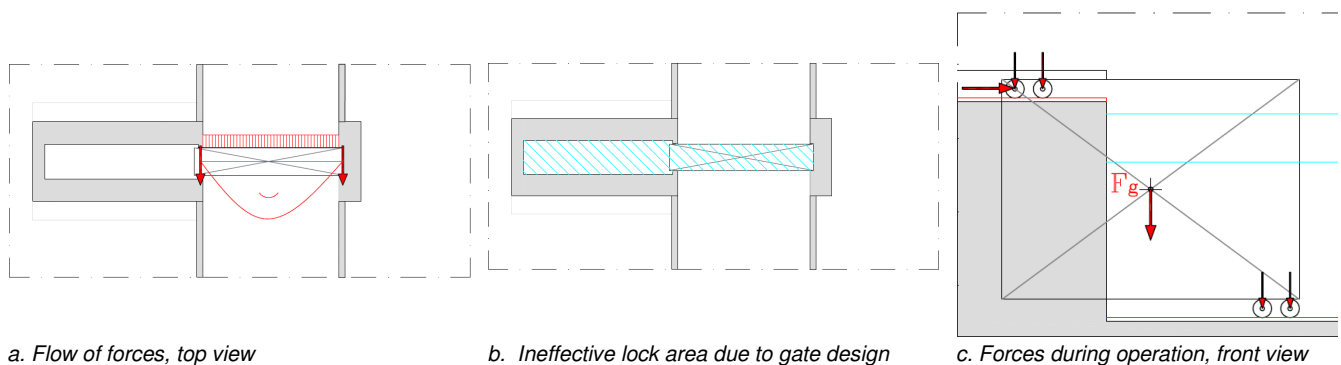
Figure 20: Gate analysis, Rolling Gate

Structural:
–   A Rolling Gate has rectangular gate plane (a), transferring the hydrostatic forces through bending to the sides of the lock head structure and results in a relatively heavy and wide gate structure. Horizontal load transfer to the floor is generally limited, as this significantly complicates the gate structure, and may not even lead to weight reduction.
–   The transfer of forces is favorable for the lock head structure, as the forces are in the direction of the lock walls, which provide support. However this is not the case when considering a double gate lay-out where the intermediate wall will be subjected to significant bending moments, due to the line load over its full height
–   Due to the heavy weight large Rolling Gates are often designed to be able to float, in order to allow transportation. This imposed further requirements to the width of the gate, which must be sufficient to obtain hydrostatic stability while floating..
–   Rolling Gates are stored in a recess adjacent to the lock, and requires a significant recess structure which must retain the soil around the lock head. This causes the lock head structure to be relatively heavy and the favorable loading in direction of the lock walls is therefore compensated by the heavy recess structure.
–   Horizontal Translation Gates can support on the lock head structure in two directions, therefore they can retain a full reversed head. This makes Rolling Gates well suited for maritime locks in tidal and wave rich areas.

Operational:

− Almost all Horizontal Translation Gates use carriages on rails for vertical support during translation. A modern variation of which is the wheel burrow lay-out (c), which reduces the amount of mechanical equipment below water and allows controlled operation of the gate (operation force applied at carriage). However, one of the carriages is permanently submerged and is difficult to inspect and maintain as are the rails over which the carriage moves. As gates become larger and heavier also do the vertical loads on the carriages, wheels and rails. A large part of the weight can be compensated by applying buoyancy chambers; however a certain vertical load is required to allow effective operation of the wheels and guidance of the gate while moving. In addition, gate must often operate with differing water levels, due to seasonal, operational or tidal influences. This causes the vertical load to increase significantly when water levels are lower, as the volume displaced by the gates structure decreases. In case of the gates designed by ACP for the Panama Canal Expansion Project the loads on the carriages increases from 250kN to almost 1500kN[26] due to the differing water levels while operating. The large vertical forces are known to cause, plastic deformation of rails[25], due to the Hertzian contact pressures[34] and the repetitive loading. The rails therefore need to be inspected regularly and must be replaced every 25 years[26] Another common problem with the submerged carriages is bearing failure, caused by the (unexpected) wear of the heavily loaded bearings, which isn't noticed as regular inspection of the submerge carriage is not possible.

− The operation forces required to move the gate are relatively low as the gate does not translate vertically and has only limited water displacement. Generally Rolling Gates are operated by means of cables and winches situated in the lock head structure above water.

− The operation of the gate is relatively fast, when considering wide locks.

− Rolling Gates are often designed with an additional horizontal guidance (wheels or sliding shoes) along the bottom, so that they can be operated in areas with waves and under a small head difference. Improving downtimes (in marine environments) and operation speed (opening with small head).

General:

− Large recesses causes increased water consumption and the use of space adjacent to the lock is significant as the recess structure is larger then the width of the lock.

− Rolling Gates are protected inside the recess from passing vessels etc.

− The recess can be designed to allow dry maintenance of the gate by including pump facilities and a bulk head.

− Rolling Gates can allow passage of road traffic on top of the gate.

− The gates can generally be floated, like a caisson for transportation.

Application at larger scales:

Rolling Gates are used for the widest locks around the globe, however their application when considering operational heads above 7m is uncommon. They are often used for maritime locks where 2 sided retaining is required. The inefficient load transfer may limit optimum performance with higher heads and magnify reliability and maintenance issues with the carriages and rails. The submerged mechanical parts may be considered a weak spot of the gate. Also the advantage of 2 sided retaining will not be as influential, because high head locks often do not require retaining a negative head. The large recess of the gate structure will also cause significant use of space adjacent to the lock, and water consumption which can be limiting factor when considering high head locks, see previous.

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[25] TRIBOLOGY ABC, *Water film of 0.1mm caries 25 tonnes of steel,* Retrieved from: http://www.tribology-abc.com/sub21.htm

[26] CONSORCIO POST-PANAMAX (CCP), (2002), Diseno Conceptual de las Eclusas Post Panamax, Task 4, Triple Lift Lock System, ACP

List of gates:
The most significant applications of Horizontal Translation Gates have been listed in the table below:

Table 3: List of Horizontal Translation Gates

Lock	Width [m]	Draft [m]	Head [m]	Remark
Berendrecht	68	18.3	5.35	Largest Span Rolling Gates
Le havre, Fransois 1	67	25	8	
Future Panama Canal 3rd lane	55		21	Largest head difference for Rolling Gates (2014)
Oranje sluizen, Amsterdam	6.55			Sliding gates, equipped with hydro-foot

5.4 Radial Gates with vertical axis (sector and Segment Gates)

Radial Gates contemplates both sector and Segment Gates, which are very similar and often confused. They both rotate around a vertical axis and consist of a space framed structure connecting the pivot point to the (mostly) curved face. The transfer of horizontal loads to the lock head structure is very efficient, mainly by compression or tension and the gate structure is very sturdy. They find their application in small to moderate sized locks with relatively low head differences and are almost only applied in situations where operation with a head difference is required (flowing water), both for inland navigation as for maritime locks.

Sector Gates have two closed leaves; the often curved front and the inside leaf. This allows operation of the gate using hydraulic pressure differences between the gates recess en the lock chamber. Operating equipment is therefore minimal.
Segment Gates only have one closed leaf per segment which is mostly the curved front plane. A Segment Gate is therefore operated with mechanical equipment, which is limited to a simple thrust drive.
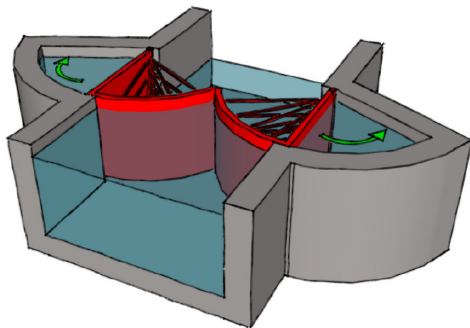
Figure 21: Right: Illustration of a Sector Gate, Left: Segment Gate of the The T.J. Obrien L&D, USA

5.4.1 Analysis, Vertical Axis Radial Gate

a. Flow of forces, top view | b. In efficient lock area due to Radial Gates | c. Operation in flowing water
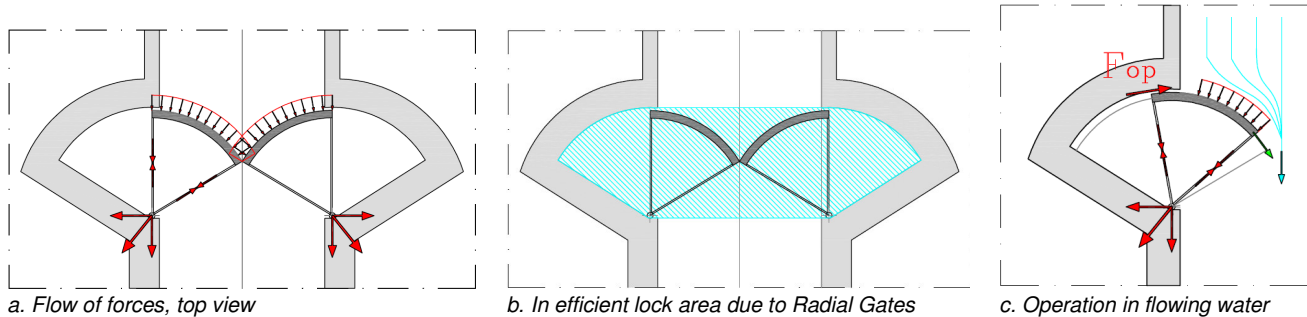
Figure 22: Gate analysis, Vertical Axis Radial Gate

Structural:

−   Radial Gates use an arched retaining plane to distribute the loads to the struts (a), which transfer the loads to the lock head structure. This triangular flow of forces allows loads to be transferred in normal forces and results in an extremely sturdy structure. However, Radial Gates are relatively heavy as the load path is long and are also complicated due to the many joints and connections, especially when the struts are constructed as frameworks.

−   When the gate is in closed position and is retaining water the loads are transferred through the hinge to the lock head structure. Subjecting the hinge to heavy loading, especially when considering large Sector Gates. This could become problematic at larger scale, as local deformations in the bearing due to creep or plastic deformations (load concentrations) increase imperfection of the hinge and may lead to increased friction and wear of the hinge.

Operational:

−   The triangular form of the structure allows the gate to be fully supported while moving. Radial Gates can therefore be operated with a significant differential head (in flowing water). However the bearings will be heavily loaded whilst they are rotating in bi-axially direction. This will significantly increase the wear of the bearing and maintenance may be expected to be intensive.

−   The forces to be delivered from the operation equipment are relatively low as the gate plane translates through the water, limiting water displacements. However, in case of Sector Gates, there are two closed leaves, resulting in large water displacements. But these gates are operated by hydraulic pressures, created by changing the water level inside the recess; therefore the loads on the operation equipment are nihil.

General:

−   The gate is vulnerable to contact with ships in opened position, as the recess hardly forms any protection from passing ships.

−   The Radial Gates cause a significant increase in length of the lock structure, and also require space adjacent to the lock.

Application at larger scales:

Although they have been applied for huge dimension storm surge barriers, up to 360m wide (Measlandt barrier), they are mostly used for small to moderate sized locks with comparatively limited head. The heavily loaded bearings, need to endure significantly more load cycles in case of lock gate application and may limit the use of Radial Gates for large locks (large loads). The complicated gate structure and the excessive use of space and water consumption may also limit optimum application at larger scales. Radial Gates find specific application where operation under head difference is required as they have relatively small structural advantages to Mitre Gates in medium widths and where operating under a head difference is not required.

6 FIELD OF INNOVATION; OBJECTIVES AND REQUIERMENTS FOR FUTRE LOCK GATES.

In this chapter the field of innovation will be demarcated; which consists of a set of quantitative (dimensional) and qualitative (requirements and objectives) boundary conditions. The area of innovation forms a boundary for the next phase (Concept Development) within this project in which the actual innovation will take place. Determining the field of innovation is more or less drawing a conclusion on the previous chapters:
- Firstly the (dimensional) area in which there is a demand (paragraph 4.2) for developing new technologies is determined in paragraph 6.1. This is achieved by analyzing the demand for increased lock gate dimensions versus the current application (paragraph 4.1.2) and limitations (Chapter 5) of current technologies. This also leads to the justification of part [2] of the hypothesis.
- Secondly the functional requirements and objectives that will be highlighted in the future are stated, in paragraph 6.2.

6.1 Limitations of current technologies and field of innovation

Considering the future projects as described in paragraph 4.2, it is clear that a number of future lock complexes require lock gates with dimensions that fall well outside the area in which current technologies have successfully been applied. It is not that current lock gate technologies have limited the development of larger locks. It was from the navigation infrastructure system, that there has not yet been demand for such lock dimensions and lock gates. It might therefore be possible to apply current technology at this scale, though this will probably require a number of technological fixes to adapt the lock gate design to the greater dimensions and can be seen as unproven technology. The application and limitations of the 4 main lock gate types, that have been, are briefly summarized in table below, see chapter 5.

- Mitre Gates find their optimum application for low and high head locks with relatively small width. The transfer of forces is very efficient as they use partial arch action, and therefore the gate structure is light. However Mitre Gates are rotated trough the water causing large water displacements and thus operation forces and loads on the hinges during rotation which limits their application for wide locks. Also Mitre Gates lengthen the lock structure significantly and cause large water losses.
- Rolling Gates find their optimum application for relatively low head but wide (large) locks where two sided retaining is required. They are heavy as they transfer loads in bending, and the permanently submerged rolling gear is sensitive and maintenance intensive. The large recess also causes significant water loss and use of space
- Vertical Lift Gates find their optimum application for low and high head locks, with limited width and are mainly used for inland navigation locks. Their use of space and water consumption is optimal. However, the major restriction is the limited head clearance.
- Sector Gates find optimum application for relatively small locks where operation in flowing water is required. Gate structure is heavy, and maintenance intensive and cause large water loss and use of space.

In short, one could state the following on the application of the two 'largest' lock gate types according to the above and Figure 12:
- Mitre Gates are effective for high heads, but only with limited width
- Rolling Gates are effective for large widths, but only with a limited head difference

Form this one could conclude that these will neither result in an optimal solution for wide, high head locks.

Further the question could be raised: Will applying proven technology operate more reliably under totally different circumstances, than a new/innovative technology, which is based on elementary analysis of the specific situation? An answer to this question cannot (yet) be given as the new/innovative technology has to be fully designed and tested in practice before such a conclusion can be drawn. But the fact that the scale lies so far outside of the current application area implies that new/innovative concepts may prove to be better suited for these large dimensions. For the gates of the Panama Canal 3rd lane, design choices where based on experiences with existing lock gates (Ijmuiden & Berendrecht) with similar widths (50-68 m vs. 55 m) but a significantly smaller head (5-6 m vs 21 m). Specifically attuned to the dimensions and future requirements, the new/innovative concepts may operate more effectively & reliably, which are key points in the future development of the navigation infrastructure system. Hereby the second part of the hypothesis; efficiently scaling up traditional gate designs is

finite and new/innovative concepts could possible prove to be better suited for future large high-head locks, is justified.

The innovation process will thus consist of an elementary analysis of lock gate functions and requirements with optimal solutions for the area not covered by current technologies. It will therefore not take-off where current lock gates have been applied, adapting a certain gate type to fit the future dimensions by means of technological fixes. It is possible that this method could lead to similar designs or combinations of existing technology, but it is assumed that it will lead to an innovative technology that is attuned to future requirements and large dimensions. The area of innovation has been defined as the area not covered between mitre and Rolling Gates; trend 3 large, high head locks. Therefore the Panama Canal Expansion Project will be used as a reference project, supplying boundary and design conditions, for the design phase and assessment further on in this research.
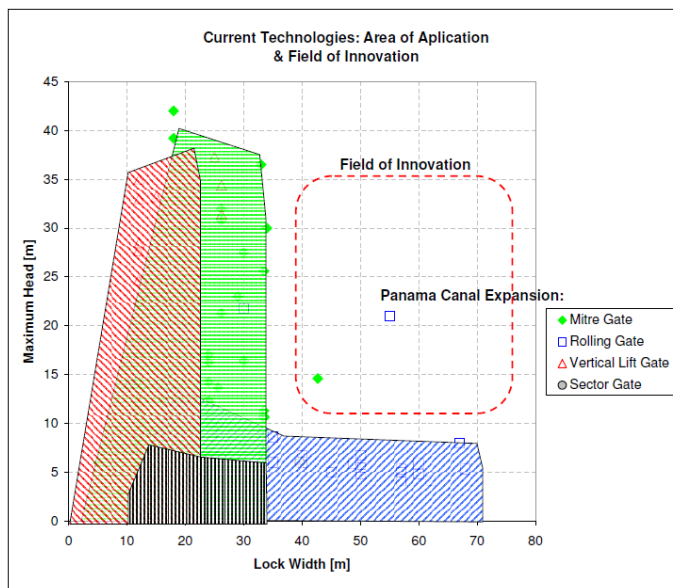
Figure 23: Field of innovation

6.2   Future Requirements

The most important design parameters and functions of locks and lock gates have been discussed in chapter 2. Now it will be determined which requirements and design aspects will be highlighted in future lock gate design. These aspects will form the innovation objectives around which the innovation process will take place.

Innovation objectives for future lock gates:
As was concluded in paragraph 4.2, the future developments of the navigation infrastructure system will increase the importance of aspects as reliability and accessibility. Large future projects impose challenging dimensions for locks; retaining water over increasing widths. The future locks are expected to operate more reliably and under greater loads due to the increased dimensions. As the area of innovation has been defined as the area in which Rolling Gates and Mitre Gates have not yet successfully been applied (Figure 23) and considers very large dimensions;

Reliability can be expressed as a low rate of break down, low maintenance interruption, high redundancy and adequate provision against flood events. Whereas accessibility is expressed by the capacity of the lock considering, dimensions, lock cycle time, number of possible yearly cycles.

During the past two decades, there has been a significant increase in the level of environmental awareness both in political decision making and among the general public. At the same time, in addition to impacts on nature, the definition of environmental impact has been extended to include health, social and visual impacts. There is no doubt that environmental issues are, and will be, among the most important questions for planning and designing a new lock; and probably even more tomorrow than today[10]. All this has led to the need for more extensive environmental studies. Environmental issues will also become more important in the future, especially as

resources such as fresh water are becoming increasingly scarce. For the design of lock gates this implies that salt water intrusion and especially <u>water consumption</u> will become increasingly important design objectives. Water scarcity can even lead to a limited number of permissible lockage cycles, having negative effects on the accessibility/capacity.

The main strength of inland and maritime navigation versus other transport modes is its <u>low energy consumption.</u> Low energy consumption is therefore also an important goal in the design of future locks.

Modern designs choices and optimizations are not only based on the construction costs but the <u>Whole Lifecycle Costs,</u> considering all the costs during construction and the operational lifetime of the structure. The influence of the lock gate design on the capacity of the lock and the congestion of traffic must also be figured into this total cost approach. Taking into account the considerable economic stakes involved in operating the canal, which depend to a great extent on the reliability of the gates and valves, it is clear that the costs are a secondary criterion to that of the required level of quality. Nevertheless costs are always an important factor in making design choices.

Locks often retain vast amounts of water. The failure of a lock can therefore have disastrous effects, not only for the users and local economies that depend on the flow of goods, but it can also cause excessive flooding. The risks are therefore very high and <u>safety</u> is of great importance. With the increasing global economy and the effects of climate change risks will increase in the future, making safety an important future design objective. The required safety measures form a trade-off between investment costs and risks and are therefore very project specific. For lock gates safety mainly translates into the ability to withstand ship collisions, earth quakes and flooding and is closely linked to rigidity and reliability. For the innovation process safety will be a important parameter but secondary provisions can be taken to increase the safety of the lock gate, which do not necessarily consider the basic design of the gate. Due to its close relation to rigidity and reliability safety will not have a top priority.

In conclusion of the above, the most important innovation objectives have been listed below after which design characteristics are given for each of these objectives:

Main objectives:
1. Increasing the accessibility (capacity) of the lock, by increasing the lock gate dimensions (span × height)
2. Increasing the water level difference over the gate, resulting in increased forces.

Primary requirements:
1. The reliability and safety of operation is paramount and the design must be geared towards maximizing this.
2. The accessibility of the lock may not decrease (limited head clearance etc.)
3. Water consumption should be kept to a minimum

Secondary requirements:
1. Use of space should be kept to a minimum
2. Minimizing energy consumption must be take in to consideration
3. Minimizing construction and maintenance costs

The Whole lifecycle costs (WLC) have not been added to the list, only indicative construction/maintenance costs. Optimum design regarding the above requirements will thus automatically lead to lower a WLC, further the WLC is almost impossible to determine or even hard to guess in such a low detailed phase and is very project specific.

6.2.1 Elaboration of requirements

Reliability
Reliability for lock gate operations can be summarized by:
- Low rate of breakdowns.
- Low maintenance interruption (but not necessarily low maintenance, nor low maintenance cost).
- High redundancy and adequate provision for flood event, icing, debris and sediment transport.

For the design of the lock gate the reliability is characterized by the following:
- <u>Simplicity:</u> A simple and pure design will lead to less vulnerability and confined points where wear and tear occur.

- Maintainability: The rate at which maintenance can take place without major interference: Accessibility for repair and maintenance in terms of working space and without the need for special rigging or cranes. - Design that anticipates and minimizes future maintenance requirements.
- Inspectability: The ease at which (visual) inspection of (critical) components of the gate structure can take place. This requires easy accessibility to the (critical) components.
- Vulnerability: The vulnerability to damage or malfunction due to forces / events that can occur during normal operation. (siltation problems, ship impact when gate is in recess ect.)

Safety
For the design of the lock gates safety is characterized by the following:
- Resistance to extreme / unusual loads: Earth quakes, ship collision, waves ect.
- Stability: Allowing certain deformations without introducing progressive collapse.
- Reliability: As described above.

Accessibility
The accessibility of the lock and it's connected reaches can also be described as the capacity and availability of the lock. For the design of the lock gate the accessibility is characterized by the following:
- Operation speed: The time needed for opening and closing the lock gates effects the total lock cycle time and thus its capacity to transfer ships. Lock gates usually take 3-4 minutes to open or close. When the operation time is in this order, speed of the gates is not such an issue, as for large locks, operating the lock gates is only 5-10% of the lock cycle time and thus slight variations of the operation speed will not greatly influence the total lock capacity.
- Head clearance: If the head clearance under a gate presents restrictions on the ship using the lock, the accessibility is negatively effected. Thus for locks transferring large vessels; unlimited clearance is perquisite. The required clearance in these cases (60-70m) is such that the design becomes irrational.
- Additional safety measures: If a lock gate design is not suited for absorbing vessel impacts, other operational and / or physical measures have to be taken to assure the safety. These measures such as; limitations on the ship speed in proximity of the lock, reduced effective lock space and extra operational time, effect the accessibility in a negative way.

Water consumption:
In case of limited supply of water to the upper reach or incase of other environmental/political implications the allowed transfer of water form the upper to the lower reach can be limited. The operative consumption of the water can limit the number of lockage cycles harming the accessibility. Water saving measures such as saving basins are costly and also increase the filling and emptying time of the chamber. For the design of the lock gates, low water consumptions is characterized by the <u>effective lock area,</u> Paragraph 2.3. <u>Of more importance (for large locks, with double gates) are the effects of the shape of the gate on the time required for filling and emptying. The time required for filling and emptying is approximately 50% for large, high head locks.</u>

Construction and maintenance costs:
Taking into account the considerable economic stakes involved in operating the canal, costs are a secondary criterion to that of the required level of quality. In the conceptual stage of the innovation process exact costs are hard to determine. Therefore they will be characterized by the following:
- Materials: The type of material needed for the gate and its required superstructure
- Volumes: The volumes of materials needed for the gate and its required superstructure
- Operating equipment: Equipment required for operating the gates also for providing maintenance and inspection.
- Fabrication method: Location and method of construction: Certain materials, dimension and components require very specific construction methods and conditions.
- Maintainability: As described above.
- Additional safety measures: As described above.

Energy consumptions
The amount of energy required for the operation of the lock gates and the influence of the lock gate design on the total consumption of energy by the lock. For the design of the lock gates the energy consumption is characterized by:
- Required operating equipment: As described above.
- Water consumption: As described above.

- 32 -

PHASE 2: CONCEPT DEVELOPMENT

7 IDEA GENERATION

From the previous chapters it became apparent that efficiently scaling up traditional gate designs is finite and new/innovative concepts could possibly prove to be better suited for future large high-head locks. In Phase 2 of this master thesis project, new and innovative techniques will be explored leading to 3 concept designs of which one will eventually be chosen for further elaboration in the final phase of the project *'Design and validation'*. In this chapter the idea generation process is shown, presenting the basic tools and methodology that have been used for generating ideas eventually leading to concept designs.

7.1   Methodology and Contents

To avoid random idea generation and to come to a set of concepts effectively a systematic approach has been taken towards the idea generation. Numerous tools can be applied, that help structure an innovative process. For this specific project a combination of TRIZ [27] (Theory of Inventive Problem Solving) and a Morphological Matrix has been chosen, due to the analytical approach to problem solving presented by TRIZ and the clear presentation of ideas and sub concepts in the Morphological Matrix, allowing easy combinations of ideas and sub concepts (building blocks) to eventually lead to full concept designs. Below the idea generation process and the contents of this Phase has been presented:

  − The effects of implementing the design objectives on the requirements for future lock gate design have been analyzed in paragraph 6.2, from which three design principles have been deduced for which concepts have been developed:
      1. Eliminate mechanical interaction and friction
      2. Minimize the weight of the barrier
      3. Eliminate/minimize the loss of water and use of space.
  − The Morphological Matrix, containing the basic building blocks for the concept development has been presented in Appendix 2.
  − The conceptual designs which have been developed according to the design principles, using the building blocks from the Morphological Matrix are presented in chapter 8.
  − Finally, in chapter 9 'Concept Selection' a comparative evaluation of these concept designs is made, of which 1 is chosen for further elaboration in phase 3 'Design and validation'.
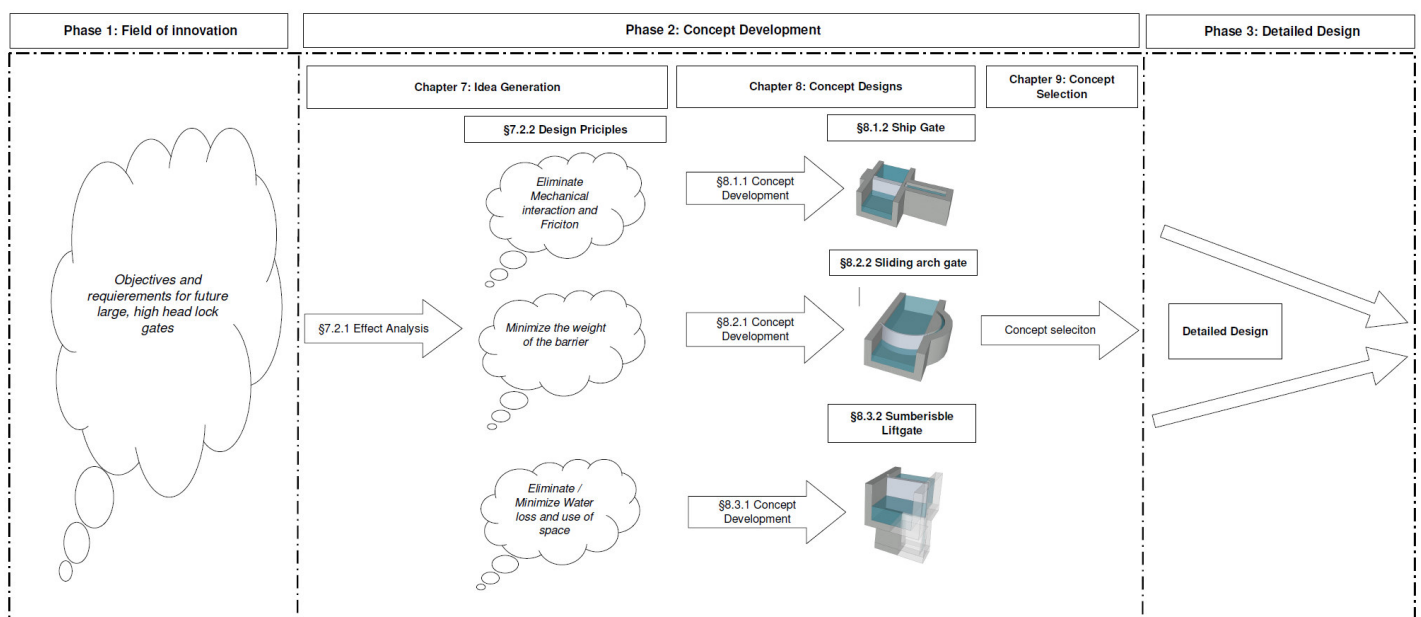
Figure 24: Schematic overview of Phase 2 'Concept Development' within the project

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[27] RANTANEN K., DOMB E., (2008), *Simplified TRIZ, Second Edition* Taylor & Francis Group LTD, Oxford

7.2   Effect Tree analysis

The main objectives as presented in chapter 6 are: Increasing the accessibility (capacity) of the lock **[O1]** and: Increasing the water level difference over the gate **[O2]**. The physical implications of these objectives for the lock gate design are to increase the wet dimensions of the lock cross section to allow larger/more ships into the lock, increasing its capacity and thus the accessibility. This means the barriers have to span wider locks **[A1]** at increasing water depths **[A2]**. When also increasing the water level difference over the lock gate, so does the retaining height of the barrier resulting in larger hydraulic loads **[A3].** These greater dimensions and loads may directly or indirectly create conflict between the objectives and the requirements. In order to come to come close to an Ideal Final Result (IFR) these conflicts or contradictions should become the main focus during the inventive problem solving phase[28]. To come to the right solutions efficiently, the cause of these conflicts is investigated, attempting to find the 'roots' of the conflicts. Once these have been found a profound solution direction is distinguished, finally resulting into a number of design principles to which the concept designs will be developed. Although the Ideal Final Result will most likely not be achieved it is always of utmost importance to focus on trying to achieve the IFR minimizing the amount of concessions. The analysis has been presented in Figure 25 as an Effect Tree for which explanations have been given hereunder and conclusions drawn in the latter.

7.2.1 Effect Tree

As guidance to the Effect Tree, an elaboration of how the requirements are negatively effected is given below:

Objective:	O1: Increasing the accessibility of the lock:
Required Actions:	A1: Increasing the length (span)
	A2: Height of the barrier:
Objective:	O2: Increasing the head over the lock gate system:
Required Actions:	A3: Increasing the retaining height of the barrier.

E1: Increased water surface area → conflict: water loss/consumption
When increasing the width of the lock, and thus the length of the barrier **A1**, the water surface area enclosed in the lock gate system increases. The wet area enclosed by the lock head (recess and gate area) cannot be used by the ships and therefore this area is 'lost' every lock cycle. The volume of water lost is equal to (A_{loss} * Δh). The increase of A_{loss} is either quadratic or linear with an increasing span.

E2: Increasing recess length → conflict: use of space
As the barrier length increases together with its width **[A1&A2]** the recess also becomes larger. For certain lock gate lay-outs this can result in a significant increase in the area used by the lock head system **[E2.1]**, which can cause excessive use of space.

E3: Increased travel distance → conflict: reliability
A wider lock increases the travel distance for horizontally translating or rotating gates. Especially for a gate that displaces a considerable amount of water while moving (like a Mitre Gate) the drag forces on the gate can increase exponentially. The speed could be decreased at which the gate travels through the water but this results in long operation times of the gate, which is considered an unwanted effect. With the increasing drag, the forces delivered by the operation equipment must also be increased. This intensifies the loads on the operating equipment **[E4.2]**, indirectly reducing the reliability of the operation equipment.

E4: Increased total load on the barrier system → conflict: reliability:
When increasing the length and height of the barrier the distance between the supports and the area which is loaded increases. In addition a greater span results in a quadratic increase of the internal bending moments and a linear increase in normal forces causing an increase of the internal stresses. And the increase of the loaded area **[A1×A2]** together with an increase of the retaining height of the barrier **[A3]** the external loads also increase. This, altogether, results in an exponential increase of the barrier weight **[E4.1]** when considering a certain cross section. Generally speaking (in terms of conventional technology), this will also cause a significant intensification of the loads on the operating system **[E4.2],** negatively affecting the reliability of the operating system. For example; for a Rolling Gate the wheel carriages and rail tracks (Guidance System) will have to bear significantly

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[28]ALTZHULLER G.,(2002), *40 Principles, Triz Keys to Technical Innovation,* Technical Innovation Center, Worchester

larger loads, resulting into more wear and reliability issues and more complex equipment situated under water. For a Vertical Lift Gate similar issues can be found with the lifting equipment (Actuation System) and for a Mitre Gate with the hinges (Guidance System).

E5: General increase in weight and dimensions → conflict: ease of repair and maintenance:
With increasing dimensions of the barrier and an increasing load **[A1,A2,A3]** the total overall dimension and weight increase. This generally makes the barrier and operating systems harder handle and transport, more complex to carry out maintenance and repairs and also makes the manufacture of the lock gates more complex.

Note: That only increasing the load on the dynamic part of the lock system (gate + operating system) is assumed to be harmful. Increasing loads on the static part of the lock (lock head) does not significantly affect the long term performance of the whole lock system. Though increasing loads will required a more robust and expensive lock head structure, but these mainly economic (negative) effects will be considered in a later stage of design.

E6: Increasing span and retaining height of the gate → conflict: accessibility of the lock :
When increasing the head difference of the lock **[A3]**, so do the filling and emptying times required to equalize the water level differences. The speed at which the water level is changed is limited due to the hydrodynamic effects on the moored ships in the lock. Translation waves, turbulence and resonance phenomena[10] can cause excessive movement of the ships and broken mooring lines/dolphins, which can result in damage to the ships and lock structures. Therefore, increasing the head will make the F&E times more dominant, which in case of excessive water loss due to the gates design **[A1]** can result in reduced lockage capacity (number of daily cycles) and thus harm the accessibility of the lock **[O1]**.
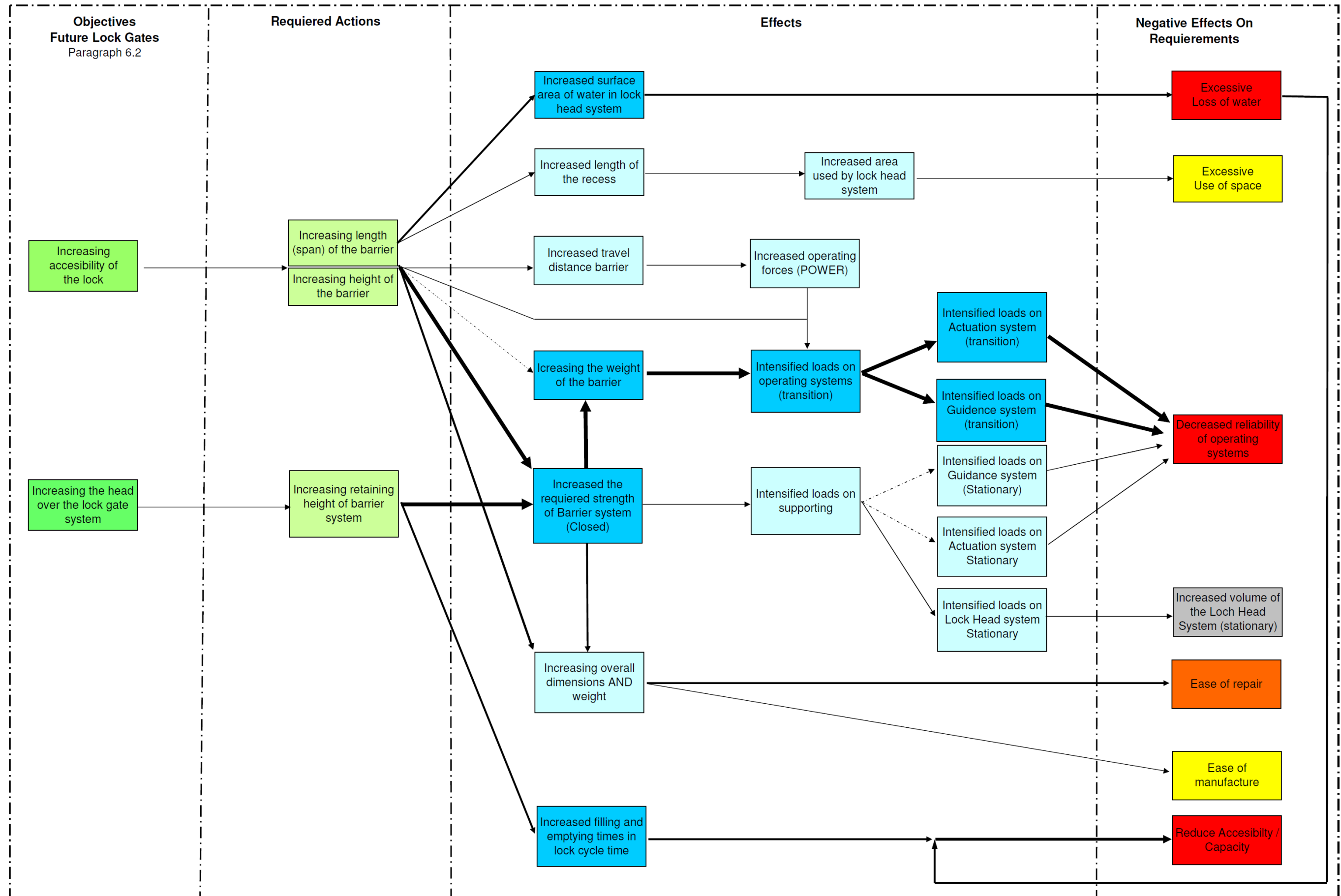
Figure 25: Effect Tree

7.2.2 Formulation of the design principals

From the Effect Tree Diagram and the above analysis it can be concluded that when up scaling <u>a general lock gate design</u> the following requirements are effected negatively:
1. The reliability of the operating system
2. Excessive use of water/ space and the influence on the locks Accessibility
3. Ease of repair/manufacture

The requirement of reliability of operation is affected most intensively by the objectives and required actions. The roots of the conflict can be found in the increasing barrier weight (buoyancy chambers generally only have a limited effect, paragraph 5.3) and the forces on the operating equipment, resulting into wear and tear. This conflict is assumed to be eliminated by either:
− Designing a barrier which light and has a low water displacement, minimizing the forces on the operating equipment.
− Designing a lock gate where there is no mechanical interaction or friction, and thus making the reliability of the gate independent of the dimensions and weight of the barrier: The increasing weight of the barrier will not increases the intensification operating forces and the complication the total system.

The requirements of the use of water/space have been coupled together as they are both in conflict with the increasing length of the barrier, and in addition, water consumption can have far going consequences considering the accessibility / capacity of the lock (paragraph 2.3). If a certain lock gate layout causes a large amount of water loss, this is due to ineffective use of the lock area (area which can not effectively be used to transfer ships), this directly also implies that there is an excessive use of space either in longitudinal direction (Mitre Gate e.g) or in perpendicular direction (Rolling Gates). Thus, if a gate maximizes effective lock area it will in most cases also minimize the use of space by the whole lock system (Vertical Lift Gate). The root of the conflict is therefore the length of the barrier or rather how the barrier is stored in open position. This assumed to be eliminated by either:
− Maximize the effective lock area, without increasing the use of space.

The requirements of ease of repair & maintenance / ease of manufacture have been coupled together as they are both in conflict with the increase of overall dimensions and weight of the barrier. Where the weight of the barrier is generally speaking the root of the problem as a light gate is generally slender and easy to handle. This conflict can be minimized by:
− Designing a lock gate, of which the components (especially the barrier) are light weight, simple and easy to reach and remove/install.

Attempting to resolve the above conflicts will be the prime focus during the concept development. When generating concepts, it will be aimed to start with simple design tasks; therefore three design principles have been assumed, each resolving (at least) one of the major conflicts. During the concept development the focus will be one of these Principles at a time; resulting in a set of fundamentally different concept designs. The three design principles have been presented below:
1. <u>Eliminate mechanical interaction and friction:</u>
2. <u>Minimize the weight of the barrier:</u>
3. <u>Eliminate/minimize the loss of water and use of space:</u>

8   CONCEPT DESIGNS

In this chapter concept designs have been developed and are elaborated in analogy with the three design principles formulated in Paragraph 7.2.2. These state 3 extreme solution directions each resolving one or more of the major conflicts that occur when up-scaling lock gate designs. According to these principles, the essential design characteristics have been selected from the Morphological Matrix (Appendix 2), forming the 'building blocks' of the concept designs. This has resulted in a set of 3 conceptual designs which are presented in this chapter. Eventually 1 design is selected (Chapter 9) for further design and validation in Phase 3. The design principles and the forthcoming concept designs are given below:

1. Minimal Mechanical Interaction and Friction → Ship Gate, Paragraph 8.1
2. Minimal Weight → Sliding Arch Gate, Paragraph 8.2
3. Minimal Loss of Water and use of Space → Submersible Gate, Paragraph 8.3

For each of the designs, the concept development has been presented, showing the background reasoning that has lead to the particular designs. A short description of each alternative is given, considering the structural and operational design and finally an elaboration is presented of the advantages and disadvantages. A more in depth analysis, considering the structural and operational designs can be found in Appendix 2. However, it must be mentioned, that due to time limitations it was not possible to work out the three alternatives to a detailed design level. Therefore the analysis and the choices made in chapter 9 are based on presumptions and basic reasoning, considering the expected performance of the concepts. Further research into the alternatives may provide new insights and ideas which could lead to a different choice of the most promising alternative (chapter 9).
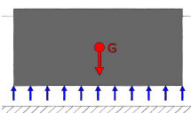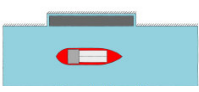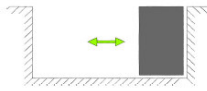
8.1   Minimal Mechanical Interaction and Friction
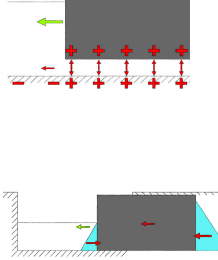
8.1.1 Concept development

In this case the concept development focuses on a lock gate design where mechanical interaction and friction are eliminated. This results in a set of design characteristics or 'building blocks' to which the concept design should comply in order to obtain the goal of minimal friction and mechanical interaction. Keypoints during the concept development will be:

- Keep the gate design and operation as simple as possible.
- No moving components may be present.
- No significant (mechanical) forces may act upon the gate (forces from operating equipment, friction e.a.).

Table 4: Concept Development; Minimal Mechanical Interaction and Friction

Minimal mechanical interaction/friction		
Characteristics of concept		
		When focusing on a gate design where no mechanical interaction or friction is allowed, one must utilize the liquid properties of water to let the barrier move or 'disappear' in and out of the lock profile. This can be done by: [A] Changing the physical state of the material, making it solid when retaining water and liquid when ship need to pass; an Ice barrier. Or [B] giving the barrier a lower density than water and letting it float so it can move through the water like a ship. Option [A] would result in an ideal lock gate but would require such enormous amounts of energy and freezing/heating installations that it is regarded as not-realistic. Option [B] is very simple and will be elaborated further.
		As the barrier is a floating object, it can not be transferred vertically without mechanical interaction to either lift the gate or change its density (by pumping air or water in and out of ballast chambers). Therefore the barrier should be stored to the side of the lock.
		When moving the barrier through the water, horizontal translation through the lock profile is the simplest manner of transition, minimizing water displacement and drag. (Compared to rotation).
		In order to avoid moving parts (hinges i.e), the barrier will consist of 1 plane.

	As the barrier has to be able to float, it needs to be relative wide to assure stability (meta centric height). Especially in case of high head locks, where a majority of the gate will be situated above water. Arch action can only efficiently be applied large length/width ratios. Therefore a rectangular gate is loaded in shear with supports in the sidewalls of the lock head will be most simple.
	In order to move the gate through the water one must transfer a force to the barrier in the direction of motion. But this has to be done without mechanical interaction. To achieve this one can either use [A] hydraulic forces supplied by the water level difference over the total lock system, or [B] use magnetism. The first option works for all but the upstream lock gate. If the lock is situated in a river, the natural water level differential can still be used by making an intake upstream, but incase of a sea or lake this will not work. Also as the gate floats, transition will be hard to control due to flow under the gate.
	Considering that the gate will be loaded in shear and bending moments and the application of magnetism, steel is the material of choice in this case.
	To reduce the force that need to be applied to the gate in order to move it through the water, the ends of the gate will be streamlined, like a ships hull.

8.1.2 Alternative 1: The Ship Gate

By combining the design characteristics derived in the table above, the conceptual design of the Ship Gate has been made. The Ship Gate is a gate that has enough buoyancy to float and is designed to be hydrostatically stable, so it can independently move through water without contact with its surroundings, see figure below.
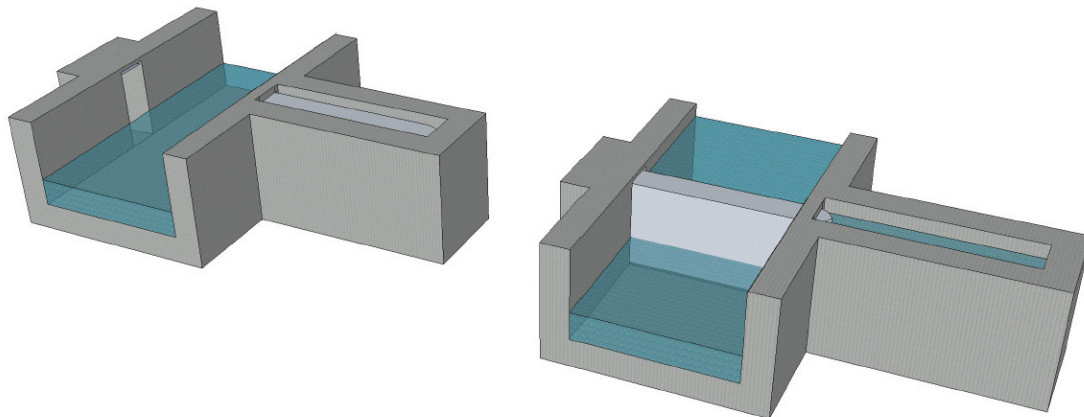
Figure 26: Conceptual Design of a Ship Gate, Minimal friction and mechanical interaction

General description and operation

The gate is quite similar to a conventional rolling gate, as it translates in and out of the lock profile and is stored adjacent to the lock in a recess. In order to move the gate in and out of the lock profile without any mechanical interaction, the application of a Electro Magnetic Propulsion (EMP) system is considered. For the Ship Gate this could be done by placing a series of permanent magnets along the length of the barrier and situating a set of active electromagnets in the lock-head as shown in the figure below. The tolerances between the barrier and the wall of the lock gate must be small (in the order of centimeters) to avoid excessive use of energy, as electro magnetic force field decays to the 4th power with the distance from the source. This seem to be rather small for

such a large gate, but the EMP system also has a stabilizing effect holding the top of the gate in place, as narrowing in distance between the track and the magnets creates strong forces to repel the magnets back to their original position, while a slight increase in distance greatly reduces the force and again returns the gate to the right separation distance. Though application of such a system might be possible, there may be some significant drawbacks associated to the strong magnetic field:

–   Influence on navigation and communication systems
–   Energy consumption and the reliability of energy supply by the grid or generators
–   Influence of corrosion of the steel gate structure

Possible further research should provide answers on this and Alternative means of operation (hydraulic, mechanical) are possible however this would be a concession to the principle of eliminating friction and mechanical interaction.
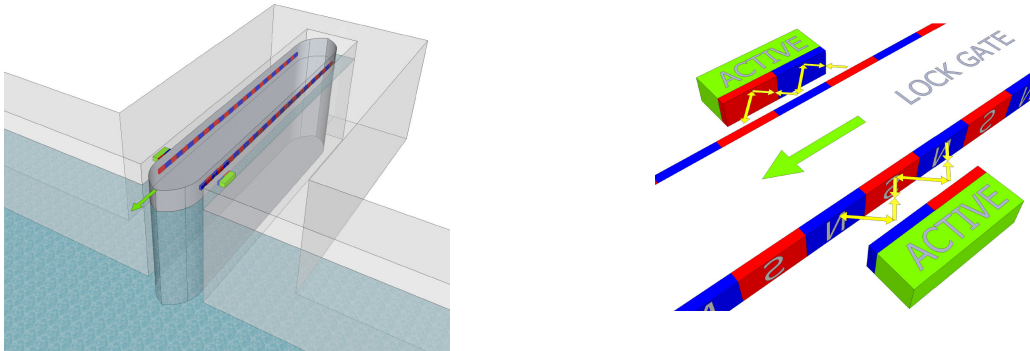
Figure 27: Schematization of a possible Electro Magnetic Propulsion System of a Ship Gate

When the gate is in closed position and is retaining water, it will support in the recesses in the side walls of the lock chamber. The gate will simply be pushed onto its support by the changing water level. Transferring forces like a simple beam on two hinged supports. In order to prevent damage to the gate structure and guarantee a water tight connection, wooden (azobé) or polymer bearing surfaces can be applied. Along the bottom of the gate, a sealing connection can be made with a sill in the lock floor. The connection should be flexible so the gate does not transfer significant forces to the floor, which would significantly complexity the gate structure, generally leading to a more expensive gate structure.

As the gate is a floating structure it should be vertically secured when in closed position to prevent the gate from floating up when the water levels are changed or in case of a flood. This could compromise the gate's retaining functions and to prevent upward movement of the gate, traverse beams are situated above the recesses. (see Figure 26).

In case of the downstream gate(s) of a lock, the transition from open to closed and vise versa commences whilst the water level in the lock is relatively low. The Ship Gate will have to be able to float and remain stable during low water level conditions. In case of High Head locks, where the water level difference is almost equal or greater than the minimum water depth of the lock, the major part of the barrier structure will be above water during floatation. This brings about hydro static stability issues as the center of gravity then lies above the center of buoyancy. In Appendix 2 calculations of the hydrostatic stability have shown that the gate structure needs to be significantly widened in order to float and remain stable. The results from the structural analysis (Appendix 2) and the stability analyses are shown in the graphs below.
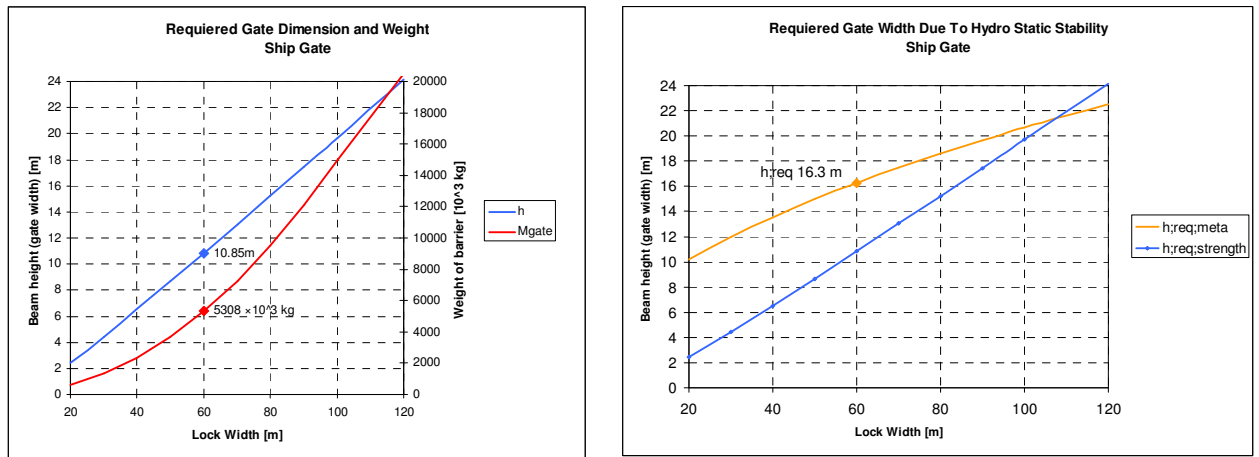
Figure 28: Required gate dimensions due to strength requirements, Ship Gate

Water usage

From the above it is clear that the hydrostatic stability is governing for the dimensions of the ship-gate, requiring a width of 16.3 m for the pilot dimensions. This means the gate recess also becomes significantly larger, resulting in a much greater water loss, see figures below:
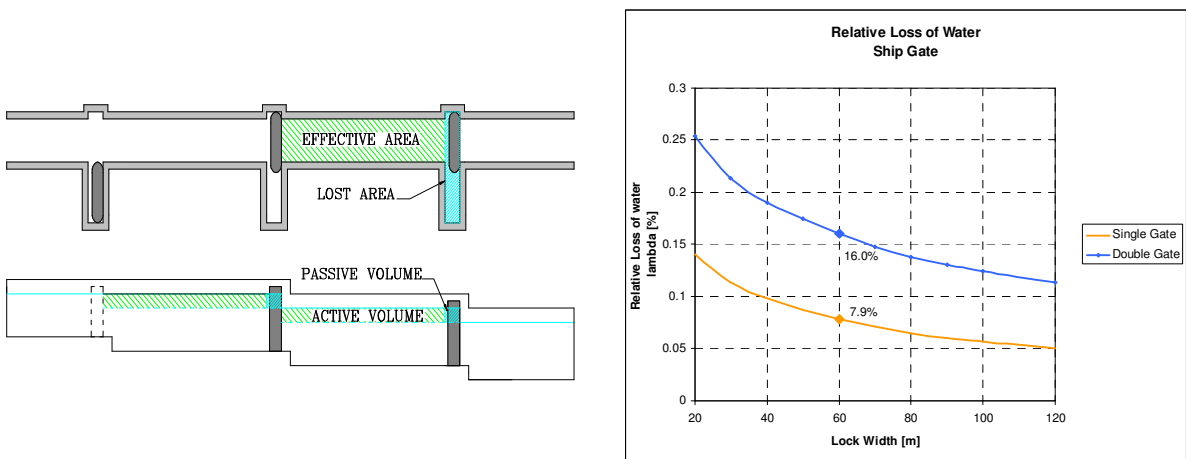
a. effective and lost area for a single gate lay-out

b. The relative water loss, is defined by:

$$\lambda_{loss} = \frac{A_{loss}}{A_{loss} + A_{eff}} \cdot 100\%$$

Figure 29: Water usage of a Ship Gate

8.1.3 Elaboration of Ship Gate concept design

To summarize the performance of the Ship Gate a short elaboration of advantages and disadvantages has been presented below:

+ No moving parts
+ No mechanical friction
+ No mechanical equipment
+ Easy transportation
+ Relatively good resistance to exceptional loads (impacts,ect)

− Sensitive to varying water levels (waves ect.) and currents during transition
− Use of space
− Loss of water
− Heavy and large gate construction
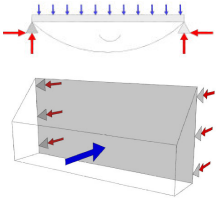− Possible large energy consumption of EMP-system
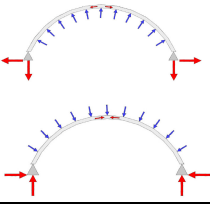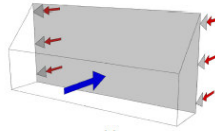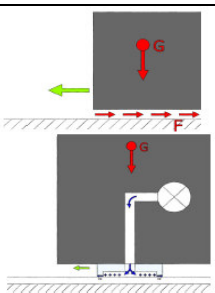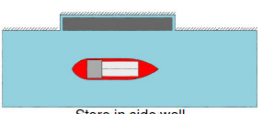
8.2 Minimal Barrier Weight

8.2.1 Concept development

In this case the concept development focuses on a lock gate design where the weight of the gate is kept to a minimum, reducing the loads on the operation system and making handling of the gate (for maintenance and repair) easier. This results in a set of design characteristics or 'building blocks' to which the concept design should comply in order to obtain the goal of minimal friction barrier weight. Key points during the concept development will be:
- Minimize internal forces and stresses, assuming hydrostatic forces will be governing
- Making a modular design, so the gate can be replaced, repaired and maintained easily and part of the gate are interchangeable with other lock gates in the total lock system

Table 5: Concept development; Minimal Weight Barrier

Minimal weight concept		
	Characteristics of concept	
		When reduction of weight is the focus, the transfer of forces is the first thing to look at. It determines to a great extent the required cross section of the barrier and thus the weight of the barrier. Arched structures, transfer distributed forces (almost) entirely through normal forces, allowing maximum utilization of material properties and resulting in light weight strong structures. Herein with there are two different types of arches, compression arches and tension arches which will be elaborated later.
		When considering a simple single arched barrier only side supports are required, the barrier is very stiff in length direction and flexible in vertical direction. It will therefore not be effective to also support the barrier at the bottom (in case of high head locks where B ~ H) as it will only transfer a minimal amount of forces to the bottom/top row of support. Support the barrier in 3 or 4 directions will also make the structure considerably more complex.
		As the arch will be relatively slender compared to its height, the gate will not be able to float and remain stable by its self (in case of high head locks). Therefore it is chosen to let the gate slide over lock floor, using hydrostatic bearings (Hydro foot) on a UHMWPE base to reduce friction and wear.
	\n\nStore in side wall	The barrier will be stored in side wall of the lock, from the weight perspective it doesn't really mater if the barrier is stored, under, above or to the side of the lock. But the most simple operation of the lock gate is obtained when stored in the side(s) of the lock head.
		The most efficient and simple way to move the barrier in and out of the lock profile is via horizontal translation, thus limiting the amount of displaced water and drag forces. This minimizes the forces on the operating system.

	The gate can be made modular by constructing the arch from a number of rings placed on top of each other (multiple elements in vertical direction). These can then be post tensioned in order to supply rigidity to the barrier especially during transition.
	The material choice for the arched gate, considering the weight of the gate would be Steel (both compression and tension) or Fiber Reinforced Polymers (in case of tension) or Concrete (in case of compression).

8.2.2 Alternative 2: Sliding Arch Gate

By combining the design characteristics derived in the table above, the conceptual design of the Sliding Arch Gate has been made and is presented in the figure below:
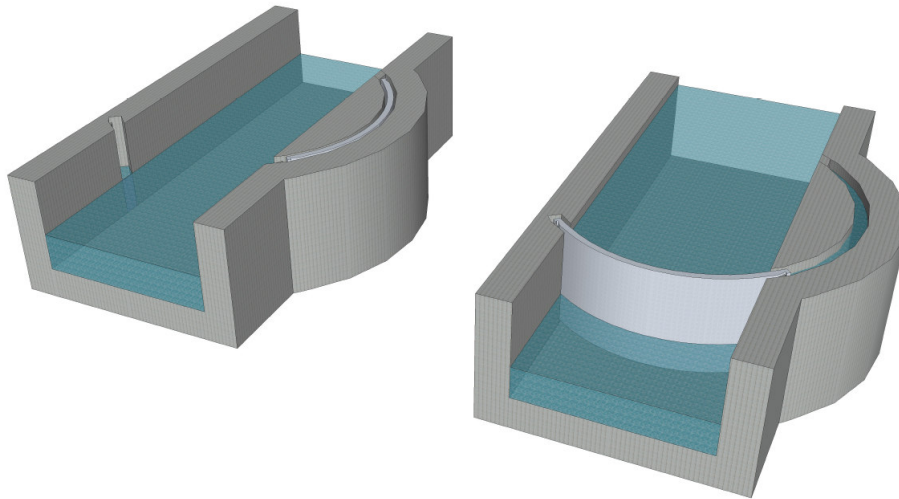
Figure 30: Sliding Arch Gate (tension arch), concept design

General description and Operation

The arched gate structure is moved in a circular path and the gate is stored in the side of the lock wall, where it is protected against contact with ships, waves, currents etc. This not only reduces the use of space (adjacent to the lock) but also increases the effective lock area, thereby reducing water loss. By making use of arch action, the evenly distributed hydraulic loads are transferred to the supports by normal force. Bending moments will be limited to load cases where uneven load distributions, like wave loading, occur. However it is expected, that in case of high head locks, the evenly distributed hydrostatic forces will be governing. This means the gate can be designed as a very slender structure, and will minimize the weight of the gate. In addition the slender gate limits the required width (and area) of the recess, reducing water usage even more.

To allow controlled circular movement of the slender structure, the gate will slide using hydrostatic bearings (hydrofoot) over a polymer plate. By creating a high pressure fluid film between the hydrofoot and the polymer base, the two surfaces are (theoretically) separated, resulting in minimal friction and wear. Any fluid can be used for such a bearing and therefore the water can be pumped directly out of the canal for use of the hydrofeet, minimizing environmental impact and keeping the required installations relatively simple. Hydrofeet have been applied for lock gates before, and the experiences regarding the hydro foots performance are satisfactory[39]. As the sliding arch gate is not buoyant, the hydrostatic stability is not an issue. However the overall stability during the movement of the gate should be checked in a later design stage, considering the interaction between the slender gate, currents, waves etc. and the uplifting force by the hydro foot.

In order to move the gate in and out lock profile an actuation system should be designed that can supply the circular motion of the gate. The forces to be delivered by the actuation system are expected to be relatively small due to the low water displacement (slender gate) and friction (hydrofoot). Therefore a light and simple linear drive mechanism can be used.

As mentioned before, the gate transfers the hydrostatic loads by normal force (tension or compression) and moves in a circular path. This is essential to the gates performance considering a light weight, low water loss gate design, but creates a major design challenge as the gate must be supported in the same direction as it is moved. This means a temporary connection to a support must be made, that can hold the gate when loaded in tension or compression. If choosing this alternative for further design, this aspect should become the prime focus.

Modular design

When the barrier needs to be repaired or removed, the gate structure cannot be moved out of the recess horizontally (like a rolling gate), because the radius of the arch is greater than half the lock width. This means the gate will have to lifted out. In order to increase the handelability and manufacturability of the gate structure, the gate is modular. The gate will consist of modular rings which are placed on top of each other and are post tensioned to assure a rigid connection. These modules can be designed identically, allowing series production and interchangeability of the modules. They will be relatively light weight can be disconnected and can then be simply lifted out of the recess by mean of a crane. The number and dimensions of the modules largely depend on the support of the gate and the lifting capacity of the crane(s). For a discussion on the application of modular design see chapter 15.2.2.

Compression vs Tension arch

In the structural analysis of the conceptual design of the Sliding Arch Gate (Appendix 2), both a tension and a compression arch have been elaborated. Considering the objectives of designing a light weight and slender lock gate, a tension arch was found to be more suitable due to the following reasons:

- Compression arches are sensitive to buckling and a 'slender' compression arch will fail before the yield strength has been reached (buckling and second order effects), especially when considering irregular load distributions. This means the compression arch needs a heavier and stiffer cross section.
- The safety of a compression arch is also significantly less due to the buckling sensitivity, in cases of accidental loads (explosions, ship impact, waves etc) as the gate does not have any reserve capacity (plastic regime) and failure will be sudden and catastrophic.

However, in case of a tension arch, fatigue phenomena must be taken into account, limiting the stresses during normal operation. Although the allowable stresses are reduced this will not decrease the ultimate load capacity nor does it require a stiffer (less slender) design.

In the figure below, the estimated weight of the Sliding Arch Gate is presented, taking into account the reduced cross section and weight when applying a tension arch:
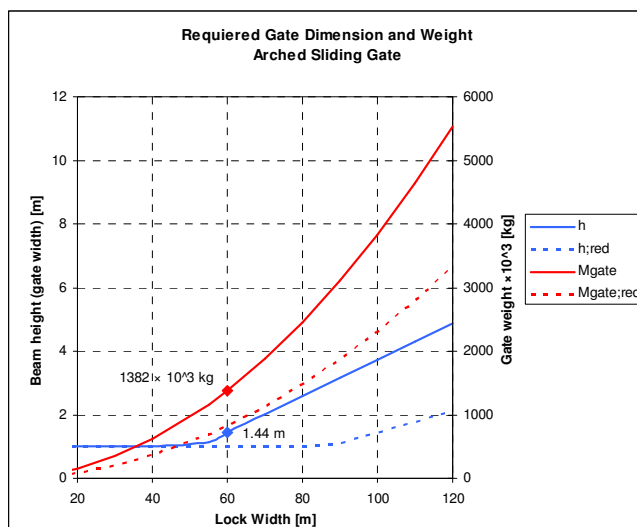
Figure 31: Required dimensions of a Sliding Arch Gate

Water usage:

As mentioned before, the slender arched gate structure does not only result in a light gate but also significantly reduces water loss and use of space. In the figures below the water loss of a single and double Sliding Arch Gate are presented.
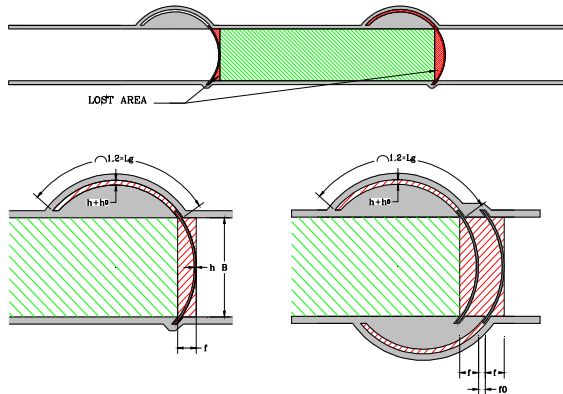
a. effective and lost area for a single gate lay-out
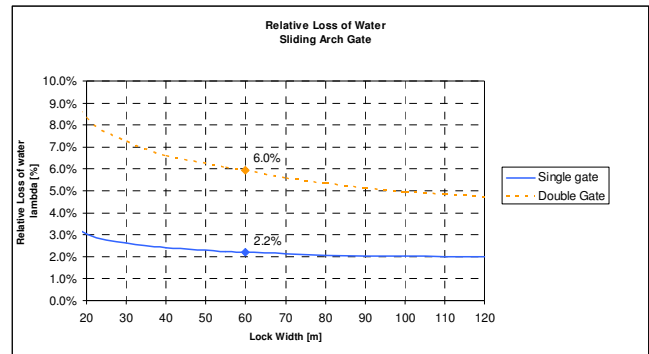
b. The relative water loss, is defined by:

$$\lambda_{loss} = \frac{A_{loss}}{A_{loss} + A_{eff}} \cdot 100\%$$

Figure 32: Water usage of a Sliding Arch Gate

8.2.3 Elaboration Sliding Arch Gate

To summarize the performance of the Sliding Arch Gate a short elaboration of advantages and disadvantages has been presented below:

+ High strength to weight ratio
+ Low water consumption
+ Low forces on operating equipment
+ Easy replacement
+ Easy and low maintenance
+ Low use of space
+ Possible 2 side retaining
− Possible stability problems during transition, caused by waves and currents
− Large construction accuracy required
− Heavy and complex lock head structure
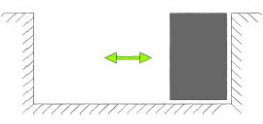− Technical Feasibility largely dependent of supporting structure (uncertainty)
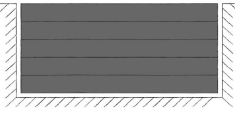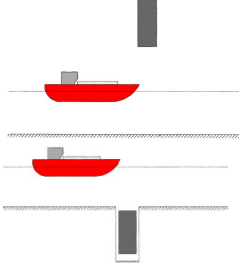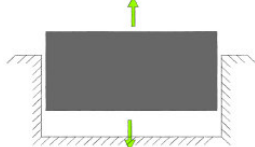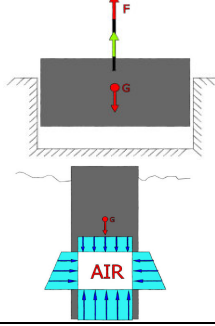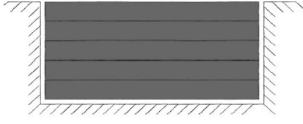
8.3 Minimal use of water and space

8.3.1 Concept development

In this case the concept development focuses on a lock gate design where the use of water and space is kept to a minimum. This results in a set of design characteristics or 'building blocks' to which the concept design should comply in order to obtain the goal of minimal use of water and space. Key-points during the concept development will be:

- − Minimize use of space adjacent to the lock.
- − Do not move the barrier through the active water segment of the lock area,

Table 6: Concept development, minimal use of water and space

Minimal use of water and space concept	
Characteristics of concept	
	When focusing on limiting space and water consumption of a lock gate, the location where the barrier is stored plays an important role. A minimal use of space and a maximization of effective lock area is obtained when storing the barrier above or under the lock. The first of which represents the Vertical Lift Gate, a well known and often applied technology. With large locks, transferring large ocean going vessels the lock gate will have to give a clearance of over 70m to allow unlimited passage. Considering a lock gate of 30-40 high this requires a super structure of approx 100-110m, this introduces a large amount of problems. These might be solvable, but it seems unrealistic and unlikely that this will lead to a high-performance design. Therefore storing the gate under the lock profile will be considered.
	To maximize the effective lock area, the barrier should span the lock in the shortest possible way, thus forces have to be transferred in shear.
	The barrier must be transferred vertically from under the lock profile. This could be done by rotation around the vertical axis, but ships will not be able to utilize the lock area in the rotation plane and therefore the lock area is not maximum. This would also require an extremely large radius when considering high head locks. Translating the gate vertically is therefore much more efficient.
	For moving the gate in and out of the lock profile vertically two methods could be considered. [A] lifting the gate mechanically or [B] inflating the gate so it floats up and then deflating the gate so it drops back into the recess again. These two option can also be combined: using buoyancy as kind of counterweight to limit lifting forces. But controlling the motion of the gate by lifting is mechanically.
	To minimize excavations the gate could be stored flat on the bottom of the lock. This requires the gate to consist of multiple elements in vertical direction with flexible connections and could be a possible optimization.
	As the barrier elements will be loaded in shear and in bending, steel would be the most suitable material. For the flexible connections between the elements reinforced rubbers could be used.

8.3.2 Alternative 3: Submersible Lift Gate

By combining the design characteristics derived in the table above, the conceptual design of the Submersible Lift Gate has been made and is presented in the figure below:
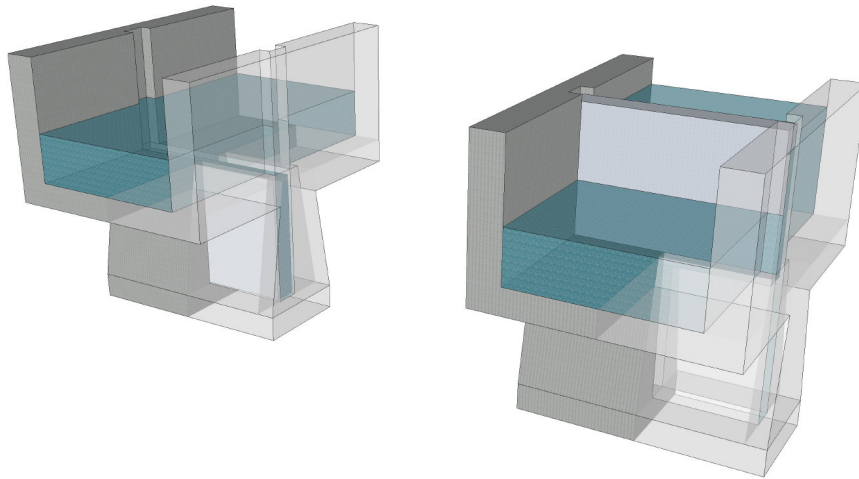
Figure 33: Submersible Lift Gate

General Description and Operation

The Submersible Lift Gate minimizes the use of space and water by translating the gate vertically and storing the barrier under the lock floor in a recess chamber, outside the active water segment of the lock. The lock head structure therefore requires a deep recess to store the barrier. Deep excavations will be required for the huge recess chamber structure. However, this maximizes the effective lock area and the absence of major recesses in the active water segment and thus reduces the water loss to a minimum. Though the barrier plane must be watertight in the active water segment (see figure below) in order to eliminate loss of water. This, however does imply that the barrier displaces a large amount of water, which results in large operation forces (Appendix 2). Taking safety into consideration and to assure the barrier will never open by itself if operation equipment fails, the mass of the gate must be balanced by its buoyancy in open position, but this will automatically be satisfied by the watertight upper segment of the gate which acts as a buoyancy chamber.

The Submersible Lift Gate, which translates vertically and is stored under the lock floor, has to be (partially) operated under water. Maintenance and inspection are therefore not an easy task and the feasibility of the design and reliability of operation is therefore largely dependent on the operation system. For which hydraulic cylinders could be used to move the gate, or the buoyancy of the gate could be altered, respectively sinking or floating the gate by pumping water in and out of the buoyancy chambers. Though due to the travel distance and the required operation forces (or volume to be pumped), operation is expected to be time and energy consuming.

The operation of the gate is also sensitive to siltation of the chamber and ruble entering the recess chamber possibly hindering operation or causing damage to the lock gate system (especially seals). Therefore, at the top of the recess chamber a sealed connection with the barrier will be made to prevent the intrusion of silt and debris into the chamber. Water supply to and from the chamber, to allow movement of the barrier, must therefore commence through channels connected with the lock / F&E system. To allow dry inspection of the lock gate, a water tight cover can be placed over the recess chamber and the chamber can then be pumped dry. This however could cause problems as the mass of the structure significantly reduces when the water is pumped out of the recess and the whole structure may become buoyant. If this occurs counter measures should be taken (ballasting the recess chamber, anchorage, toe structures).

Normally lock gates are moved into their opened or closed position before the water level is changed. However, due to the fact that the Submersible Lift Gate moves in the same direction as the changing water level, moving the gate while the filling/emptying of the lock takes place, becomes possible. This results in faster operation of the gate and reduced forces on the operation equipment; though the guidance system of the gate will become more

complex as the gate has to retain water during transition and must ensure a watertight connection. Both the operation schemes of the gate will be considered in the following.

The Submersible Lift Gate transfers the hydrostatic forces to the side walls of the lock head through bending shear like the Ship Gate. When considering the simplified model of a pinned-pinned beam the results of approximating the gate dimensions according to the strength criteria will give the same results as for the Ship Gate, see Appendix 2:
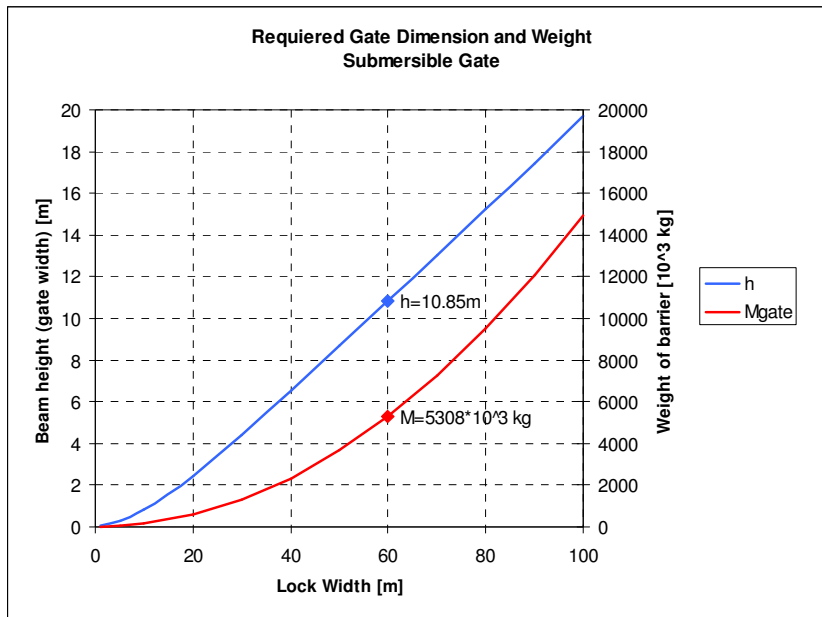
Figure 34: Required dimensions of a Submersible Lift Gate

Water usage:
The submersible lift gate is designed to eliminate use of water and space. However when applying a double gate lay-out some water loss does occur, see figures below:
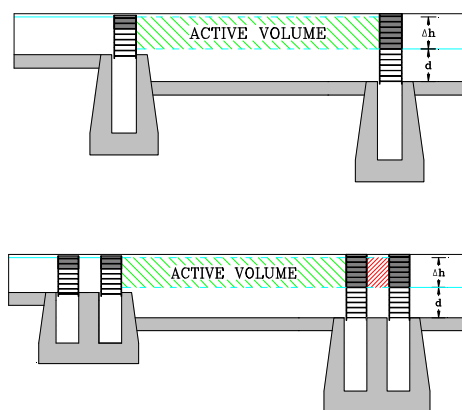
a. effective and lost area for a single gate lay-out
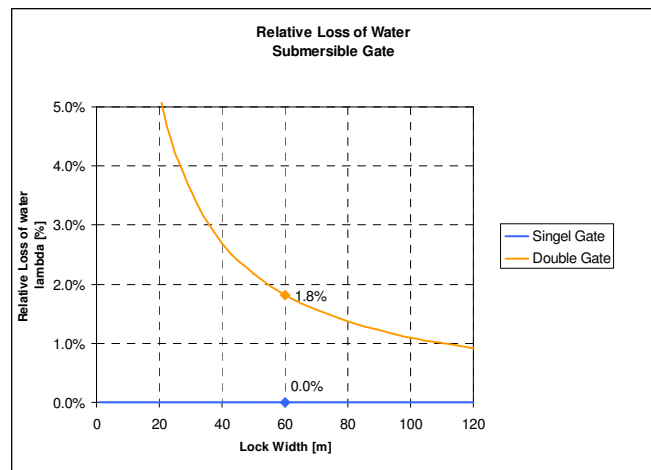
b. The relative water loss, is defined by:

$$\lambda_{loss} = \frac{A_{loss}}{A_{loss} + A_{eff}} \cdot 100\%$$

Figure 35: Water consumption of a Submersible Lift Gate

8.3.3 Elaboration

To summarize the performance of the Submersible Lift Gate a short elaboration of advantages and disadvantages has been presented below:

+ Could be used as emergency gate, can close in flowing water and can be operated under a head difference.
+ No water use when applying a single gate layout and only a slight water loss when applying a double gate lay-out
+ Minimal use of space
+ Good resistance to exceptional loads
− Deep excavation required, resulting in a very heavy lock head structure
− Poor inspect ability, maintainability and reparability. In order to perform standard maintenance and inspection works, divers are required or the recess chamber has to be closed of and pumped dry.
− Heavy loads to be supplied by operation equipment, requiring enormous hydraulic jacks with a large high pressure pump capacity.
− Wear issues when operation scheme 2 is applied.

9   CONCEPT SELECTION

In this chapter, a selection is made of the most 'promising' conceptual design, regarding the best overall performance for 'future large and high head locks'. The designs have been evaluated according to the requirements for future lock gates that have been derived in chapter 6, and in order to visualize the expected performance a Multi Criteria Analysis (MCA) matrix is presented in 9.1. Finally, the gate with the best overall performance is selected and a final evaluation is given in paragraph 9.2. The elected design will then be worked out to a detailed operational design level, in Phase 3 of this master thesis project, and it will be compared to conventional technologies using the Panama Canal Expansion Project as a reference project.

The concept selection the following designs have been considered:
- Ship Gate: (Design Principle: Eliminate friction and mechanical interaction)
- Sliding Arch Gate, tension: (Design Principle: Minimize weight)
- Submersible Lift Gate: (Design Principle: Minimize water consumption and use of space)
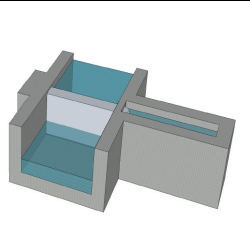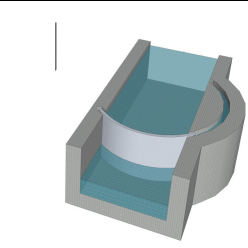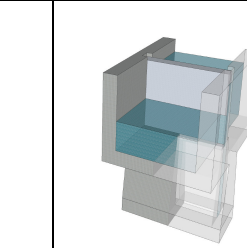
It must be remarked, that the evaluations and choices which are made in this chapter are based on conceptual designs that have only been worked out to a limited detail level due to time restrictions. Presumptions on the expected performance of each of the designs have been made based upon basic engineering knowledge. Therefore further research into the conceptual designs may provide new insights and maybe even other alternatives, which could change the outcome of the concept selection.

9.1   Multi Criteria Analysis

The results of the Multi Criteria Analysis have been presented in the matrix below, after which the evaluations according to the requirements of future locks have been presented. The scores for the performance according to each requirement have been added up form a total score, indicating the all-round performance of the gate.

The scores for the performance of the he concept designs will be +2,+1,0,-1,-2, where +2 will be rewarded for the best performing design and -2 for the worst. A score of 0 will be rewarded when neutral. To designate the scores from the primary and secondary requirements the scores connected to the primary requirements will be multiplied by ×2.

Table 7: Multi Criteria Analysis, Performance Matrix

	Ship Gate	**Sliding Arch (Tension)**	**Submersible gate**
Reliability	+4	+4	-4
Safety	+2	0	+4
Accesibility	0	+2	0
Water consumption	-4	+2	+4
Use of Space	-2	+1	+2
Energy Consumption	+1	+1	-2
Total score	**+1**	**+10**	**+4**

9.1.1   *Evaluation*

Reliability [×2]

Ship Gate [+2]
Due to the absence of moving parts, friction and thus wear and tear, the breakdown probability will be low as for the required maintenance works. Though, it must be mentioned that the feasibility of a reliable EMP system needs further investigation. Small scale maintenance can easily be preformed in a dry environment in the recess which can be closed with a bulkhead and the recess drained. In case of large scale repair or replacement the gate can be transported to a external dry dock, as it can float and is hydrostatically stable. The maintainability and inspectability are therefore considered to be good. This, in combination with the simplicity of the design, results in a score of +2.

Sliding Arch Gate (Tension) [+1]:
The Sliding Arch Gate will require relatively small operation forces, and wear & tear of the hyrdo-foot system have found to be very small[23], though this will require further investigation when applied to a large scale. As the gate simply translates horizontally; a simple, light weight actuation system can be applied for which also a back-up system can be installed in case of breakdown. Small maintenance can be done in the recess, and when large scale maintenance/repair is required the modular gate design allows the gate to be simply lifted out of the recess by crane. The Sliding Arch Gate can therefore be seen as a reliable concept, but the presence of moving parts (above water) and risks/uncertainties involved with the large scale application of the hydro foot system result in a score of +1

Submersible Lift Gate [-2]:
The huge forces required to operate the Submersible Lift Gate, will require a heavy operating system. In combination with relatively difficult access and poor maintainability and inspect ability and submerged moving parts, the risk of break downs and long term outages due to complex repair works is relatively high. Also the sensitivity to siltation and debris contributes to the above risks, resulting a score of -2

Safety [×2]

Submersible Lift Gate [+2]:
The Submersible Lift Gate transfers loads through bending and shear to its supports, where the reaction forces are transmitted in longitudinal direction of the lock walls. This means the gate can be designed to have considerable deformation capacity (in the plastic regime) before structural failure and loss of its retaining functions. This makes the gate redundant to impact loads from ship collisions and other unexpected extreme loads. Also, due to the vertical translation of the gate and as it is supported fully during transition, it could be designed to be closed under a considerable head difference, making emergency closure, incase of an unexpected failure of another gate possible. This results in a high safety (in extreme conditions).

Ship Gate [+1]
The Ship Gate transfers forces in the same way as the Submersible Lift Gate and therefore has the same redundancy advantages. However due to its horizontal translation, without mechanical guidance, closure under a significant head difference will not be possible resulting in a score of +1.

Sliding Arch Gate (Tension) [0]:
The Sliding Arch Gate becomes stronger when deformations increase as the radius of the gate becomes smaller. In case of the point load this isn't necessarily the case, but as plastic deformation sets in the arch will start to react as a cable, giving the gate considerable deformation capacity before failure and loss of its retaining function. However, this does require significant rotation capacity at the supports, and huge reaction (brace) forces to be delivered by the lock head structure perpendicular to the lock walls. If the deformation capacity is sufficient the gate could be redundant to extreme, unexpected forces. But due to the uncertainties about the technical feasibility of this the score for safety will be reduced to 0, instead of +1 (similar to the Ship Gate).

Accessibility [×2]

None of the concept designs directly effects the accessibility of the lock in a negative way, as the head clearance for all the gates is unlimited. However the operation speed and additional safety measures can influence the accessibility of the lock. The effects of water consumption on the lock cycle time and therefore accessibility have not been accounted for here, as this already has been done for the water consumption requirement.

Sliding Arch Gate (Tension) [+1]:
The light and slender gate can possibly be operated relatively fast, and due to its redundancy no extra secondary safety measures will be required that negatively effect the accessibility. Therefore the accessibility of the lock in case of a Sliding Tension Arch can be considered to be good. But due to uncertainties described under the previous requirement the score will be reduced from +2 to +1.

Ship Gate [+1]:
Due to the enormous dimensions of the Ship Gate, operation might take slightly longer then for a Sliding Arch Gate or a standard Rolling Gate, although it does has a high redundancy and secondary safety measures will not be required resulting in a score of +1.

Submersible Lift Gate [-1]:
Although the Submersible Lift Gate can partially be operated whilst the water level is changed, the huge operation forces will probably result in a relatively long operation time. Even tough the gate has a high redundancy and extra secondary safety measures will not be required, the uncertainties about the long operation time results in a score of -1.

Water consumption [×2]
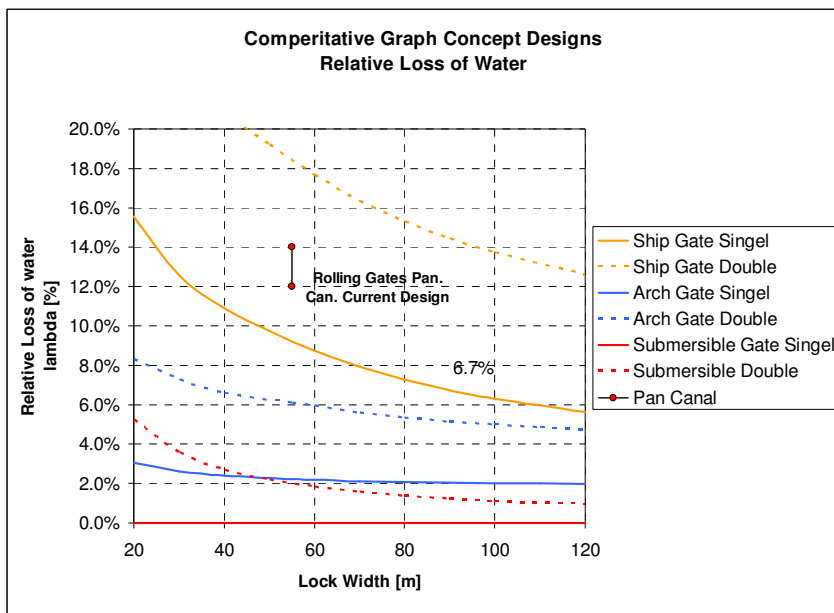
Figure 36: Comperitative Graph considering the relative loss of water

Submersible Lift Gate [+2]:
The submersible lock gate performs the best, eliminating water extra water loss totally and will be rewarded +2.

Sliding Arch Gate (Tension) [+1]:
The Sliding Arch Gates do cause a reasonable amount of extra water loss but still far less than that of conventional rolling or Mitre Gates, and thus will be rewarded +1.

Ship Gate [+2]
The Ship Gate, due to its enormous dimensions, contributes significantly to the water consumption of the gate and is rewarded -2 though it could be considered that applying a double door layout in case of the Ship Gate might not be required.

Use of space [×1]

Submersible Lift Gate [+2]:
As the lock gate is stored under the lock profile, the use of space is minimal, resulting in a score of +2

Sliding Arch Gate (Tension) [+1]
Due to the smart storage of the Sliding Arch Gate, the design does not use a lot of space in perpendicular direction of the lock, nor do they lengthen the lock complex considerably, resulting in a score of +1.

Ship Gate [-2]
The Ship Gate use allot of space perpendicularly to the lock axis and due to the large width of the lock gate, required for hydraulic stability they also lengthen the lock complex considerably, resulting in a score of -2.

Energy consumption [×1]
As the operation of all the concepts require an external source of energy (electricity, fuel) none of the designs will be rewarded +2. In order to give educated score, further investigation is required. However, it is clear, that the Submersible Lift Gate will consume considerably more energy for its operation then the other alternatives, due to the large operation forces and scores have been rewarded as following:
Ship Gate [+1],
Sliding Arch Gate (Tension) [+1]:
Submersible Lift Gate [-2]:

9.2   Concept selection

Form the Multi Criteria Analysis the Sliding Arch Gate (tension), seems to be the most suitable concept design for future large, high-head locks. It delivers the most all-round performance on all the criteria, mainly due to; its light weight, small operating forces, good maintainability and inspectabiliy, relatively low water consumption and use of space. It also seems to be the most elegant and innovative concept design, however there are a number of uncertainties governing its performance, considering:

- Its redundancy to ship impact
- Technical feasibility of the support structure
- Large scale application of the hydro foot system, especially considering the flatness requirements of the lock head floor.
- Operation in turbulent water

This not only makes the Sliding Ach Gate the most 'promising' but also the most interesting for further investigation and therefore the Sliding Arch Gate has been selected for the detailed design stage. See chapter 12 for presentation of the fully worked out design.
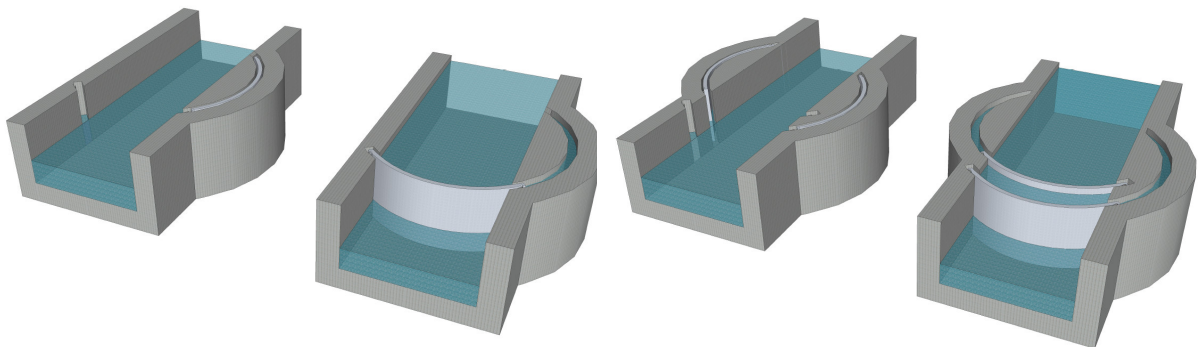
Figure 37: Selected Concept, the sliding arch gate (tension), also shown as possible double gate lay-out

PHASE 3: DETAILED DESIGN AND VALIDATION

54 -

10 DESIGN METHODOLOGY

In Phase 3 of this Master thesis project, the conceptual design of the Sliding Arch Gate, that was selected during the previous phase, will be worked out to a full mechanical and structural design. To do so, the Panama Canal Expansion Project (PCEP) has been used to supply realistic boundary conditions that also fit the field of innovation (Chapter6). The focus will lay on obtaining a design that 'works', rather then a full optimized re-design of all the Panama gates as this master thesis project concerns new technology and a great amount of pioneering work has to be done. Finally a comparison will be made with conventional technologies considered for the PCEP's concept design, reaching consensus on the final part of the hypothesis that; 'new/innovative concepts (The Sliding Arch Gate) could prove to outperform up-scaled conventional technologies'

This chapter will outline the methodology and contents of this Phase. An overview of this phase within the total project is illustrated in Figure 38 and the design methodology and its relations to the context of this report are presented in paragraph 10.1. In paragraph 10.2 a short introduction on the history and the current expansion of the Panama Canal is given.

10.1 Methodology and Contents

The main goal of the case study is to work out the design of the Sliding Arch Gate, using realistic boundary conditions that fit within the field of innovation, (see chapter 6).
Designing is generally an chaotic and iterative process, a continuous cycle of analysis, specification, designing and reanalyzing getting more and more into technical details, attempting to find optimal solutions. In order to structurize this process and to prevent running into too many dead ends, the design process has concentrated on focusing on solutions that fit the future requirements of lock gates mentioned in chapter 7. Together with boundary conditions and requirements derived from PCEP this forms the basis of design (chapter 11), giving guidance to the solution directions and aiding to the convergence of the design process. In addition functional and operational analyses have been preformed, to uncover the relations and interactions between the different sub systems and elements of the lock gate system. These operational analyses are not presented though the results have been listed as criteria for the specific design elements.

The contents of Phase 3 'Design and Validation' is based on the results of the design process. In the figure on the next page the design methodology and contents have been presented, also displaying the relations with the previous phases (Figure 38).

- First the Basis of Design is presented in Chapter 11, listing the requirements, starting points, boundary conditions and load cases that govern the design of the Sliding Arch Gate.
- In Chapter 12 the general design and operation of the gate are presented by means of detailed illustrations with short explanation. References to the paragraphs in which the specific design details have been worked out are given, in order to help the reader navigate the detailed content of the following chapters.
- Chapter 13 describes, and presents the results of the mathematical model, used for determining the forces in the gate structure and the reaction forces required to be delivered by the supports.
- In chapter 14 the support system is designed, considering a number of alternatives and presenting a detailed design of the 'Pin Support System' which is used for to support the Sliding Arch Gate.
- The design of the gate structure is discussed in Chapter 15. The application of modular design is discussed and the structural design of the representative gate module is presented. An indicative design of the module connections and deviating module designs (top, bottom module and buoyancy chambers) is given.
- An indicative design of the lock head structure is presented in Chapter 16, geared toward determining rough dimensions and quantities.
- The detailed mechanical design of the operation equipment is presented in chapter 17, considering the design of the hydrofoot installations, horizontal guidance and finally the actuation system which will be supplied by a linear motion, direct drive mechanism.
- Finally in Chapter 18 'Cost and Validation' a conclusion is drawn on the design and performance of the Sliding Arch Gate in comparison to conventional technologies. And part [3] of the hypothesis: that new/innovative concepts could prove to outperform up-scaled conventional technologies, is justified
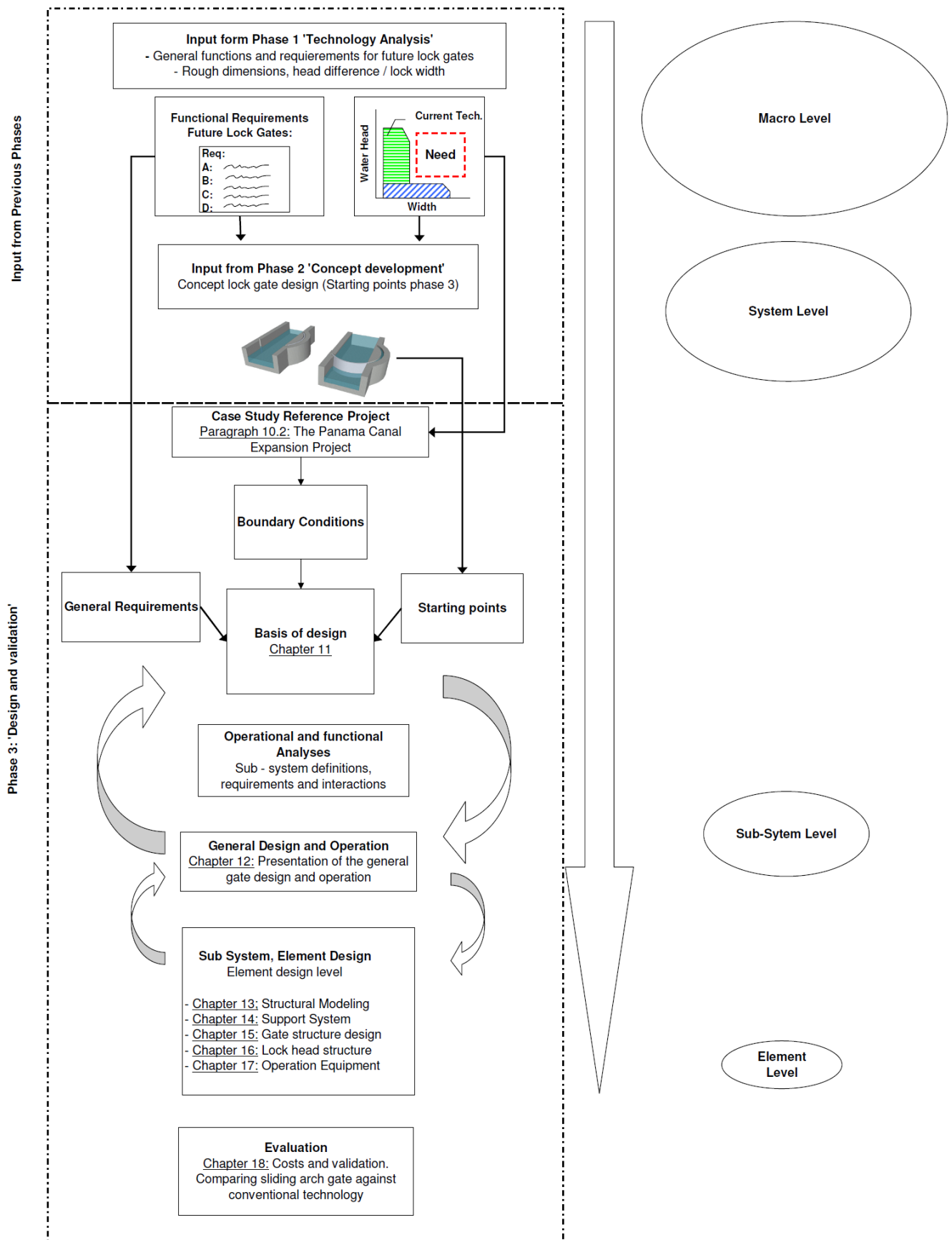
Figure 38: Design methodology and context of Phase 3 'Design and Validation

10.2 Case study project the Panama Canal Expansion Project

10.2.1   Backgrounds

The current Panama Canal, constructed in 1914, is a man-made waterway joining the Pacific and Atlantic Oceans and is considered as one of the largest and most difficult engineering projects ever undertaken, consisting of an artificial lake - Lake Gatun - channels and three sets of locks. It is the focal point of many international trade routes, shortening the dangerous inter-ocean shipping route via the 'Cape of Good Hope' considerably.

For many, however, the construction of the canal remained an illusion as many never saw its completion or even the start of its construction. The delirious effects of only thoughts on building a canal that would connect the Atlantic and Pacific and its forthcoming profits, also known as 'Panama Fever', sparked heroic attempts to build such a canal of which the first date back to 1534. Many wars, ten thousands casualties, a few revolutions and 4 centuries onward the canal was finally completed.

Figure 39: Map of the Panama Canal

Now almost 100 years later, the current Panama Canal will be expanded with a third lane of locks, able to transit today's largest container vessels and doubling the canals capacity[14]. The expansion program is intending to increase the transit capacity of the canal to meet the growing cargo carrying demand along major international maritime trade routes. Execution of the project has already begun and is planned to be completed in 2014 exactly 100 years after opening the current Panama Canal.

The expansion of the Panama Canal will consist of two new lock complexes, one on each side of Lake Gatun. The lock complexes, each consisting of three lock chambers will be connected with the current shipping routes by new entrance channels and the current waterways through the lake and to the oceans will be widened and deepened. The cost estimation of this Mega-project is approximately $5250 mln, of which $3350 mln [14] will only be used for the construction of the lock complexes.
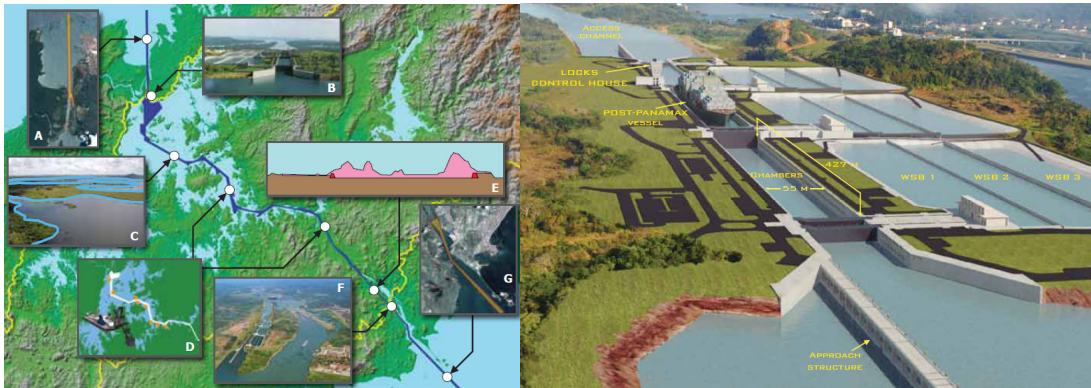
Figure 40: Expansion project overview [14]

The lock complexes will consist of three lock chambers, as presented in the figure below. The chambers will be 427 m (1,400') long, by 55 m (180') wide, and 18.3 m (60') deep, allowing the transit of a 12.000 (TEU) Container vessel which has a deadweight of 160.000 ton, is 366m long, has a 15 m draft and 49 m beam.

The filling and emptying system of the lock chambers will work by gravity force and in order to limit the water consumption of the locks operation, huge Water Saving Basins will be constructed adjacent to the lock, see figure below). At a total cost of $620 mln the Water Saving Basins reduce the water consumption by 67%.

10.2.2 Lock lay-out

As stated in the previous paragraph, the case study will consider only the design of the lock gates. Though, the design must fit into the current design, taking notice of the filling and emptying systems and other structures nearby. In the figure below the lay-out of the lock structure of the Pacific Lock has been presented. Each lock chamber has an effective length of 427.0m, which is the inside measurement of the inner lock gates and is required for transferring the design vessel. This distance is considerably less then the distance between the outer lock gates, 488 m. For the new design only the inner dimensions, required for transferring the vessels, will be governing.
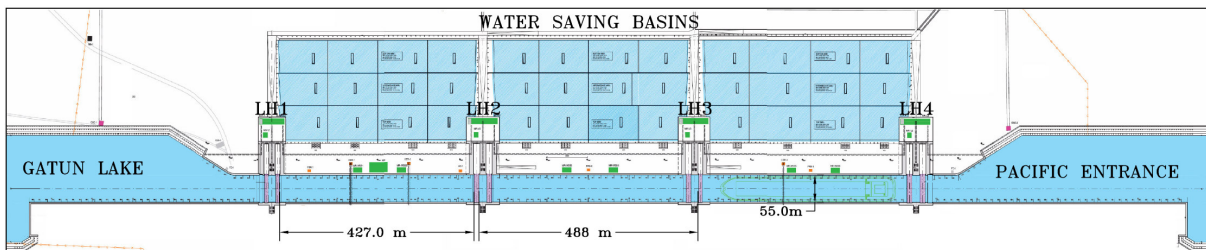
Figure 41: Lock Lay-out of current conceptual design by ACP.

Dimensions lock chambers:
Width (min.):   55 m
Depth (min.)   18.3 m (considering lowest operation water levels and mean low tides)
Eff. length (min.)   427-488 m (depending on which doors are closed)

Dimensions Lock complex (Current Design):
Total length: 1405 m
Length approach structure: 525 m
Length total: 2455 m
Water level difference (max): 30.5 m

Design Ship:

Length: 366 m
Width: 49 m
Draft: 15.2 m
DWT: 165000 ton

10.2.3 Design of Current Lock Gates[26]

For the design of the lock gates a number of conventional technologies where considered of which Rolling Gates where considered the most appropriate, due to the good experiences with this gate type at the large maritime locks of Berendrecht (BE), Ijmuiden (NL) and Le Havre (FR), which have similar widths, 55-68m but considerably less retaining height approx 5.5m, compared to a retaining height of 21m under normal operating conditions for the Panama Canal lock gates. For safety reasons and in order to guarantee continuous operation each lock head has been fitted with 2 Rolling Gates. Both the gates will always be used simultaneously in exception of a brake down of one of the gates or when an extremely large ship has to be transferred.
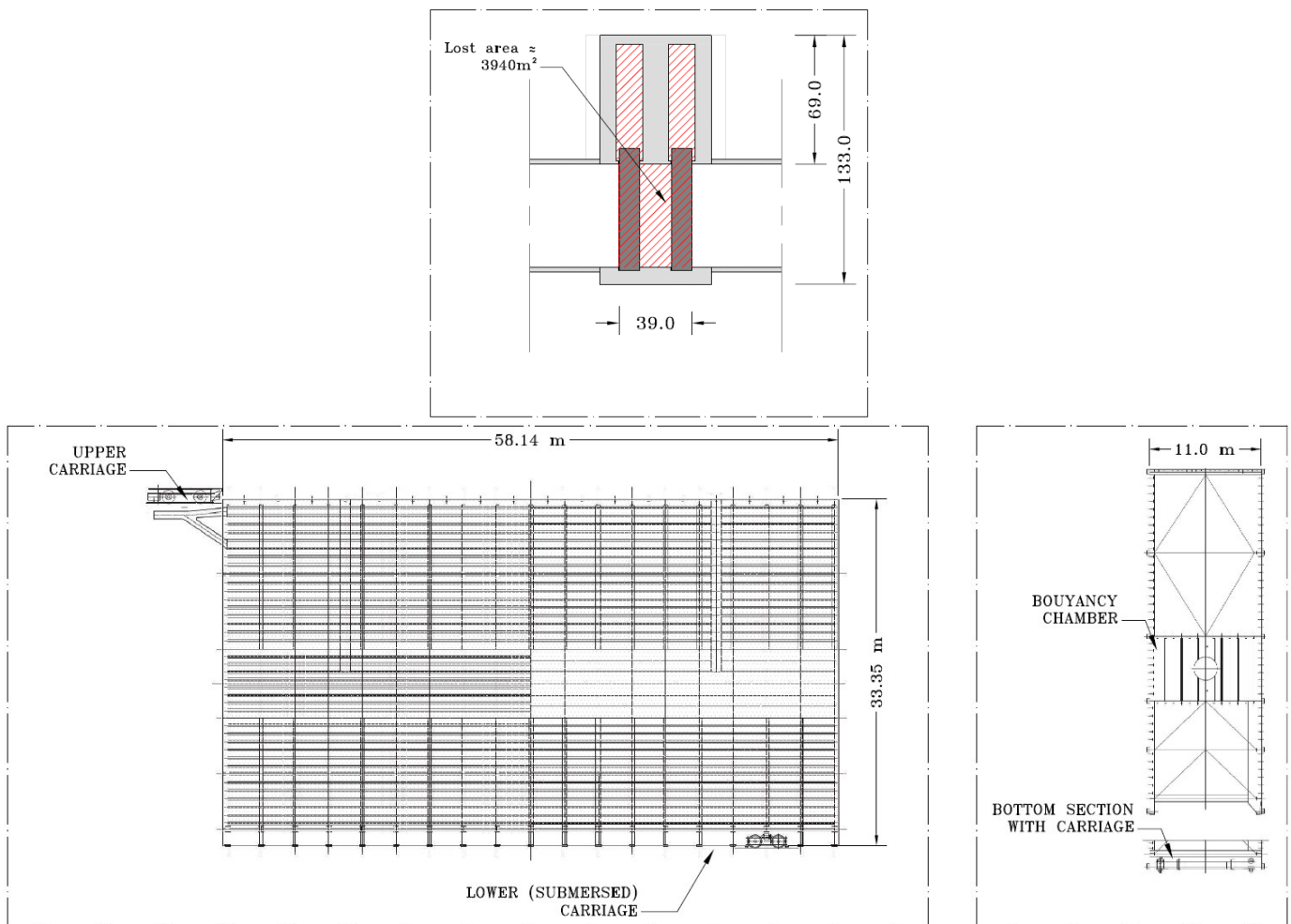
Figure 42: Current lock head and lock gate design, concept design ACP

The rolling lock gates will translate by means carriages running on tracks and the gate will be actuated by a wire pull system, as can be seen in the picture above. Each of the gates will be approximately 58m long, 9-11m wide and weigh approximately 2500-4000 ton. In order to reduce the loads on the tracks and wheels buoyancy chambers have been fitted inside the gates structure. The water loss, due to the ineffective wet area of the lock gates and their recesses is approx 12-14% of the total wet lock area.

11 BASIS OF DESIGN [26] [29] [30]

In this chapter the basis of design has been presented. It forms the major input for the design phase and governs the solution directions and criteria to which the design of the Sliding Arch Gate must comply. The general requirements governing the performance and functionality of the Sliding Arch Gate are presented in paragraph 11.1. After which the starting points, considering the conceptual design of the gate have been listed in paragraph 11.2. As the Panama Canal Expansion Project (PCEP) is being used as a reference project, the boundary conditions have been derived from the available project data and have been presented in paragraph 11.3. Finally, the load cases, which have been formulated in accordance with the supervisors of this master thesis project and to which the Sliding Arch Gate must be designed are presented in paragraph 11.4.

11.1 General Requirements

The general requirements governing the performance and functionality of the gates design are derived from chapter 7 and are listed below: The requirements are qualitative and will be quantified in the actual design.
- The gate must be able to retain water, in closed position, allowing the transfer of ships in vertical direction.
- When retaining water, the gate must provide a water tight connection.
- The gate must be able to be move out of the lock profile, allowing ships to transfer in horizontal direction.
- Incase of dry lock maintenance closure the lock gates must be able to provide as retaining structure allowing the lock chambers to be fully emptied.
- The gate design must limit water consumption.
- The gate design must limit the use of space.
- The reliability and safety of operation is paramount and the design must be geared towards maximizing this.
- The gate design must be able to closed in approximately 5 minutes in order to enhance the accessibility of the lock
- The gate structure must be transportable to allow installation and removal at the start and end of its lifetime and for large scale repair and maintenance in a workshop or special dock

11.2 Starting points

The sliding tension arch gate as presented in chapter 9 (phase 2) will be used as starting point for further design, of which the most important aspects have been summarized below. These starting points are not binding and may change according to further design.
- The gate structure is a slender, circular arch, using arch action to transfer the forces to the lock head and foundation.
- The gate structure design will be modular. Using one module to build up the gate structure, for discussion see 15.2.2.
- Hydro-foot installations will be applied to reduce friction forces during transition
- Gate width: h = 2.0 m
- Module height: h_m = 3.0 m
- Number of mod. N = 11

11.3 Boundary conditions

The boundary conditions for the design of the Sliding Arch Gate, have been derived using the Panama Canal Expansion project as reference. Most of the values have thus been obtained from documentation supplied by the Autoridad Canal de Panama (ACP) or have been assumed. As mentioned before, only the design of 1 gate will be considered. From the conceptual design of the new Panama Canal locks it appears that the most governing hydraulic boundary conditions prevail at lock head 3 of the Pacific Lock complex. Therefore the design of the Sliding Arch Gate will consider boundary conditions that hold for this lock head.

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[29] CONSORCIO POST-PANAMAX, (2005), Diseno Conceptual de las Esclusas Post Panamax, Task 2, Part A General Design Criteria, ACP

[30] AUTORIDAD CANAL DE PANAMA, (2009), RFP-76161, Employer's Requirements, Design and Construction of the Third Set of Locks, Amendment no. 23

Materials and general definitions:
The following specifications regarding materials and general definitions have been assumed, and will be used unless stated otherwise.

Table 8: Material properties and general definitions

Material properties and general definitions			
Gravitation	g	9.81	m/s²
Density of water	ρ_w	1025	kg/m³
Construction steel quality	σ_{yd}	355	N/mm²
Reinforcement steel quality	σ_{yd}	435	N/mm²
Density of steel	ρ_s	7850	kg/m³
Concrete class		Var.	
Density of concrete	ρ_c	2400	kg/m³

Levels and dimensions:
The levels used for the design of the Sliding Arch Gate are presented in the table below.

Table 9: Levels and Dimensions
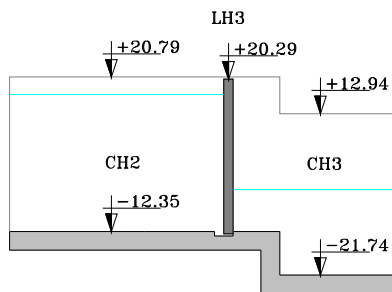
Levels and dimensions at Lock Head 3 (LH3)		
Lock width	55.0	m
Lock length	427	m
Minimum operation depth	18.3	m
Minimum freeboard lock structure	1.5	m
Minimum freeboard gate structure	1.0	m
Top of structure level upper chamber*	+20.79	m PLD
Floor level upper chamber	-12.95	m PLD
Top of structure level lower chamber*	+12.94	m PLD
Floor level upper chamber	-21.74	m PLD
Top of structure level lock gate*	+20.29	m PLD

* These values have been based on the minimum freeboard requirements and the operation water levels. These levels may be changed if the gate design requires that, however the minimum freeboard requirements will prevail.

Hydraulic boundary conditions:
The hydraulic boundary conditions that have been used for the design of the Sliding Arch Gate are given in the table below, and represent the most governing values considering the PCEP.

Table 10: Hydraulic boundary conditions: Water levels

Water levels at Lock Head 3 (LH3)	Up stream	Down stream	
Operation water levels, retaining			
Maximum operation levels 1	+19.29	+3.60	m PLD
Maximum operation levels 2	+16.94	-3.44	m PLD
Maximum head difference	+20.38	-	m PLD
Operation water levels, gate operation			
Minimum depth during translation	18.3	-	m
Maximum depth during translation	23.8	-	m
Water levels during maintenance closer			
Maintenance in down stream chamber	+19.29	floor	m PLD
Maintenance in up stream chamber	floor	+11.44	m PLD
Water levels during flood event			
Water height above structure	0.3	-	m
Flood water level	+21.09	+13.24	m PLD
Maximum Head	7.84	-	m

| a. Maximum operation head | b. Maintenance closure | c. Maintenance closure |
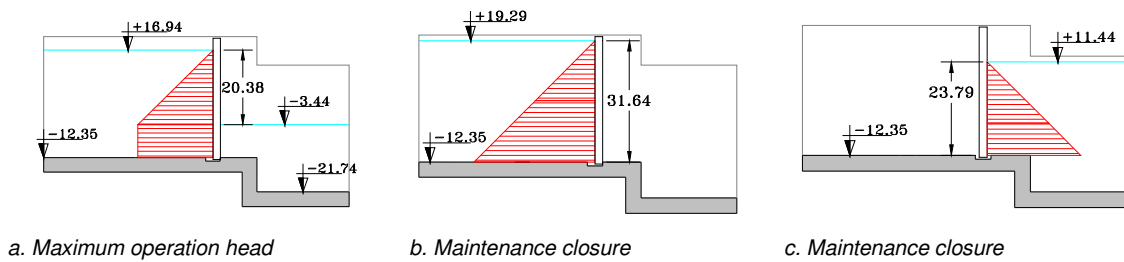
Figure 43: Overview of governing water levels for the design of the Sliding Arch Gate

Waves, currents etc:

No specifications on these boundary conditions have been given by ACP. Exactly determining these boundary conditions is time consuming and therefore the following assumptions have made:

  − To take possible hydraulic loads during the transition of the gate into account, the gate must be designed to be able to operate with a head difference of 0.1m. This will be modeled by a surface pressure of 1 kN/m² on the gates surface while it is in transition.
  − As arches are sensitive to non-evenly distributed loads, a water level difference of 1m (+0.5 m,-0.5 m) will be taken into account along the length of the gate. Representing a wave load which doesn't have the same length along the length of the arch.
  − Dynamic wave phenomena have not been taken into account and the resonance frequencies (modes) of the gate should be checked in future research, both in retaining position as during transition.

Design life:

For the design life of the structures ACP has dictated the following criteria. This will primarily be of importance when determining safety factors, dimensions of wearing parts, mechanical equipment and the fatigue design of the steel structure. Each cycle represents full loading and unloading of the gate.

Table 11: Design Life Criteria

Design life criteria		
Element	Design Life	Cycles
	[Years]	[N]
Concrete (lock structures)	100	900,000
Steel structures (gate)	50	450,000 (250,000)*
Embedded metals	100	900,000
Bearing surfaces (permanently submerged)	30	270,000
Seals**	15	135,000
Bearing surfaces**	15	135,000
Operating machinery	35	320,000

Number of cycles for fatigue design at maximum operation conditions
** When attached to gate*

Geological boundary conditions

Large – high head locks are generally situated in area's where foundation on rock is available, with some exception of large maritime locks. In case of the Panama Canal, the locks will be situated in rock (Basalt) and sandstone formations (La Boca). For the design of the lock head structure, foundation in the La Boca Layer has been assumed:

  − Uni-axial compressive strength 20MPA
  − Deformation modules 6,6 GPA
  − 2200 kg/m³

Seismic activity:

The Panama Isthmus is a seismically active region, however the magnitude of the earth quakes is moderate. It is assumed that the hydrodynamic effects which form the main seismic load component for a lock gate[31] , will not be governing for the design of the sliding arch gate, considering operational conditions. The permissible stresses during normal operation conditions are significantly decreased due to fatigue phenomena, giving the gate a large reserve capacity for incidental loads like earthquakes. This assumption should be checked in future research as

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[31] Versluis M.,(2010), Hydrodynamic pressures on large lock structures, Master Thesis Report, Technical University of Delft, Delft

should the risks and possible effects of an earth quake occurring whilst the gate is moving which may prove to be harmful.

Heavy lifting crane:
The gate design has been assumed to be modular, to allow installation and removal of the gate by means of a crane. In order to do so, the weight of the gate modules must be limited such that the crane to lift them and place them on a barge or low-bed. The Panama Canal authorities have a heavy lifting floating crane at their disposal, which is used for the current locks. It has been assumed that the modules must be able to be lifted by this crane. The capacity of this crane has been presented in the table below:

Table 12: Crane Capacity

Crane Capacity 'Titan'			
Reach over side, from fender	Capacity (metric tons)	Reach over side, from fender	Capacity (metric tons)
[m]	[ton]	[m]	[ton]
18.0	350	25.0	260
18.9	330	29.9	200
19.8	300	36.0	130

Codes and norms:
The following code and norms have been used as design guide line:
- Concrete structures have been designed according to; Euro code 2 'Design of Concrete structures'
- Steel structures have been designed according to Euro code 3 'Design of Steel Structures'
- Partial safety factors have been determined from the Euro Code and the hand book of lock design[23]

11.4 Loads and Load Cases

This paragraph presents a short overview of the loads and load cases that will be taken into account for the design of the Sliding Arch Gate. The number of loads and load cases considered will remain limited to the operational loads that will occur during the gates lifetime and which are essential to the gates design. Incidental loads (ship impacts, earthquakes ect.) and loads with no significant impact (transport, wind and traffic loads on gate) on the gates design will not be taken into account. The following load cases will be taken into account and the design values are presented in Table 13:
- Load Case 1, considers the loading of the gate when in closed position during normal operation conditions.
- Load Case 5, considers loads associated with dry lock maintenance:
   o LC5A: Considering maintenance in the lower lock chamber which will result in a positive retaining head over the full height of the gate.
   o LC5B: Considering a possible negative head over the gate loading the arch in compression. For further specification of the design, the gate is not required to retain this negative head, as it will only have to do so a few times during its lifetime, and other measures can be taken. However if it is possible for the gate to retain a negative head this would be great advantage. The possibility of retaining a negative head will therefore only be evaluated and no actual calculation will be made.
- Load Case 6, considers the operation of the gate during normal operation conditions.
- Load Case 7, considers the operation of the gate with added friction, or if hydrofoot system fails.

Table 13: Load Case overview

Load Case Overview							
Load Case		**LC1**	**LC5A**	**LC5B**	**LC6A**	**LC6B**	**LC7**
		Normal Operation	Dry lock Maintenance closure	Dry lock Maintenance closure	Normal operation Transition	Normal operation Transition	Transition with increased friction
General							
Upstream water level	m PLD	16.94	19.29	*-12.35*	5.95	11.45	5.95
Downstream water level	m PLD	-3.44	-12.35	*12.99**	5.95	11.45	5.95
Retaining height	m	20.38	31.64	25.34	-	-	-
Wave height	m	±0.5	-	-	-	-	-
Additional water pressure difference	kN/m²	-	-	-	1	1	-
Deadweight of gate	-	-	-	-	-	YES	YES	-
Other	-	-	-	-	-	-	-
Lock head and support system							
Loads from gate structure	-	YES	YES	YES	-	-	-
Active soil pressure	-	YES	YES	YES	-	-	-
Ground level	m PLD	20.79	20.79	20.79	-	-	-
Ground water level	m PLD	16.94	19.29	12.99	-	-	-
Surface load	-	?	?	?	-	-	-
Operation equipment							
Loads from gate structure	-	YES*	YES*	YES*	YES	YES	YES
Deadweight of gate	-	-	-	-	YES	YES	YES

12 DESIGN AND OPERATION OF THE SLIDING ARCH GATE

In this chapter an overview of the design of the Sliding (tension) Arch Gate and an illustration of its operation are presented, in the figures below and on the following pages. It can be used by the reader as a reference, creating a clear image of the gate before getting into the details. Important aspects and details of the gates design and operation have been highlighted, and references to the relevant paragraphs are given. A list of the drawings that are presented in this chapter is given below:
  − Figure 44: Top view of lock chamber with Sliding Arch Gates
  − Figure 45: Top view of lock head, Sliding Arch Gate
  − Figure 46: Operation scheme, Sliding Arch Gate
  − Figure 47: Top views and cross sections at pin support
  − Figure 48: Gate structure, frontt view and cross sections
  − Figure 49: Gate structure cross sections, details and lock head cross section
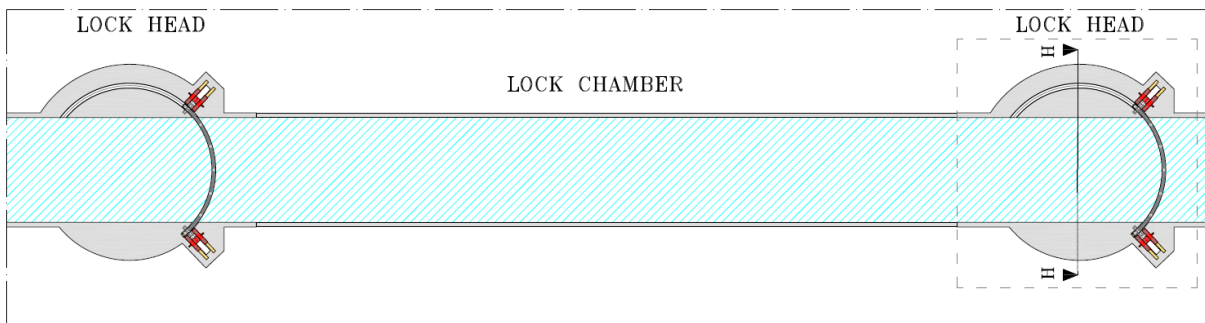
Figure 44: Top view of lock chamber with Sliding Arch Gates

Figure 45: Top view of lock head, Sliding Arch Gate

GATE ACTUATION AND HORIZONTAL
SUPPORT AT TOP OF GATE BY
FRICTION DRIVE MECHANISM §17.3
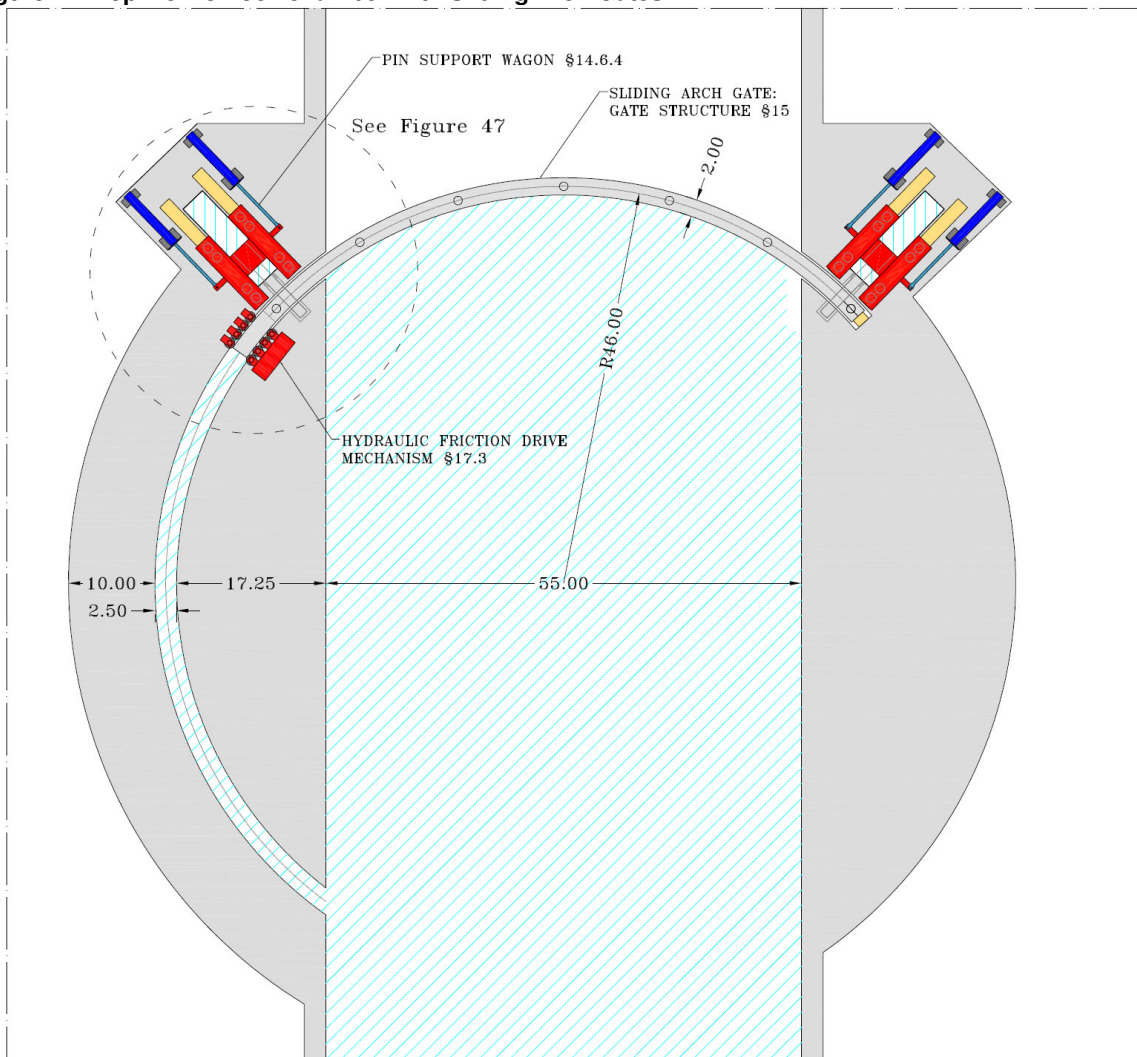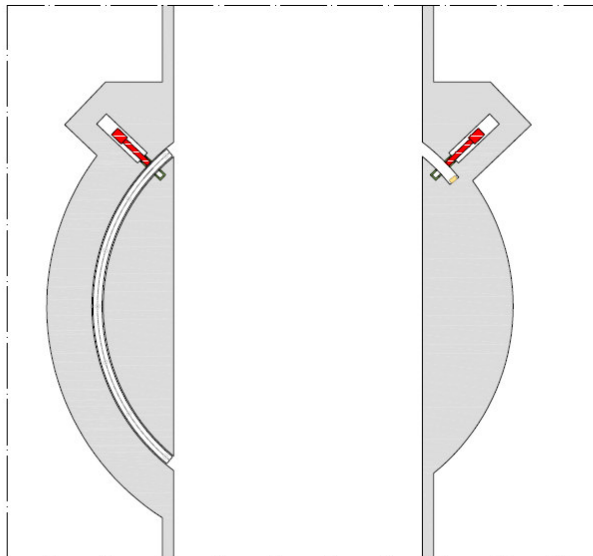
OPERATION PHASE 1

GATE IN OPENED POSITION:
- SHIPS CAN TRANSFER THROUGH LOCK HEAD
- GATE IS INSIDE RECESS, PROTECTED FROM WAVES CURRENT AND
POSSIBLE COLLISION
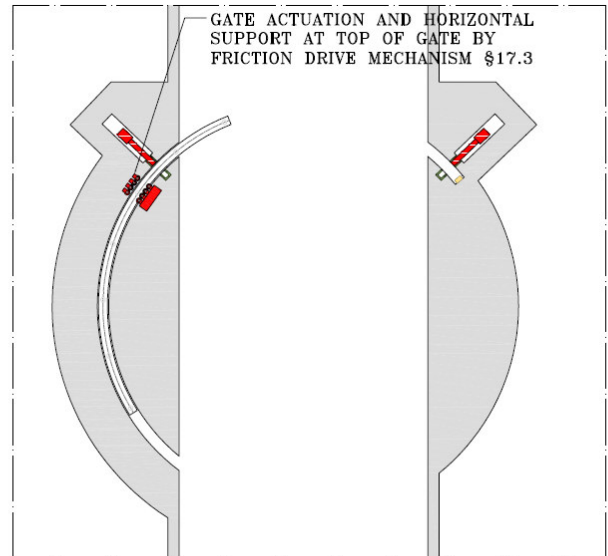
OPERATION PHASE 2A

GATE IS MOVED FROM OPENED TO CLOSED:
- MOVEMENT SUPPLIED BY THE FRICTION DRIVE MECHANISM §17.3
- HYDROFOOT INSTALLATIONS ARE OPERATIVE AND REDUCE FRICTION /
SUPPORT VERTICALLY §17.1

HORIZONTAL SLIDING
SUPPORTS ALLONG
BOTTOM §17.2

HORIZONTAL SUPPORT
AT TOP OF GATE
STRUCTURE (FRICTION
DRIVE MECHANISM)
§17.3
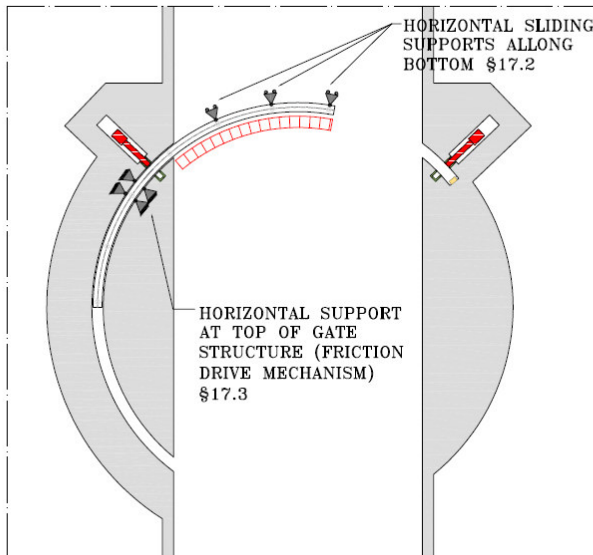
OPERATION PHASE 2B

GATE CAN BE LOADED BY A WATER LEVEL DIFFERENCE DURING TRANLATION:
- HORIZONTAL GUIDANCE SYSTEM WILL SUPPORT THE GATE ALLONG THE
BOTTOM BY MEANS OF SLIDING SHOES §17.2
- THE ACTUATION SYSTEM (FRICTION DRIVE) WILL ALSO SUPPORT THE GATE
ATE THE TOP §17.3
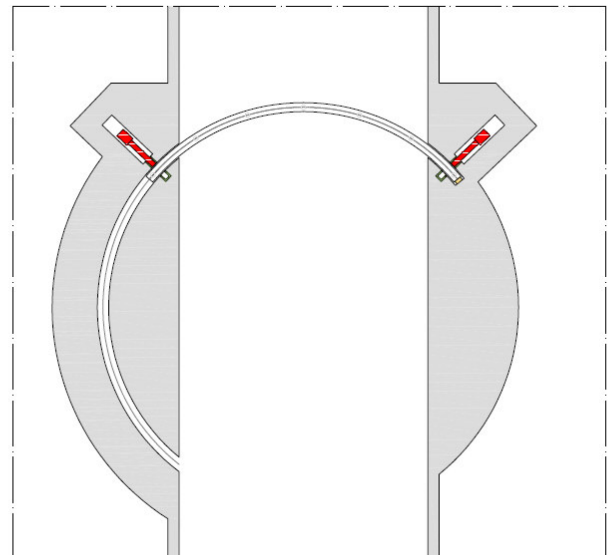
OPERATION PHASE 2C

GATE IS IN CLOSED POSITION:
- STOPPAGE FENDER ASSURES CORRECT ALLIGNMENT OF GATE STRUCTRE.
- HYDROFOOT INSTALLATIONS ARE SWITCHED OFF

Figure 46: Operation scheme, Sliding Arch Gate

VERTICAL MEMBER FOR
PIN CONNECTION
§14.4.4

RECESS FOR PIN SUPPORT
SYSTEM LARGE ENOUGH TO
LIFT OUT PIN SUPPORT
SYSTEM

STEEL PIN §14.6.2

NYLON SUPPORT SOCKETS FOR
LOAD DISTRIBUTION §14.6

63.91
55.00

E
E

R46.00

12.50
3.00
7.50

3.10
5.00
2.00
1.10

STOPPAGE FENDER §17.3
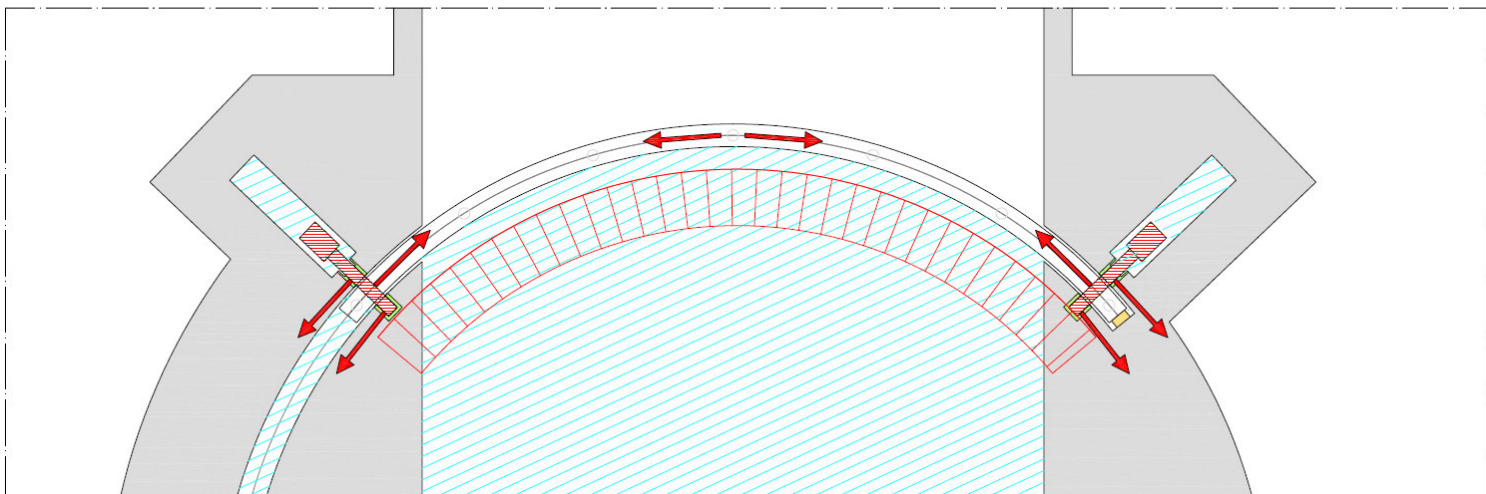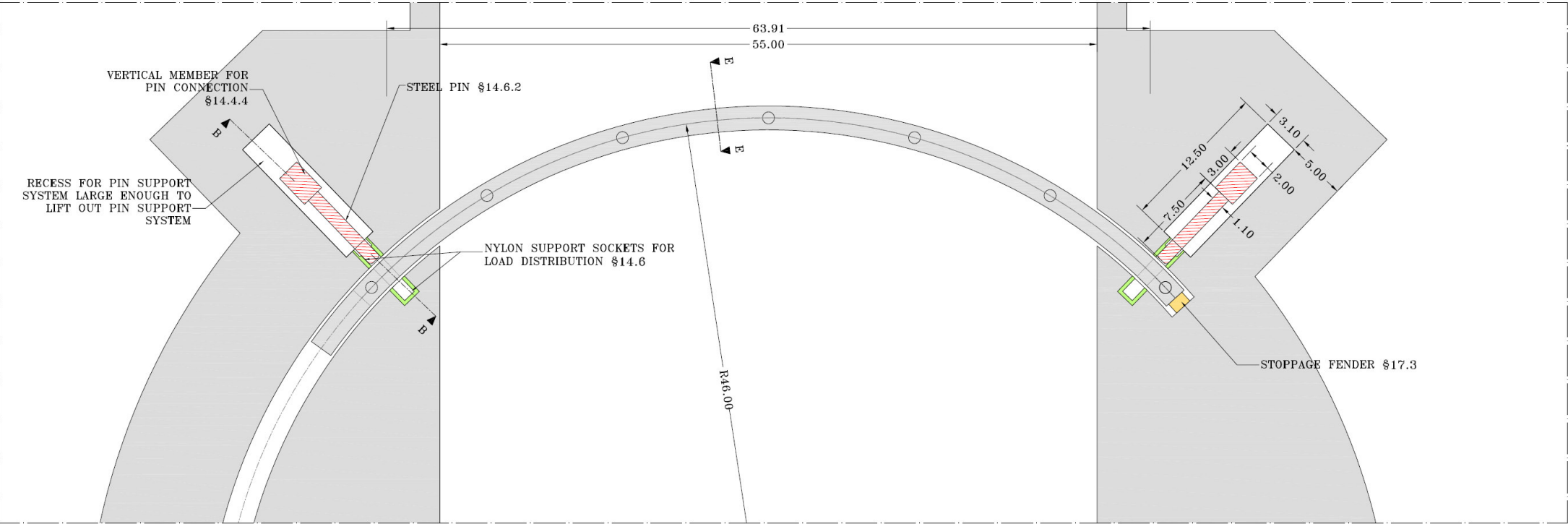
TOP VIEW, OPERATION PHASE 2C, SECTION A-A
PIN SUPPORT SYSTEM AND GENERAL LAYOUT,
PINS ARE RETRACTED

VERTICAL MEMBER FOR
PIN CONNECTION
§14.6.4

NYLON SUPPORT SOCKETS
FOR LOAD DISTRIBUTION
§14.6.3

+20.79
3.00

A
A

ADJUSTABLE CONNECTION
PIN - VERT. MEMBER

ROUNDED FRONT OF PIN TO
PREVENT JAMMING

+5.95

3.00
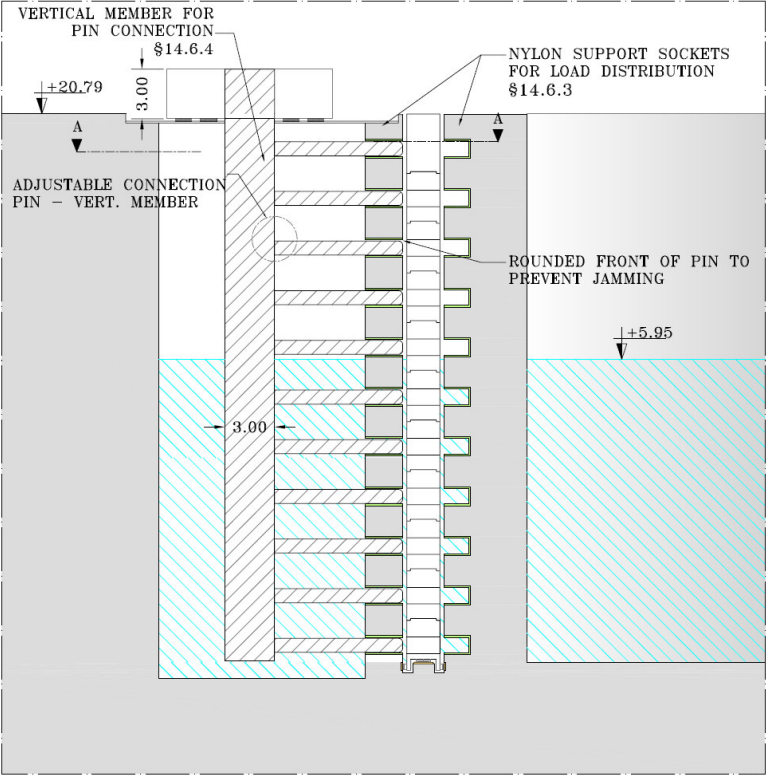
CROSS SECTION B-B
PIN SUPPORT SYSTEM IN RETRACTED POSITION, GATE CAN BE MOVED

PIN SUPPORT WAGON §14.6.4

HYDRALIC CILINDERS
FOR PIN OPERATION
§14.6.4

SLIDING SURFACE FOR
PIN SUPPORT WAGON,
UHMWPE §14.6.4

HYDRAULIC FRICTION
DRIVE MECHANISM
§17.3

D
D

1.50
7.30
10.00
3.10
3.10
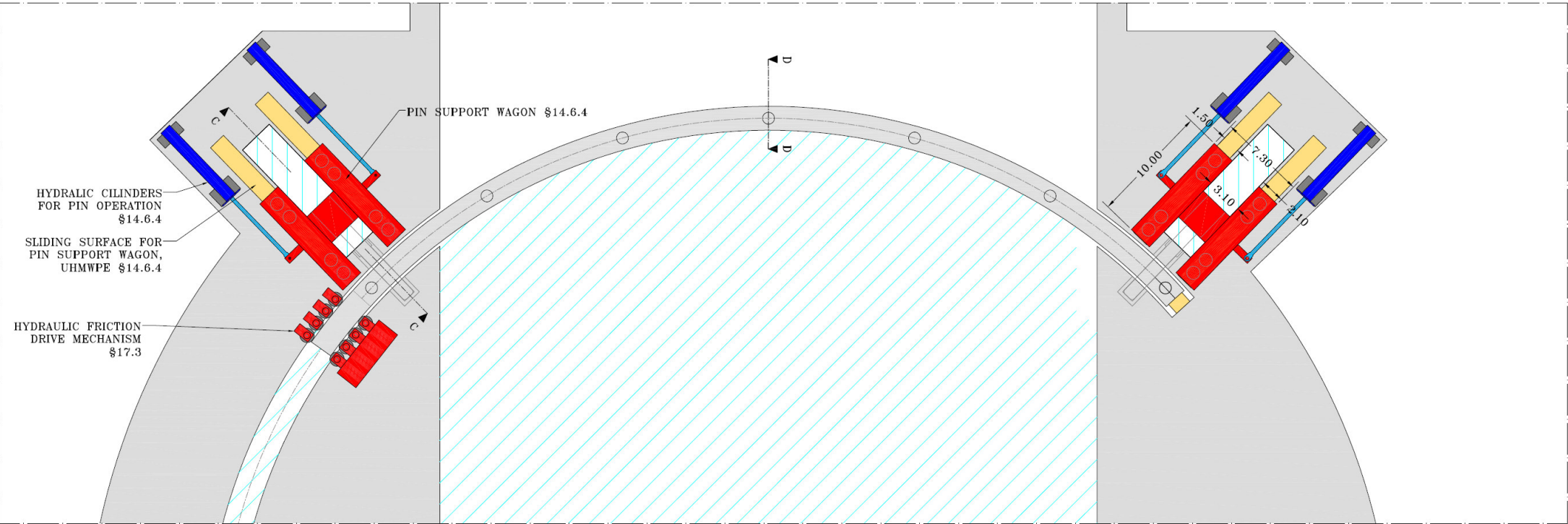
TOP VIEW OPERATION PHASE 3
PIN SUPPORT SYSTEM AND GENERAL LAY-OUT
PINS ARE INSERTED, GATE IN RETAINING POSITION

HYDROFEET FOR OPERATION
OF PIN SUPPORT SYSTEM

2.50
2.00

+20.79

+19.29

3.00

0.85

+12.35
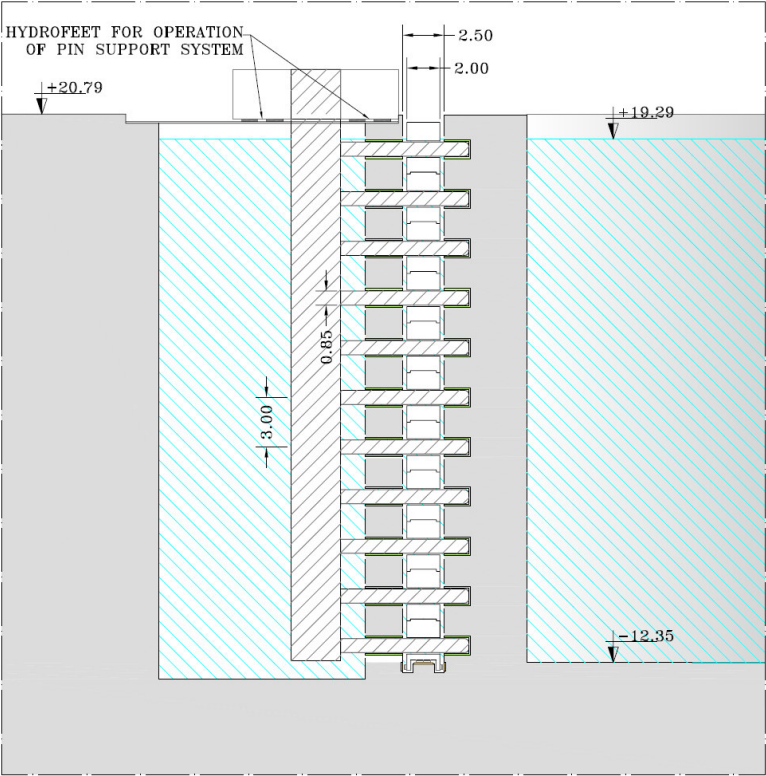
CROSS SECTION C-C
PIN SUPPORT SYSTEM IN SUPPORTING POSITION
GATE IS RETAINING WATER

Figure 47: Top views and cross sections at pin support
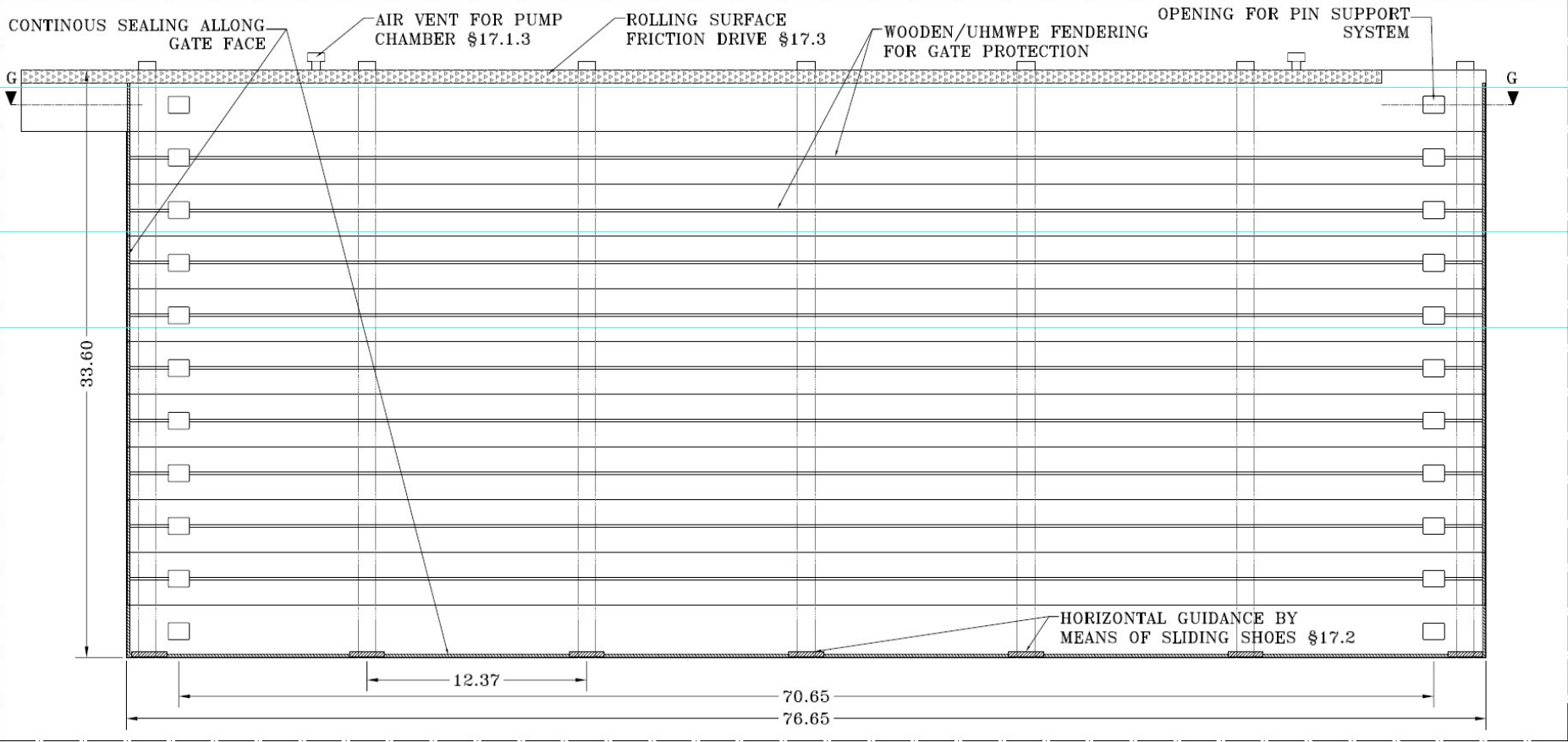
FRONT VIEW OF GATE STRUCTURE
PROJECTED VIEW

CONTINOUS SEALING ALLONG GATE FACE

AIR VENT FOR PUMP CHAMBER §17.1.3

ROLLING SURFACE FRICTION DRIVE §17.3

WOODEN/UHMWPE FENDERING FOR GATE PROTECTION

OPENING FOR PIN SUPPORT SYSTEM

HORIZONTAL GUIDANCE BY MEANS OF SLIDING SHOES §17.2

G   G

33.60

12.37

70.65

76.65
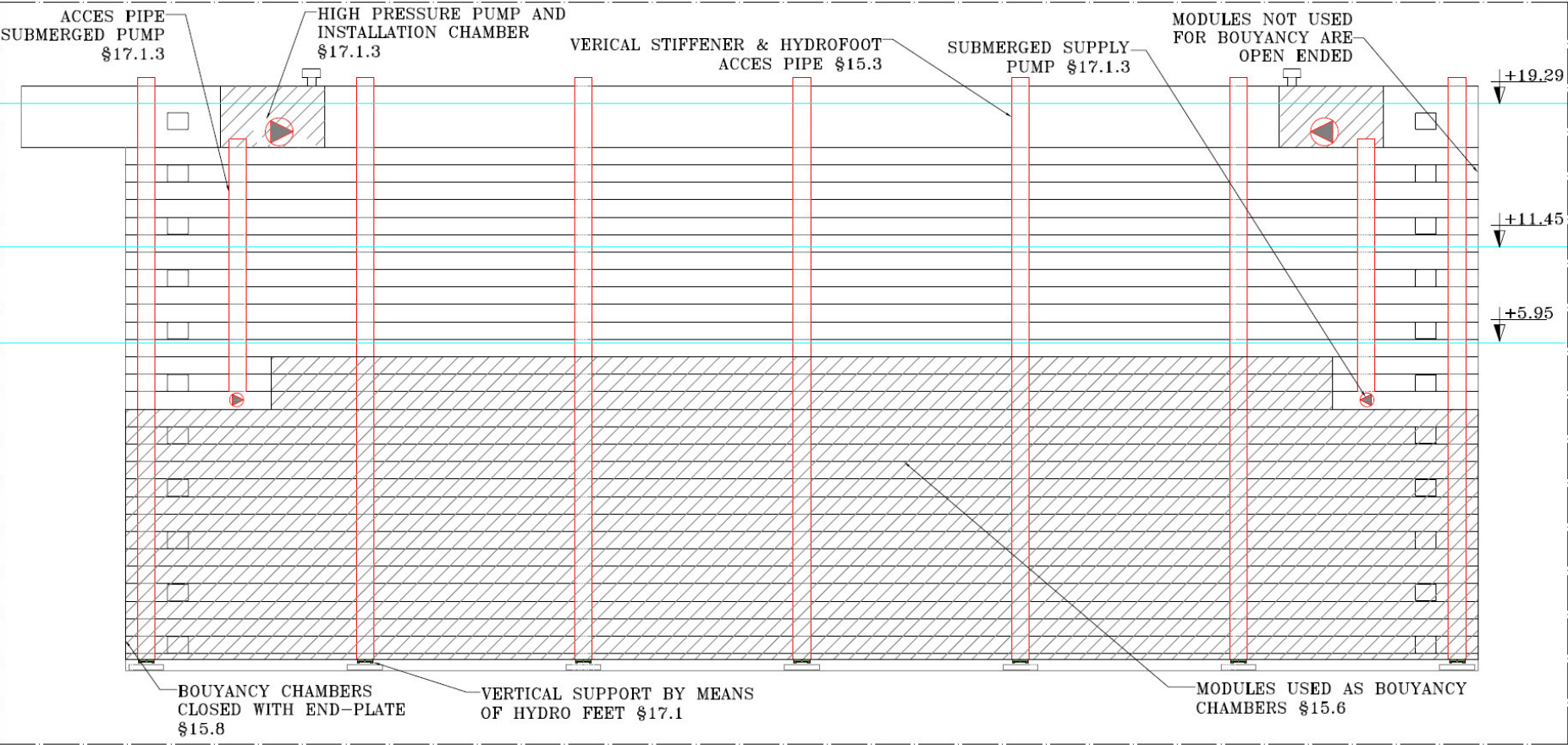
CROSS SECTION F-F
PROJECTED VIEW OF MODULES AND INSTALLATIONS

ACCES PIPE SUBMERGED PUMP §17.1.3

HIGH PRESSURE PUMP AND INSTALLATION CHAMBER §17.1.3

VERICAL STIFFENER & HYDROFOOT ACCES PIPE §15.3

SUBMERGED SUPPLY PUMP §17.1.3

MODULES NOT USED FOR BOUYANCY ARE OPEN ENDED

BOUYANCY CHAMBERS CLOSED WITH END-PLATE §15.8

VERTICAL SUPPORT BY MEANS OF HYDRO FEET §17.1

MODULES USED AS BOUYANCY CHAMBERS §15.6

+19.29
+11.45
+5.95
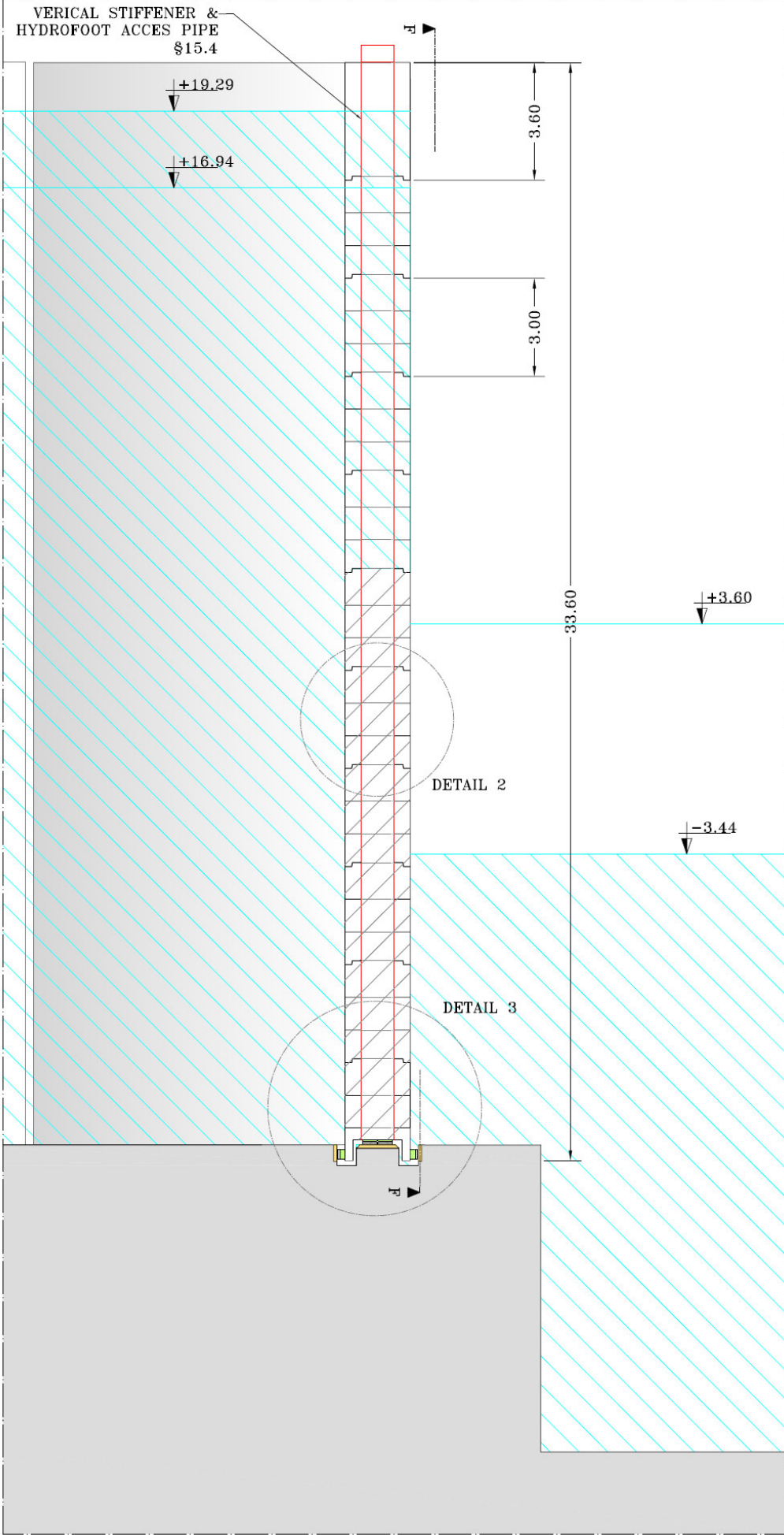
CROSS SECTION D-D
GATE CROSS SECTION AT VERTICAL STIFFENER

VERICAL STIFFENER & HYDROFOOT ACCES PIPE §15.4

+19.29
+16.94

F

3.60

3.00

33.60

+3.60

DETAIL 2

-3.44

DETAIL 3

F

Figure 48: Gate structure, frontt view and cross sections

GATE STRUCTURE SECTION G-G
MODULE AND INSTALLATIONS

82.07
76.65
2.00
PUMPS ACCESIBLE THROUGH
WATER TIGHT HATCH §17.1.3
63.91

CROSS SECTION E-E
GENERAL GATE CROSS SECTION

+20.79
MODULES USED AS BOUYANCY
CHAMBERS §15.8
+11.45   MAX. OPERATION LEVEL
+5.95   MIN. OPERATION LEVEL
DETAIL 1
−12.35
−13.35
ELEVATED SLIDING
SURFACE §17.1.4
−21.74

DETAIL 1
GENERAL MODULE CROSS SECTION

FOR STRUCTURAL DESIGN OF
MODULE SEE §15.3
3.00
2.00

DETAIL 2
MODULE CROSS SECTION & VERTICAL STIFFENER

LINING TUBE IN
MODULE §15.4
VERTICAL STIFFENER
§15.4

DETAIL 3
BOTTOM MODULE

HIGH PRESSURE
SUPPLY PIPES,
§17.1.3
CONNECTION OF
VERTICAL STIFFENER
§15.5
HYDROFOOT §17.1.3
STEEL SLIDING
SHOE §17.2
UHMWP SLIDING
SURFACE §17.1.4
FLEXIBLE SUPPORT

CROSS SECTION H-H
INDICATION OF LOCK HEAD CROSS SECTION

10.00
17.5
+20.79
55.00
23.5
LOCK HEAD DESIGN, §16
33.14
−12.35
CULVERTS FOR FILLING
AND EMPTYING SYSTEM
(INDICATION)

Figure 49: Gate structure cross sections, details and lock head cross section

13   STRUCTURAL MODELING OF THE GATE STRUCTURE

When designing a structure, one must know, to good approximation, the internal forces within the structure to determine the required cross sections modulus and area and keeping the material stresses and deformations within the required limits, eventually dictating the dimensions and weight of the structure. In chapter 9 the forces in the arched gate structure where determined using the simple ring formula, which is only valid for evenly distributed loads. However, slender arches, mainly designed to transfer normal forces, have a relatively low stiffness and are very sensitive to unevenly distributed or concentrated loads. Taking this sensitivity into account in combination with possible (uneven) wave loading a model has been made with which the displacements, normal forces, moments and shear forces can be determined for a slender circular arch for any given load condition. This chapter presents a description of the mathematical model (§13.1) which has been used to determine the forces and displacements of the gate structure. The input used for the model (§13.2), is based certain parameters which have been defined later on in the design phase. And finally the results, which is essential input for the design phase are presented (§13.3). The actual model has been programmed in Maple and the output has been analyzed further in Excel. Both the model and the out-put can be found in Appendix 3.

Figure 50: Flow of forces, note: Gray blocks have not been taken into account
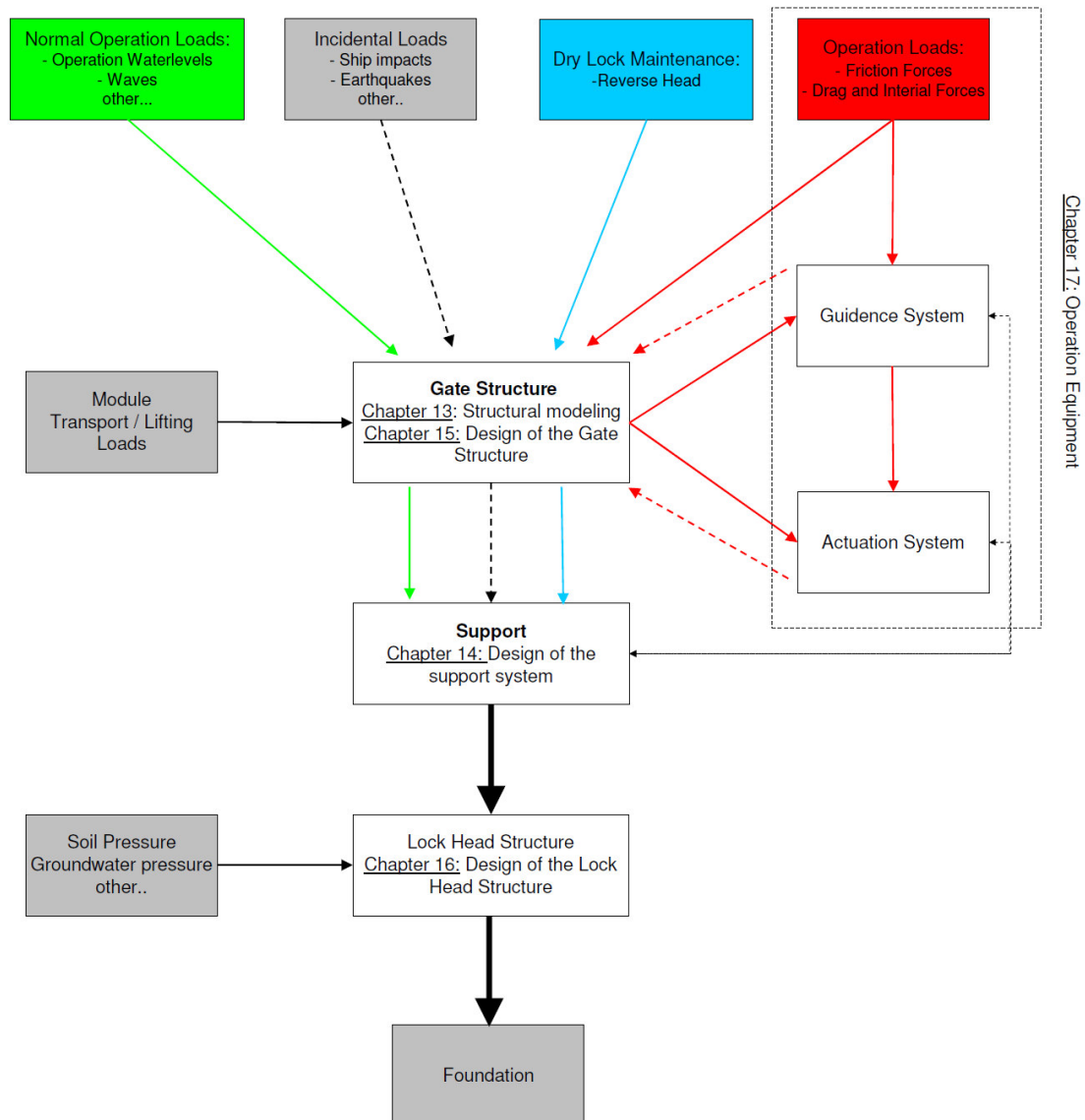
13.1 Model description

The modules of the Sliding Arch Gate have been schematized as arched members loaded in radial direction by the hydraulic loads, as can be seen in the figure below.

a. Model definition   b. Equilibrium of a segment ds
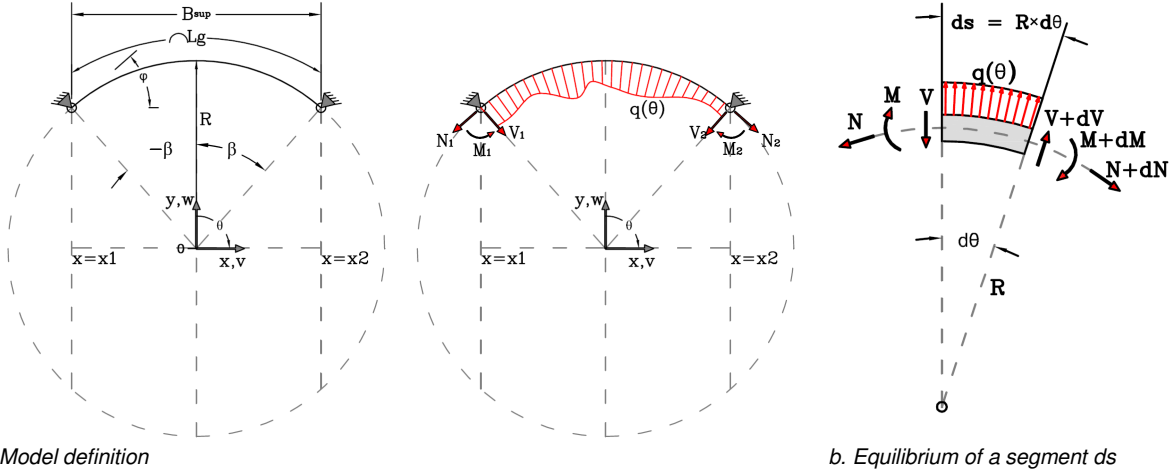
Figure 51: Model definition

In order to determine the relations between the external (hydraulic) forces and internal (structure) force and to find the related displacements of the structure (modules) the required equations have been derived considering the equilibrium, kinematic and constitutive relations, where:
  – The equilibrium equations govern the relationship between the internal and external forces.
  – The kinematic relations govern the relations between the internal deformations and external displacements.
  – The constitutive relations govern the relations between the internal deformations and the internal forces, taking into account material and cross section properties.

Eventually this leads to the following set of equations (see Appendix 3) as function of the radial load q(theta). Considering the equilibrium, Figure 51b:

$$\frac{d^2 N(\theta)}{d\theta^2} + N(\theta) = q(\theta) \cdot R \ , \qquad V(\theta) = -\frac{dN(\theta)}{d\theta} \ , \qquad \frac{1}{R} M(\theta) + N(\theta) = q_0 \cdot R$$

In Which:
$N(\theta)$: Normal force distribution along the gate module [kN]
$M(\theta)$: Moment distribution along the gate module [kNm]
$V(\theta)$: Shear forces distribution along the gate module [kN]
R : Radius of the module's arch [m]
$q(\theta)$: The load function of the hydrostatic loads along the module [kN/m]:

$$q(\theta) = q1 \cdot \cos(n\theta) + q2$$

    $q1$: Amplitude of the wave load [kN/m]
    $q2$: Load due to average retaining height [kN/m]

    n : Wave number, governs the shape of the wave load. $n = \dfrac{\pi}{\beta}$, [1/rad]

Note: If the radial load q = constant, then the shear force and bending moments would be zero, resulting into the expression N = q *R which is the simple ring formula.

From the kinematic and constitutive relations it follows:

$$\frac{d^2 w(\theta)}{d\theta^2} + w(\theta) = -\frac{M(\theta) \cdot R^2}{EI}$$

In Which:
EI   : Stiffness of the gate module [kN×m²]
w(θ)   : Displacements of the gate module [m]

When solving the differential equations there are 4 unknown constants, which can be found from the boundary conditions at the support. <u>As the design of the support mechanism still has to be determined and it is possible that the support will (partially) clamp the gate's structure restricting free rotation at the supports, both a hinged and a clamped support will be considered and the most governing values will be used for design</u>. The truth will lie somewhere in between, and the boundary conditions for a hinged and clamped support are given below:

For a <u>hinged beam</u> the boundary conditions at the support (θ =-β , β) are:

$$w = 0 \qquad M = 0 \qquad \textit{Support is hinged so no translation and no bending moments}$$

For a <u>clamped beam</u> the boundary conditions at the support (θ =-β , β) are:

$$w = 0 \qquad \frac{dw}{d\theta} = 0 \qquad \textit{Support is clamped so no translation and no rotation}$$

The model will give a good approximation of the internal forces and displacements

Assumptions and limitations:
The linear elastic model has been made to give a good estimation of the internal forces and displacements of the gate, the assumptions and limitations of the model are discussed below:

  − Deformations due to normal-extensions are neglected. When considering elastic behavior of the module the strain of the steel is max. 0.17% for which it can be considered that the deformations due to normal forces are small and can be neglected.
  − Deformations due to shear deformations have been neglected which holds for h<<R[32].
  − Applying the Bernoulli bending beam theory it is assumed that plane sections remain plane, which is true for slender structures[33], and linear elastic behavior of the module is assumed.
  − Deformations associated with the Pin Support System are assumed to be negligible.
  − The modules have been modeled as 1D elements and are assumed to react independently from each other. In reality the vertical stiffeners in the gate will provide connection between the modules and they will thus not be able to deform independently. However these deformations are a result of the wave load, which is approximately equal over the height of the gate and thus over the modules. The slight differences that could occur would lead to some interaction forces between the modules that are transferred through the stiffeners. As these stiffeners will result in concentrated loads on the modules, it is assumed that no significant loads are required to even out the deformations.

13.2   Input

In the tables below, the input used for the model has been presented. In accordance with the project boundaries, only one module has been considered. The geometrical input is the result of further design and will be confirmed in the following chapters.

---

[32] BOUMA A.L., (2000), Mechanica van constructies, Elastostatica van slanke structuren, VSSD, Delft

[33] SIMONE A. (2010), An Introduction to the analysis of slender structures, Course Syllabus, CT4190, TUDelft, Delft

Table 14: Geometrical input

Geometrical input			
Effective span	B_{sup}	63.91	m
Radius of the arch	R	46.00*	m
Support angle	β	0.77	rad
Module height	h_m	3.0	m
Gate width	h	2.0	m
Elasticity modulus of the gate	E	2.1×10^8	kN/m²
Second moment of area	I_y	0.24	m⁴

The radius has been derived as a practical minimum value. If the radius would be any shorter the gate would not fit into the recess in the lock head structure. (See figures chapter 12) Considering a minimal radius will result in the lowest normal forces and thus lightest gate cross section. A larger radius would result in a heavier cross section, however would reduce water consumption. This is an optimization that should be investigated in further research.

Table 15: External loads working on the gate module

External loads		Load Case 1	Load Case 5	
Hydraulic load due to normal operation head				
Line load on module	q2	614.78	909.20	kN/m
Hydraulic load due to wave				
Line load on module	q1	15.08	15.08	kN/m
	n	3.89	3.89	1/rad

* the load function has been presented in Figure 52

13.3 Results

The results of the model have been presented in the figures below, and the most governing values, which will form the main input for further design of the Sliding Arch Gate have been summarized in Table 16. The polar coordinates (θ) have been transformed to Cartesian coordinates (x), where mid-span is x=0 and the support location is   x = -32.07 , 32.07m
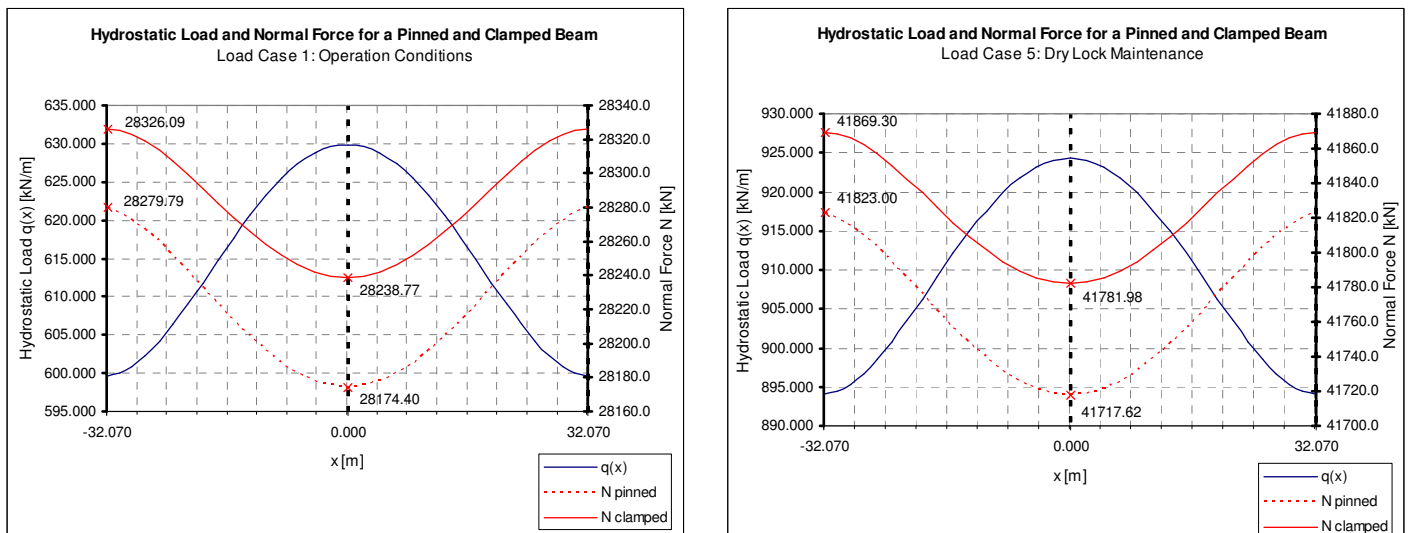
Figure 52: Hydrostatic loads and normal forces
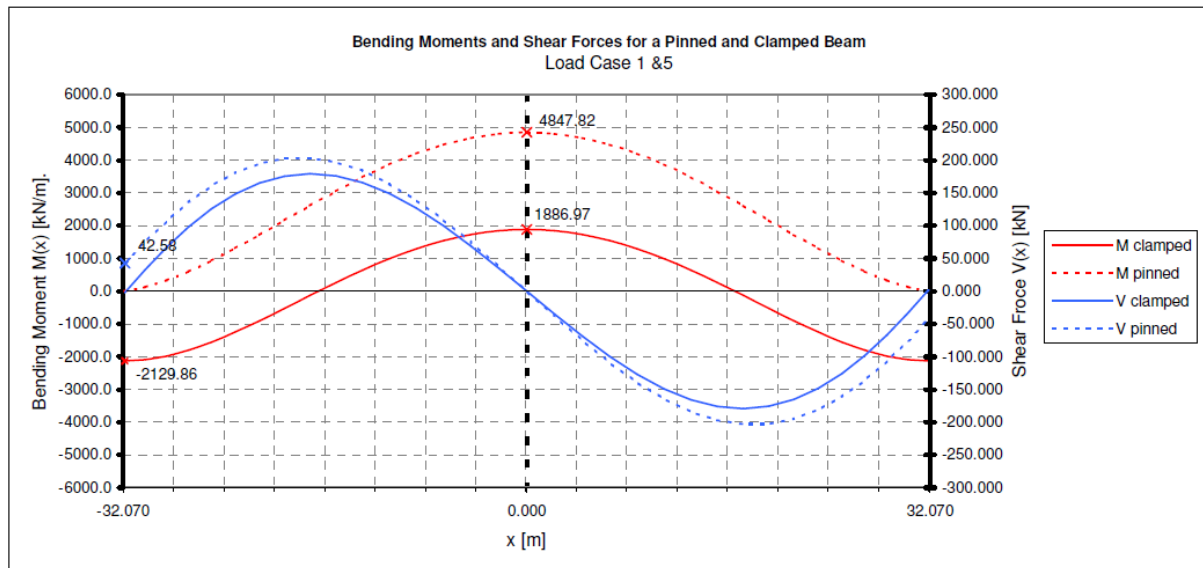
Figure 53: Moment and shear distribution due to wave action LC1 &LC5

The figure above shows the bending moments and shear forces in Load Case 1 and 5. In both load cases the same results are found. This can be explained by the fact that the bending moments and shear forces are only caused by the un-even wave loading, which has assumed to be the same during both load cases. The average hydrostatic load, which does differ in LC1 and LC5 does not contribute to this as the load is constant along the arches length.

In the table below, the governing results per Load Case have been presented. Also the design values have been given, where the safety factor for fatigue has assumed to be γ=1.0 and for the ultimate limit case LC5 γ=1.25.

Table 16: Governing values of the internal forces, gate module

Governing values					
	At support		Mid-span		
	Rep. value	Design value	Rep value	Design value	
Load Case 1		γ=1.0		γ=1.0	
Nlc1	28326.1	28326.1	28238.8	28238.8	kN
Mlc1	-2129.9	-2129.9	4847.8	4847.8	kNm
Vlc1	42.6	42.6	0.0	0.0	kN
Load Case 5					
Nlc5	41869.3	52336.6	41782.0	52227.5	kN
Mlc5	-2129.9	-2662.3	4847.8	6059.8	kNm
Vlc5	42.6	53.2	0.0	0.0	kN

14 DESIGN OF THE SUPPORT SYSTEM

In this chapter the design of the support system, which transfers the loads from the (movable) gate structure to the (static) lock head structure is presented. The support system must therefore hold the gate when it is in closed position (Operation Phase 3, figures chapter 12) but must also allow movement of the gate when it is operated (Operation Phase 2, figures chapter 12). In case of the Sliding Arch Gate, this results in a rather unique problem; that the gate must be supported in the same direction as it must be moved. No standard solutions for this problem exist, as hydraulic gates generally move in a different direction than the force transition, making the design of the support system critical for the gates performance. In order to come to a solution of this problem and to find a solutions that works and has minimal (negative) effects on the performance of the gate the following steps have been undertaken:

- The basic considerations regarding the support design have are discussed in paragraph 14.1, from which 3 alternatives have been derived.
- The 3 alternative support systems have been worked out and described shortly in paragraph 15.2 to 15.4, after which they are evaluated and the most promising alternative is selected for further design, in paragraph 15.5: 'Pin Support System'
- Finally, the design of the Pin Support System is treated in more detail in paragraph 15.6

14.1 Basic considerations regarding the support design

As mentioned in the above, the gate must be moved in the same direction as it must be supported. This assumes the gate must be supported and travel in tangent direction (along the circular path of the gate's structure), which is essential for the performance of the Sliding Arch Gate as:

- <u>The movement in tangential direction</u>, allows for a small recess area and small water displacements of the gate.
    - o Moving the gate like a rectangular rolling gate, perpendicular to the gates axis, would require a large recess adjacent to the lock and the profile of the gate would have to be pushed through the water. Also the thrust forces are still in the same direction of the movement of the gate, thus not solving the problem.
    - o Rotating the gate like a Mitre Gate will only solve the problem when being loaded in compression like a Mitre Gate, and rotating the gate plane will also require hughe amount of water displacements and thus operation forces, not to speak of the additional water losses that will occur due to the large length of the recess in direction of the locks axis.
    - o Lifting the gate (like a Vertical Lift Gate) would also solve the problem, however the gate must then be stored above or below the lock resulting in major operational complications or possible limitations on the ships allowable height when it travels under the gate, which is generally considered unacceptable for maritime locks.
- <u>The support of the gate in tangential direction is essential</u> to the performance of the Sliding Arch Gate, as it allows the forces to be transferred via arch action. If this is not the case, the forces will be transferred through bending and shear and not by arch action, as the thrust forces, perpendicular to locks axis) cannot be transferred. Resulting in comparable internal bending and shear stresses as for a 'straight' Rolling Gate and thus also the dimensions and weight of the gate would be comparable, making the possible advantages of the Sliding Arch Gate (small use of space, low water consumption, low operating forces) minimal or not existent.

Thus avoiding the problem without compromising the basic idea and advantages of the Sliding Arch Gate is still possible and the problem will therefore have to be tackled head-on.

When considering the operation of the gate as: the gate must first be able to move freely along its tangent axis during translation form open to closed (OP2), but must then be fixed in tangent and radial direction in order to transfers forces to the lock head structure (OP3). The gate has to be somehow connected and disconnected from its support and in order to realize this, there are two basic options regarding the connection of the gate to the support:

- a. Move the gate to its support
- b. Move the support to the gate

Option A 'Move the gate to its support':

When moving the gate onto its support the gate will have to make an extra translation in the direction of the lock axis in order to connect to the support, see Figure 54. This is required to allow free translation of the gate during (OP2) and fixation of the gate during (OP3). As the gate has to move onto its support and the support is fixed to, or is part of, the lock head structure, the support will have to be a kind of notch and the gate have to have a kind of hook structure at both its end in order to clamp around the notch. This limits the variation in possible designs principles for the support considering option a. Therefore one alternative shall be considered for this option:

Alternative A: The Hook Support System;

Option B Move the support to the gate

When moving the support to the gate, no extra translation of the gate in direction of the lock axis is required. However, an extra installation is required to move the support to the gate, connecting the gate and the lock head through some kind of movable structure. For the design of such a system there are numerous possibilities. Though, considering the extremely large forces to be transferred and the wish for a simple system two alternatives where found to be possibly 'suitable' and will be considered as alternatives:

 − Alternative B1: The Wedge Support System: where the gate is designed with T- shaped ends and wedges are lowered vertically through recesses in the lock head structure, allowing the T-shaped ends to support on the wedges which are clamped by the lock head structure.
 − Alternative B2: The Pin Support System: Where a number of steel pins are inserted through holes in the gate, and which are supported in sockets in the lock head structure.

14.2 Alternative A: Hook Support System

General description and operation:

The Hook Support System, is based on the consideration to move the gate onto the support. The gate structure will therefore be fitted with hook –like ends, hence the name. These hooks will eventually clamp around a concrete notch, which directly transfers the forces to the lock head structure. However, this connection will require the gate structure to be operated in two phases, as also can be seen in Figure 54:

 − First, the gate will translate in <u>tangent direction</u> until the hooks and the notches are aligned.
 − Secondly, the gate must be moved in <u>direction of the locks axis</u>, to place the hooks over the notches, forming the required connection to transfer the tension forces.
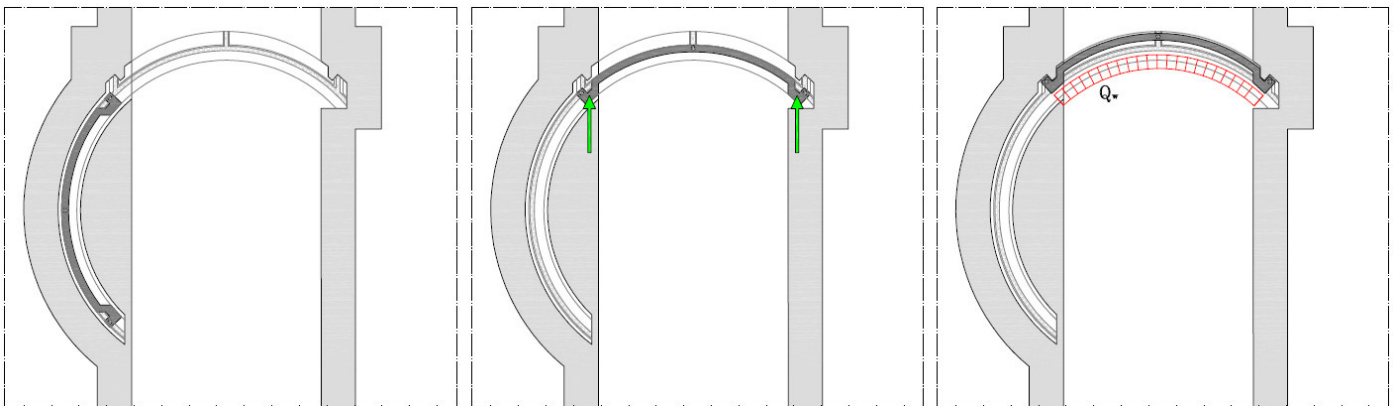
Figure 54: Sliding Arch Gate with Hook Support System in opened and closed position

The distance that the gate must be moved in the direction of the lock axis, is determined by the dimensions of the hook, as the hook and gate structure must be able to pass both the notches before they are connected. This distance in order of the width of the gate structure (2m) and brings about the following operational complications.

 − When moving the gate in the direction of the locks axis, the whole gate plane has to be pushed through the water, causing a enormous amount of water displacement. This will result in very large operation forces.
 − When considering Load Case 6, the gate must be designed to be able to operate with a water level difference over the gate of approximately 0.1m, in either direction, during the entire operation. This means that in addition to the operation forces associated with the large water displacement, a surface

load of 1kN/m² over the wet area over the gate must be overcome and considering the approximate area of the gate this will result in a additional 1830 kN to be delivered by the operation equipment.
Note: the situation is the same when opening the gate and moving the gate off the support, as the water level difference can be from either direction and the water displacement is the same.

– When moving the gate too and off the support, the operation forces must be supplied at both the top and the bottom of the gate, or at the location of the resultant hydraulic force in order to prevent the gate from toppling over. This implies that at least part of the operation system will be situated under water, as can be seen in Figure 55.

– During the translation of the gate (in tangent direction) the gate also needs to be supported horizontally (in radial direction) in the lock floor due to the possible water level difference during translation. However when the gate needs to be moved onto the support, these horizontal supports may not hinder the movement of the gate. This requires either:
  o The horizontal supports to be temporarily be removed.
  o The supports to be moved through slots in the floor. However attention must be paid for the gate not to get stuck whilst moving in tangent direction.
  o The gate to lifted slightly in order to translate to the support.
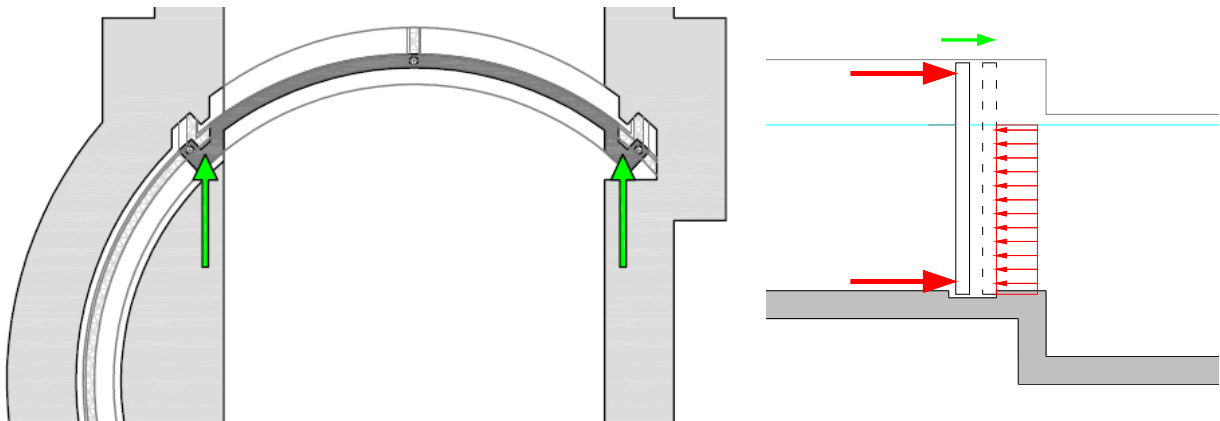
Figure 55: Moving the gate onto its support

As can be seen in the figures above, the dimensions of the hook, govern the dimensions of the required recess, as this must be wide enough to accommodate free movement of the gate. This will result in significantly more water consumption than if the gate would be straight.

Load transfer to the lock head:
In order for the gate to transfer the normal forces to the concrete support notch, the normal forces must travel through the hook, causing eccentricity and resulting in large bending moments and shear forces in the gate structure (see figure below).

To prevent large bending moments throughout the whole length of the gate and to keep the moments local, the resultant force of the support reaction, must aligned with the neutral line of the gate cross section. Otherwise, even when considering small eccentricities, the bending moments throughout the gates structure will become large, compromising the slender design of the Sliding Arch Gate. In the figure below a simplified mechanical schematization has been given of the hook support and how it transfers forces to the concrete lock head structure.
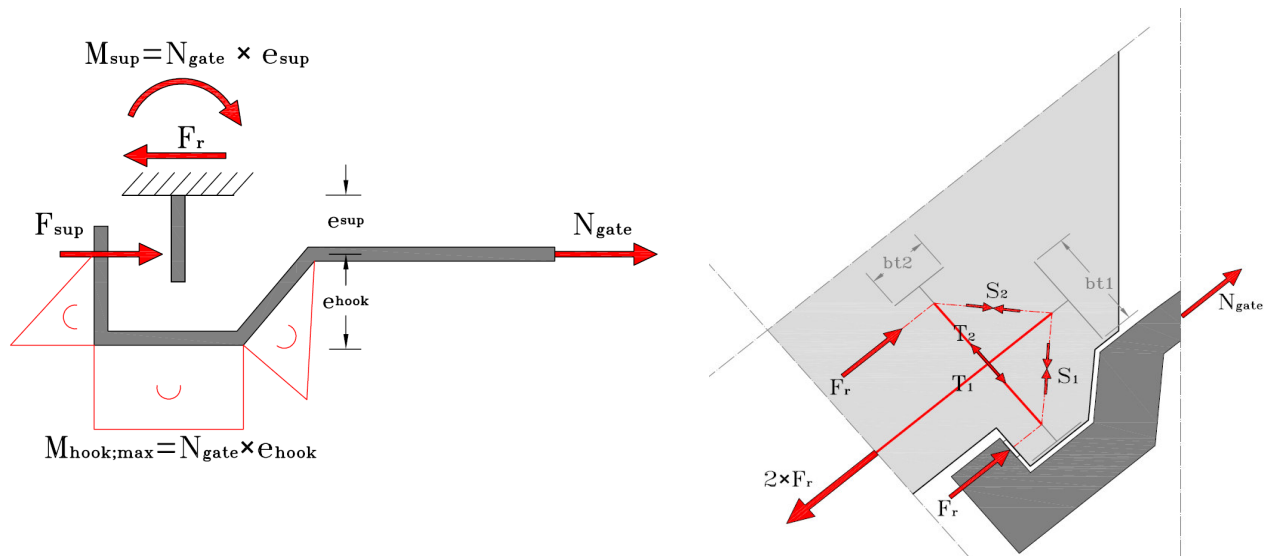
Figure 56: Left: Force transition to the lock head structure, Hook Support System, Right: Strut and Tie model

Strut and Tie Model:
The figure above (left) gives a basic mechanical schematization of the hook support. The concrete structure may, due to its massive (non slender) dimension, not be designed assuming linear strain relations and the assumption that plain surfaces may remain plain is not valid. This means general design rules that apply to slender structures, beams, plates and columns, where the relation $M = \kappa \times EI$ is used, may not be applied. According to the Euro Code 2 the structure must be designed as a strut and tie model. Schematizing the structure as a framework of compression struts and tension ties (and thus no bending members) as shown in the right hand side of the above figure. These struts and ties do not have to be actual separate elements, but the struts and ties may be designed in the massive concrete structure, governed by the positioning of the rebar.

For the design of such a strut and tie model the constraints apply:
  – Forces must be in equilibrium, internally in the joints and externally.
  – The stress in the joints must be checked acc EC2.
  – Angles of the struts must be between less than 45 deg.

In Figure 56 a strut and tie model for the hook support is presented, which has been dimensioned by rough calculations. Due to the large normal force in the gate the required width of the tension ties (bst1, bst2) will become significant, due to the required rebar quantities, and will dictate the size of the support and the distance of the support to the lock wall. The main tension tie, T1 will even have to transfer twice the normal force in the gate, as a result of the eccentric support on the notch. The compression struts will have smaller required dimensions as higher concrete classes have significant compressive strengths, and the effective area involved in transfer of compressive forces is 100% opposed when considering tension forces where $A_{eff} = A_{rebar}/A_{conc}$.

Evaluation
The Hook Support System has shortly been evaluated below summarizing the advantages and disadvantages:
  - Large operation forces required to move the gate onto the support.
  - Permanently submerged operation equipment is required.
  - Large moments in the hook will lead to a heavy design, requiring a considerable recess width.
  - Large water losses due to large recess width.
  - Unfavorable transition of forces to concrete structure.

14.3 Alternative B1: Wedge Support System

General description and operation:
For the Wedge Support System, the gate structure will be fitted with T shaped ends, which support on concrete notches on one side and on steel wedge members on the other side. These wedges are lowered into a recess in

the lock head structure, once the gate is in place. Thereby, the gate only needs to translate in tangent direction, minimizing water displacement, as the gate 'cuts' through the water. The operation of the steel wedge members requires only vertical movement of the wedges and the operation equipment can be situated above water, making the required installations easy to reach for inspection and maintenance. With the T shaped ends, the gate is supported on both sides, keeping the required additional width of the T limited to the area needed for the support. Therefore the additional width of the recess and water loss remains limited.
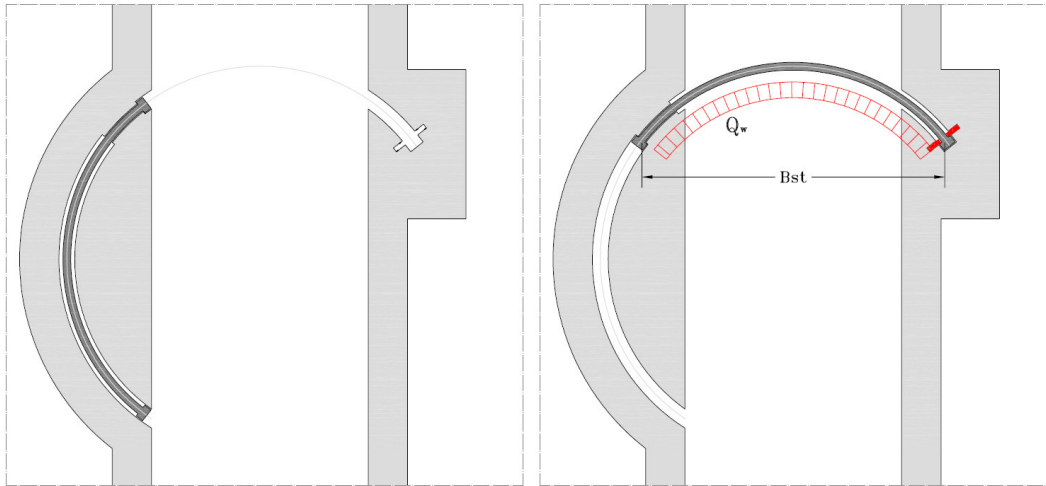
Figure 57: Sliding Arch Gate with Wedge Support System in opened and closed position

Load transfer to the lock head structure
On the side of the gate recess the gate simply supports on concrete notches see Figure 57, with similar load transition compared to the notch of the Hook Support System, but with smaller eccentricity and only half the normal force per notch. On the other side of the gate, a T – shaped end supports on the wedge members, which need to be clamped in the lock head structure, as they are only supported at one side of the recess the concrete structure must be able to supply a counter moment to achieve equilibrium. In Figure 58, a simplified mechanical schematization has been given of the wedged support. Where the reaction forces (F_{rb} & F_s) are to be supplied by the concrete structure. The reaction force F_{rb} translates directly into a compressive force in the concrete. The reaction force F_{ra}, however transfers the compressive support load to the inside corner, which is basically hung-up in the lock head structure. The force F_{ra} must therefore be equalized by a tension force (in opposite direction) causing a bending moment over this inside corner (see figure below, right)
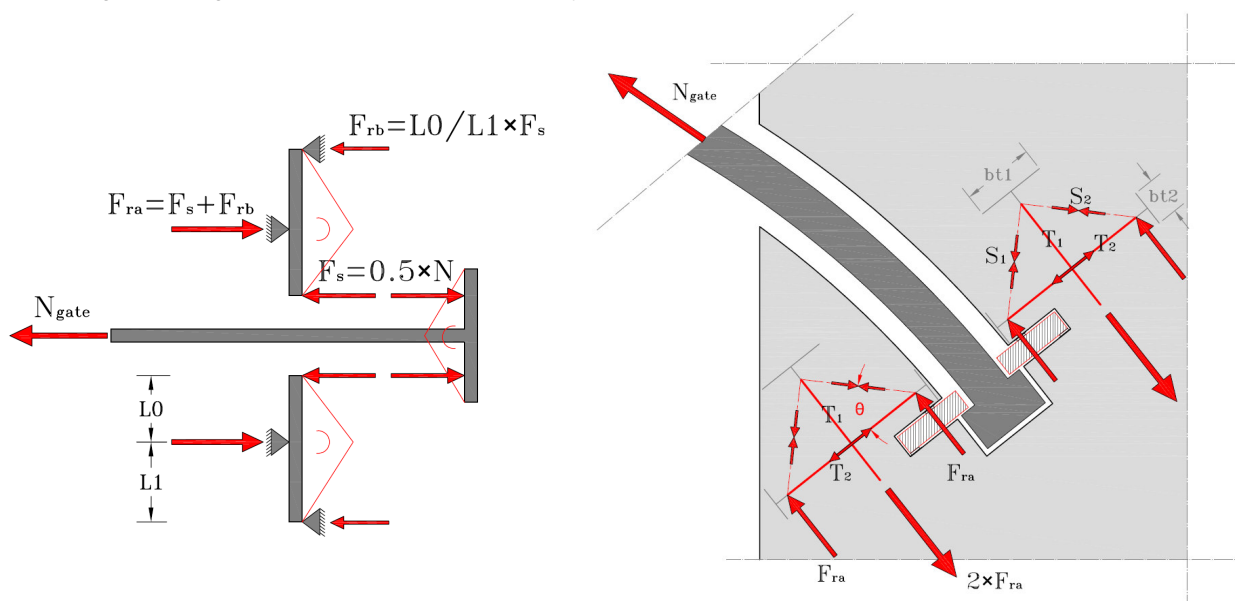
Figure 58: Force transition to the lock head structure, Wedge Support System

Again, as explained in paragraph 14.2, due to the massive dimensions, the structure must be designed using a strut and tie model. In this case the support with the wedges is considered, as the load transfer at the concrete notches (on the other side of the lock) are similar, however slightly less unfavorable due to the absence of the wedge recess. From calculations it appeared that the required width of the tension ties dictate the required distance between the wedge and the inside of the lock. The inside corner of the lock head, (in the right figure above), is critical, and in order to supply sufficient space for the rebar, the wedge support must be situated 11m inside the lock head structure resulting in a effective span of the gate of 77m, significantly more than the lock width of 55m, resulting in the following consequences:

- As the distance between the supports becomes larger, the gate must become longer:
  o Increasing the weight of the gate
  o Increasing the operation forces that are associated to the water level difference during transition of the gate.
  o Increasing the water consumption
- Due to the longer gate length, the radius of the arc also has to be enlarged to approximately 49m in order for the gate to fit into its recess, which results into
  o In higher normal forces and a heavier gate.
  o Increasing water consumption

The transfer of forces, mainly due to the critical inside corner and the wedge recess is thus rather inefficient, though calculations show it is possible. However, expert judgment suspects that large cracks formations could occur from the corners inside of the recess making the situation even less favorable and maybe requiring extra distance between the tension tie T1 and the wedge recess.

Evaluation
The Wedge Support System has shortly been evaluated below summarizing the advantages and disadvantages:
- + Simple vertical operation of the wedge members
- + Relatively light weight wedges, built up from standard profiles
- - Inefficient transfer of forces, resulting in a large area required for
  - Large, heavily reinforced area, Serious risk for large crack formations, however this must be checked by Finite Element Modeling
  - Larger distance between supports
  - Larger arch radius
  - Longer gate
  - Larger normal forces in gate
  Heavier gate structure
- - Increased water consumption

14.4 Alternative B2: Pin Support System

General description and operation:
The Pin Support System is based on the idea of <u>moving the support (steel pins) trough the gate.</u> At each end of the gate, every module will have an opening for a pin to pass through, such that every module is supported individually. Applying more then 11 pins would result in multiple pins being inserted into 1 module decreasing the effective cross section area to the concrete and the steel module section. <u>The number of pins is therefore determined by the choice of applying modular design</u> and the number of modules applied, off which a discussion can be found in paragraph 15.2.2.
The pins will be moved through the gate and into a socket in the opposing wall of the lock head and will be supported on two sides, transferring the normal forces from the gate structure to the steel pin which on its turn transfers the forces through bending to both the supports in the concrete structure. When the gate needs to be opened again the steel pins are retracted into a recess, disconnecting the gate from its support and forming no obstruction for the translation of the gate. As the gate is supported internally, in the gates structure, there is no need for added width of the gates recess, saving considerable amounts of water. However the water level inside the pin recess will fluctuate every lock cycle, adding to the water consumption, but this area is relatively small.
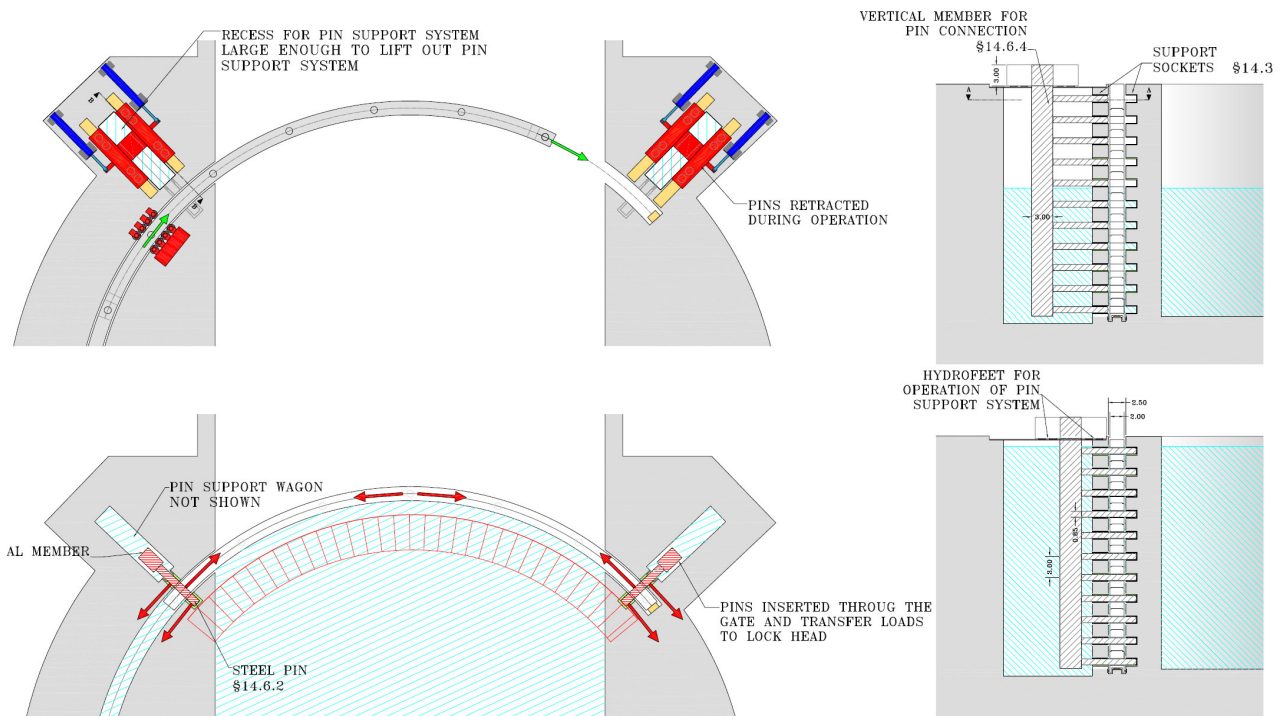
Figure 59: operation of the Pin Support System, for large version see chapter 12

Operation:

The pins must be moved in a straight line, in and out of the gate, every lock cycle with a travel distance of approximately 3 m. In order to prevent that all the pins need to be operated separately and to avoid moving parts under water; the pins will be connected to each other through a vertical member. This vertical member is connected to a 'wagon' which moves over the top of the lock structure (dry) and is operated using hydraulic cylinders (only movement in a straight line over a short distance). The required operation forces to move the pins in and out of the gate, could become significant as some mechanical friction between the pins and the gate or sockets may be expected. The vertical member and the wagon must therefore be stiff enough to transfer the operation forces to the pins without causing large rotations, which could cause the pins to jam. The wagon, which can move either by means of wheels on tracks or hydrofeet, must also be sufficiently heavy to keep positive wheel pressure. This could also be overcome by supporting the wagon in along the top, but this will result in less favorable forces in the concrete structure and would limit the accessibility of the mechanical parts. The total structure required for operating the pins will be a heavy steel structure, however the operation and the required equipment, is simple, based on proven technologies, and very well accessible.

Other considerations:

Operation using hydraulic forces by changing the water level at the back of the vertical member has been considered, however, this requires dynamic sealing at hard to reach places and the applied forces and movement of the gate is less predictable / controllable.

Load transfer to the lock head structure:

According to paragraph 13.3, the pins must be designed to transfer a normal force of approximately 25000-50000 kN, per module, to the concrete structure. This will require a considerable cross section of the pin and in order to keep the size of the required openings in the gate and concrete structure to a minimum, compact and rigid steel pins will be used. The gate modules will be designed so the vertical side panels of the gate module transfer the normal force to the pin. This results in two point loads, situated close to the supports in the concrete structure and thus limit bending moments in the pin, see figure below.

The pin, supported on both sides in the lock head structure, has been modeled as a continuous beam on hinged supports and transfers the loads from the gate through bending. The major advantage of the continuous pins is that no bending moments are introduced in the concrete structure, as there is no notch or clamped structure. The support pressure is simply introduced in the concrete as compressive force, and the reinforcement, which travels

around the pin, is simply anchored in the compressive zone. However splitting reinforcement will be required. In order to assure sufficient spreading of the support load, to avoid crushing of the concrete, a nylon lining will be inserted into the sockets.
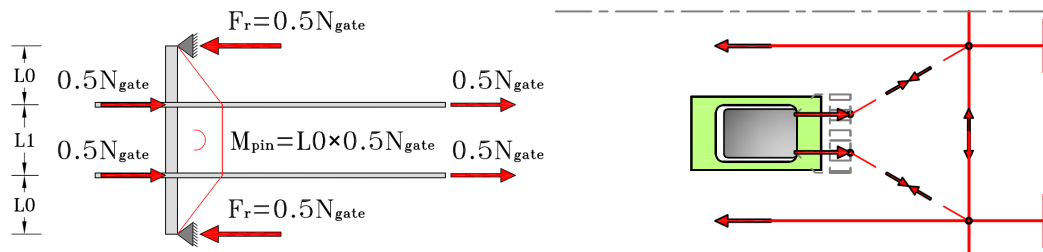
Figure 60: Force transition of the Pin Support System

This simple transfer of forces, allows the support to be placed close to the lock profile, resulting in a considerably shorter span (64.14 m) and the radius (44.34 m) of the gate, which results in less water consumption and a lighter gate. However the operation equipment required for operating the pins is significantly heavier.

Evaluation
The Pin Support System has shortly been evaluated below summarizing the advantages and disadvantages:
+   Efficient transfer of forces, no bending moments at support location in the concrete.
+   Low water losses due to slender recess design
+   Low operation forces gate structure
+   No moving mechanical parts below water
+   Lighter gate structure
-     Heavy massive steel pins and wagon structure
-     Risks of pin failure and possible jamming need further research
-     More complex civil works on the lock head structure

14.5 Evaluation

For the support system of the Sliding Arch Gate, three alternatives have been considered.
The Hook Support System, Needs to be moved on and off its support and extra operation equipment is required to move the gate perpendicularly to its normal translation. The forces that need to be supplied by the operation equipment are significant, due to the large displacement of the gate when moving it on and off the support. Additionally part of the equipment is permanently submerged, which is preferably avoided if possible, as these installations are hard to inspect and maintain / repair. Therefore this alternative is considered to be unsuitable.

The Wedge Support System, is simple in operation, as it only requires movement of the wedge members in vertical direction and all the operation equipment can be situated above water. Also the gate only needs to translate in tangent direction, simplifying the operation system of the gate structure significantly, if compared to the Hook Support System. However, due to the inefficient load transfer to the lock head structure, the inside corner of the lock head is heavily loaded and sensitive to cracking. In order to supply sufficient room for the reinforcement of the concrete structure, the gate distance between the support and the inside of the lock structure must be approximately 11m, resulting in higher water consumption and a heavier gate as is show in table Table 17.

The Pin Support System, where support pins are moved through the gate and which support on both sides of the recess, requires no extra width of the gate at support location and the recess dimensions can be decreased to a minimum as can the water consumption. However, the operation equipment of the support system is heavier and more complex then that of the Wedge Support System. Though the basic operation is quite straight forward and the mechanical parts can be situated above water. The great advantage of the Pin Support System is the effective transfer of forces to the lock head structure, resulting in NO bending moments in the concrete structure and relatively light reinforcement. This results in only a limited area behind the support required for the reinforcement, allowing a relatively short span between the supports, and thus a shorter gate structure, lower normal forces and a lighter gate.

Table 17: Comperitative table, Wedge vs. Pin Support System

Comperitative table Wedge vs Pin Support System.		Wedge Support	Pin Support	
Effective span	B_{sup}	77	63.91	m
Radius	R	49	46.00	m
Gate length	L_g	92.6	76.65	m
Max. normal force	$N_{LC5;d}$	58548.3	52336.63	kN
Max. bending moment	$M_{LC5;d}$	-3474.3	-2662.248	kNm
Approximate weight of gate	G_{gate}	4090	2663.1	ton
Approximate weight of op. equip.	G_{op}	150	952	ton
Area of waterloss	A_{loss}	1072	931	m²

In the above table the differences in the amount of rebar have not been mentioned. As can be concluded from the above, this would also be significantly less (approx 4×) in case of the Pin Support System compared to the Wedge Support System. The advantages of the Pin Support System are clear, mainly due to the efficient load transfer, and will therefore be considered for further design.

14.6 Design of the Pin Support System

In the previous the in support system has been briefly described, in this paragraph the most governing design aspects of the pin supports system design have been worked out:
- A structural model of the pin support is described in paragraph 14.6.1
- The design of the pin is elaborated in 14.6.2
- The design of the support socket and the introduction of the forces in the concrete structure are treated in 14.6.3
- The operation system of the Pin Support System 14.6.4

14.6.1 Modeling of the support pin

In paragraph 14.4, it was mentioned that the pin can be simplified as a beam on hinged supports. This assumption is only valid if the support length is relatively small compared to the span. However, in case of the Pin Support System, the support length (L_{sup}) needs to be large enough to spread the support load and limit the pressure on the concrete, so it doesn't crush. In order to determine the required support length and to check the pressure in concrete the pin has been modeled as an Euler-Bernoulli Bending beam, on flexible distributed supports, as shown in the figure below. Assuming the displacements are small, and plain sections remain plain.

As can be seen in the figure below, the load introduction from the gate has been modeled by two concentrated loads, F_{st1} an F_{st2}, representing the side panels (vertical plates of the gate module see paragraph 15.3. The displacement of the Euler Bernoulli Beam are governed by the equilibrium equations [32], given below, and by solving the differential equations, the displacements are found of which the moment and shear distribution are derivatives. Due to the discontinuities (at F and k_{st}), the beam is modeled using 5 differential equations, which are given below. At each interface 4 continuity conditions have been formulated and each end 2 boundary conditions, resulting in 20 equations with 20 unknowns. This system of algebraic equations has been solved in maple, and for the script file see Appendix 4.
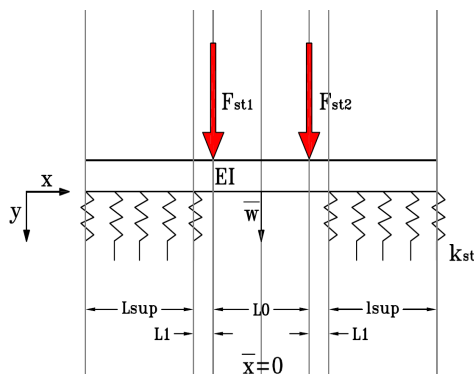
Equilibrium Equations:

Free beam

$$EI \frac{d^4 w_n(x)}{dx^4} = q_n(x) \qquad n = \begin{cases} 1 & for & -x1 \le x \le x1 \\ 2 & for & x1 \le x \le x2 \\ 4 & for & -x2 \le x \le -x1 \end{cases}$$

Beam supported on spring bed:

$$\frac{d^4 w_n(x)}{dx^4} + \alpha^4 w_n(x) = q_n(x) \qquad n = \begin{cases} 4 & for & x2 \le x \le x3 \\ 5 & for & -x3 \le x \le -x2 \end{cases}$$

Figure 61: Modeling of the pin Support, Euler Bernoulli beam with flexible supports

In Which:
EI   : the stiffness of the pin [kN×m²]
w_n(x)   : displacements of the pin
q_n(x)   : distributed load along pin: $q_n = 0$, [kN/m]
α   : Stiffness coefficient:

$$\alpha = \sqrt[4]{\frac{k_{st}}{EI}}$$

k_{st} : Spring coefficient of the support. [kN/m]

Model Input:
The input used for the pin model has been presented in the table below. Some of the input values will be clarified in later paragraphs, see remarks.

Table 18: Model Input for support pin

Model Input						
Geometrical				**Loads**		
L0*	1.85	m		**LC1**	**LC5**	
L1*	0.325	m	N_{std}	25237.8	52336.63	kN
Lsup**	1.25	m	M_{st}	2222.45	2662.25	kNm
k_{st}**	8.197×10⁶	kN/m	F_{st1d}	13788.6	23700.2	kN
E	2.1×10⁸	kN/m²	F_{st2d}	11449.2	26624.4	kN
I**	0.0365	m⁴				

*   Dependent of gate geometry, see paragraph 15.3
**   Dependent on pin and socket design, see paragraph 14.6.3

Results:
The results of the model, have been plotted in the figure below:

$w_{p;max;1}$ =	0.0021	m	$M_{p;max;d1}$ =	10159.27	kNm	$V_{p;max;d1}$ =	-13185.62	kN
$w_{p;max;5}$ =	0.0042	m	$M_{p;max;d5}$ =	20257.76	kNm	$V_{p;max;d5}$ =	-25870.69	kN
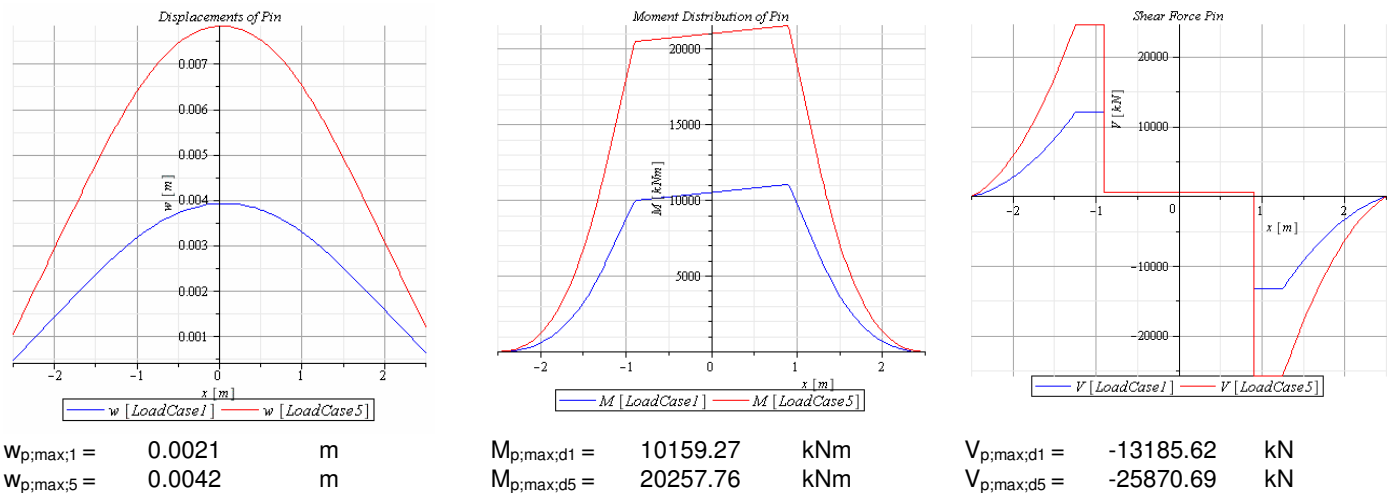
Figure 62: Displacements, Moments and Shear forces in the Support Pin

14.6.2   Pin Design

As can be seen from Figure 62, the pin has to transfer significant bending moments and shear forces, and accordingly this will require a heavy cross section design. In the figure below a sketch is given of the pin cross section, which has been designed as a welded built up section, consisting of two large H profiles welded together, with welded-in side plates for extra stiffness. The design was made according to the following considerations:
– Limitations considering dimensions of pin: keep opening in gate structure limited
– Rectangular: tolerances, maximize contact area

- Designing for fatigue LC1, acc. to Euro Code 3- Part 1-9: Fatigue.
- Designing for ultimate stress LC5, acc. to Euro Code 3
- The internal stability of the cross section has not been checked as the pin is built up from standard hot-rolled sections (class 1) which automatically satisfy these checks. In addition the extra side plates (with the same thickness as the profile web thickness) will be welded on the profiles to give the pin greater stiffness. See figure below: In Appendix 4 the design calculations of the pin can be found.

In the table below the design of the pin has been presented, the general method of designing according to the Euro Code considering ultimate stress and fatigue is presented in paragraph 15.3.

Figure 63: General cross section of the pin
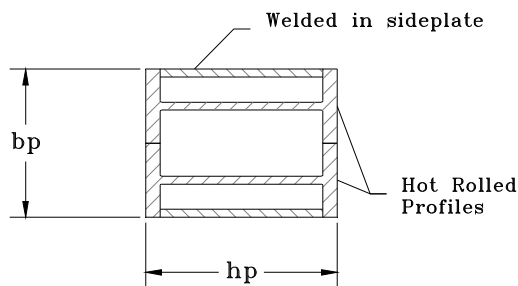
Cross section properties of pin			
Profile type		HE-L 1000 x 883	
Steel grade	σ_y	355	N/mm²
Modulus of elasticity	E	2.1×10^8	kN/m²
Side plate thickness	t_p	0.0455	m
Combined	I**	0.0480	m⁴
Combined Section Modulus	W_{el}	0.0879	m³
Combined Area	A	0.310	m²
Height of pin	h_p	1.092	m
Width of pin	b_p	0.828	m

14.6.3 Support Socket design

The steel pins are supported in a cavity in the concrete structure; this cavity is referred to as the support socket. The design of the support socket governs the pressure distribution along the support and therefore also the introduction of forces into the concrete lock head structure.

Support stiffness:
Factors influencing support pressure:
- Length of the support: Determines the length along which the support loads are distributed. Generally the longer the support length the lower the maximum support pressure, but as the support becomes longer, the resultant reaction forces of the support are further apart and therefore the bending moments and displacements of the pin become larger. The length of the support is however limited to the effective length of the support: the length at which separation between the support and the pin occur.
- The stiffness coefficient: is the relation between the spring stiffness of the support and the pin stiffness (α). It determines the effective length of the support; the theoretical length at which no separation between the pin and the support occurs (wavelength of flexible support). And how the support pressures are distributed along the support.

$$\alpha = \sqrt[4]{\frac{k_{st}}{EI}}$$

Assuming the stiffness of the beam is given, the effects of the support stiffness (k_{st}) are discussed below:
- a) If the support is very stiff then α is relatively large, the effective length of the support (and the support area) will be small and therefore the support pressures must be high. However: the bending moments in the pin will relatively small as the distance between the resultant reaction forces decreases.
- b) If the support is flexible then α is relatively small, the effective length of the support will be large. This will result in lower support pressures even if the actual support length is kept the same in b. However: the bending moments in the pin will relatively large as the distance between the resultant reaction forces increases.

The support pressures for the Pin Support System have been calculated using the pin model described in paragraph 14.6.2. Where the support pressure is equal to:

$$p_{sup}(x) = \frac{w(x) \cdot k_{st}}{b_{sup}}$$

In Which:
$p_{sup}(x)$: Support Pressure [kN/m²]
$w(x)$: displacement of the pin [m]
b_{sup} : support width [m]
k_{st} : the distributed support stiffness [kN×m²]

And the distributed support stiffness has been approximated with:

$$k_{st} = \frac{E_{sup} \cdot b_{sup}}{d_i}$$

In Which:
E_{sup} : Modulus of elasticity of the support material [GPa]
d_i : Interference depth, lining thickness [m]

Material selection of the support socket
When calculating the support pressures assuming the pin to be supported directly on the concrete surface, the support pressures found where significantly larger than the compressive strength of the concrete $p_{sup;max}$ >100MPa. This is due to the fact that concrete has a relatively high (compressive) elasticity modulus, which increases with the compressive strength, and therefore using High Strength Concrete will not solve the problem. A number of alternative solutions have been considered:

- Increasing the pin width / the support area. However this is limited due to the fact that it will result in a larger opening in the gate and no significant increase of the support area can be obtained, without jeopardizing the gate structure.
- Increasing the support length and thus increasing the support area, however this is limited to the effective support length and doesn't allow significant increase of the support area.
- Applying a high strength polymer lining, thus reducing the support stiffness and spreading the pressure before it reaches the concrete.

The third option has found to be the simplest and most effective option. For indicative design, Nylon, PolyAmide type 6 has is assumed to be a suitable material as it can (unlike most polymers with similar properties) be cast in a mould at atmospheric pressure, not requiring high pressure molds and high investment techniques. Therefore relatively large nylon profiles can be produced at low cost. [CES EDUPack]. However, the specific material choice and composition should be preformed by a specialist. The stiffness of nylon is generally 10× lower then that of concrete with comparable compressive strength. PA polymers can also be reinforced and additives can be added to produce an array of material properties making them suitable for marine use, with good friction, wear, impact and fatigue properties. The figure below shows the clear difference in support pressure, comparing the support pressures of a concrete support or that of a support with a 0.3m thick Nylon lining. With next to a table presenting some indicative material property values obtained from [CES EduPack] [MatWeb].
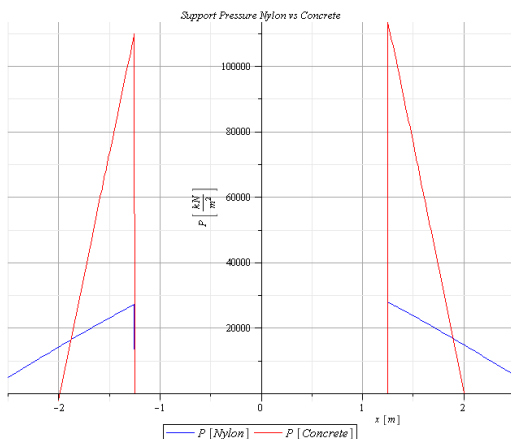
Material properties of lining			
Density	ρ	1150	kg/m³
Mod. of elasticity	E	2.93	GPa
Compressive yield	σ_{yc}	69.30	N/mm²
Tension yield	σ_{yt}	70.40	N/mm²
Shear yield	σ_{ys}	66.50	N/mm²
Fatigue strength (N= 10^7 cycles)	σ_e	28.00	N/mm²
Coeff. of friction	f	0.20	-
Wear coeff.	k_{wear}	2.16×10^{-15}	m³/N
Price		2.0-3.0	€/kg

Figure 64: Support Pressure distribution and material properties of Nylon lining

Considering the design of the support socket, various different values for the support length, the thickness of the lining, width of the pin etc. have been considered, however finding an optimum has not been achieved, this would be very time consuming and is dependent variable material properties. However the following practical values have been found:

Table 19: Overview of support socket design

Overview Support Socket Design			
Support length	L_{sup}	1.25	m
Lining thickness	d	0.3	m
Support stiffness	k_{st}	8.20×10^6	kN/m²
Maximum support pressure			
Load Case 1	$p_{sup;max;1}$	20.43	MPa
Load Case 5	$p_{sup;max;5}$	40.37	MPa

Introduction of forces into the concrete structure:

The supports sockets are hung-up in the lock head structure, and the support loads from the pin must be transferred to the reinforced tensions ties (T1 &T2), which distribute the loads to the lock head structure, see figure below. The transition of these compressive support loads to the tensions ties can be modeled as a strut and tie model according to Euro Code 2 'Design of Concrete structures'. The loads are transferred through the compression struts to the tension ties (similar to a truss girder). The intersections of these ties and struts are called knot's, the forces in these knots must be in equilibrium and the internal stresses must be checked according to EC2 art 6.4. Calculations of the reinforcement and checks of the allowable stress acc. to EC2 have been presented in Appendix 4. These calculations ultimately lead to the minimum required distance of the support to the lock wall (Xmin), which determines the effective span of the lock gate. In this section a short explanation of the strut and tie model is given and the results of the calculations can be found in Appendix 4.

a. Cross section at support
(3 support are shown)

b. Top view of pin support

c. Force transition to lock head
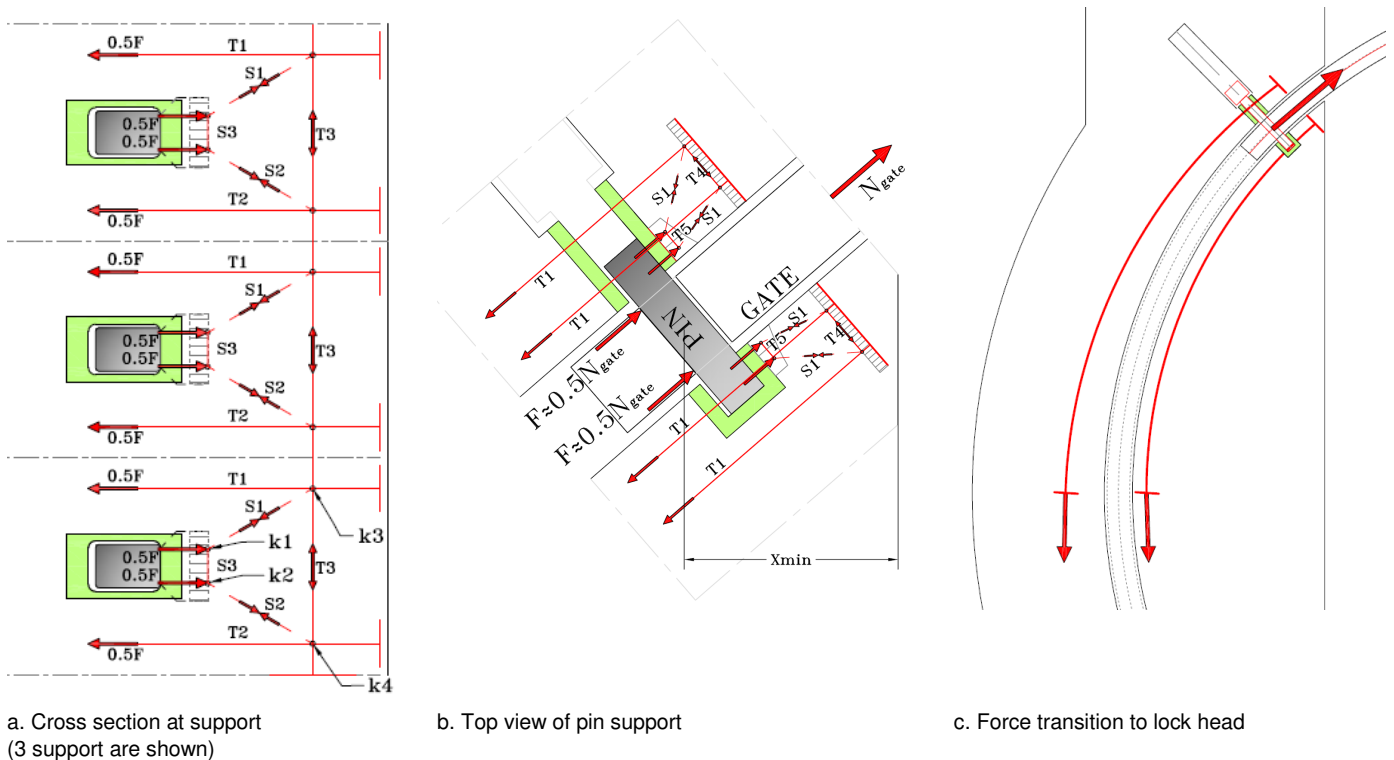
Figure 65: Introduction of support loads into the concrete structure, strut and tie model

The support pressure is assumed to first spread through the nylon lining before being introduced in the concrete structure. Then the support load is transferred by compression struts S1 and S2 under an angle of 45 degrees to the tension ties. In order to maintain equilibrium in k1 and k2 a compression strut must be present between them (S3). The compression struts then intersect with the reinforced tension ties T1 and T2 also under an angle of 45 deg. The reinforced tension tie T3 assures equilibrium of the intersections and prevents the concrete from splitting. The reinforcement of the tension ties T1 and T2 is anchored in the compressive zone behind knot k3.

The support loads do not only spread vertically as described above, but also in horizontal direction, due to the required width of the tension ties T1 and T2. In order to illustrate this, tension tie T1 and strut S1 have been split up in two, each representing half the force. The knots K1 and K3 have also been split up accordingly, each located at the resultant forces of T1 and S1. As can be seen in the figure above, the angle of the struts differ, resulting in tension forces in horizontal direction. This requires extra reinforced tension ties T4 and T5 that supply sufficient splitting reinforcement.

14.6.4   Operation system of the pin support

As mentioned in 14.4 the pins will be connected by a vertical member so they can be simultaneously operated from the top of preventing moving parts below water. The vertical member is then stiffly connected to a horizontal member which acts as a kind of wagon and is moved over the top of the lock head structure. (operation is illustrated in chapter 12). The whole structure must be stiff enough to prevent large displacements and rotations due to the operation forces, which could cause the pins to jam and the weight of the wagon must be sufficient to maintain positive wheel pressure.

Operation Forces:
The operation forces that can occur have been assessed, and the following possible operation forces have been considered and are dived into two categories:
1. Normal operation forces associated to 'freely moving the gate':
   a. Inertia forces
   b. Drag forces
   c. Friction forces caused by the wagon
2. Accidental operation forces associated with mechanical interaction between the pins and the lock head or lock gate structure:
   a. Immediate jamming of the pins in the sockets or gate opening
   b. Immediate jamming due to sway
   c. Immediate jamming, due to miss alignment
   d. Friction forces, caused by the gate 'hanging' on the pin while removing the pin due to residual water level differences during operation.
   e. Trash, not been taken into account, risks are assumed to be minimal

a. Part. Jamming due to sway   b. Immediate jamming due to sway   c. Immediate jamming due to miss-alignment   d. Pin loaded by gate during pin retreat.
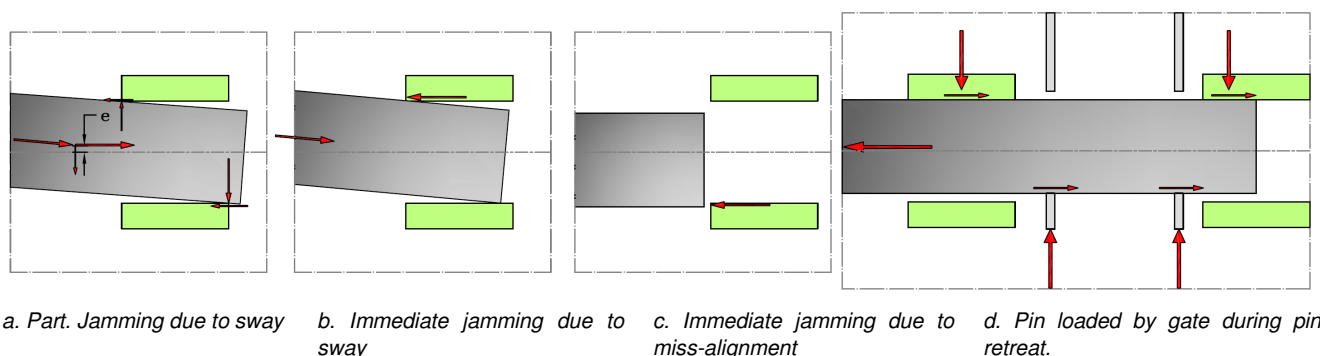
Figure 66: Accidental operation forces of Pin Support System

The forces of the first category are considered inevitable, as they are associated to the basic operation of the gate, though there magnitude can be influenced by the design. The second category can (partially) be prevented, if adequate precautions are taken in the design. It has appeared from calculations that these forces can be significant, or can even prevent the pin from being operated and measures to mitigate these accidental operation forces have been discussed below:

Mitigating Measures for accidental operation forces and jamming:
Prevention [a,b,c]:
- Pre alignment: Bolting the pins to be vertical members with horizontal slots in the vertical member to allow pre-alignment at installation and if required later adjustments.
- Rounding the front of the pin: allowing the operation system to slightly correct small miss alignments and preventing immediate (c) in case of small misalignments.
- Limited retreat of the pin:
- Keeping the tolerances between the pin and the concrete small
- Allow significant Vertical play (assumed: 0.05m):
- Allowing sufficient tolerances between the pin and the gate. However may not be to large because internal forces in the gate during deformation will become large.
- Providing horizontal guidance of wagon

Prevention [d]:
If the horizontal play between the pin and the gate is sufficient, the support pins will not be in contact with the gate while the pins are operated and therefore accidental load d will not occur. Why there will be no contact between the pin and the gate is illustrated in below:

a. Gate in neutral position, no contact with hor. Supports. Neutral play between pin and gate $s=s_0$

b. Gate loaded during transition, contact with support which compress slightly du_1. play reduced to $s=s_1$

c. Water level diff. increases, horizontal support deform with du_2 until there is contact with pin $s=0$
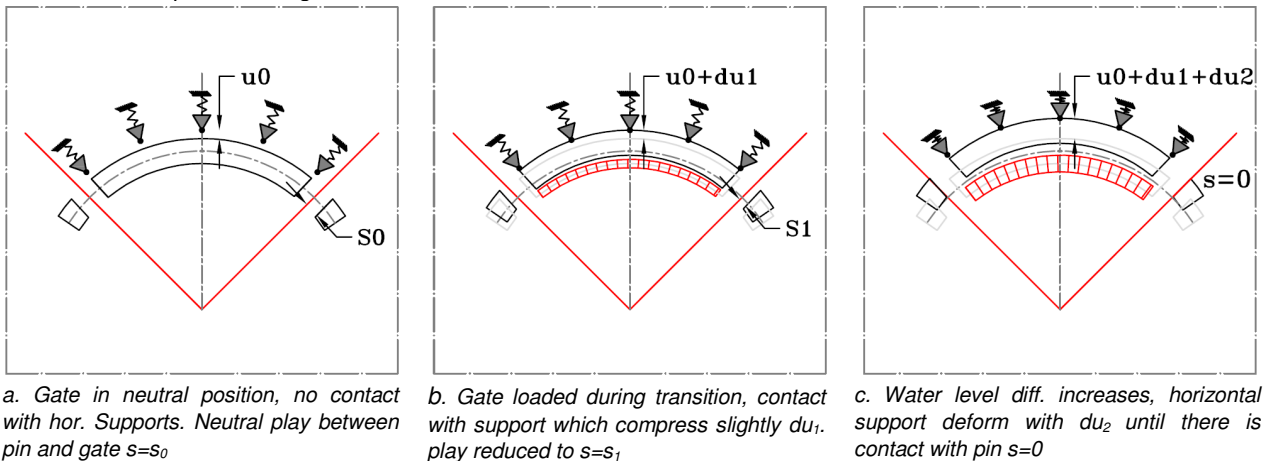
Figure 67: Pin and gate contact

When in transition, the gate is designed to be loaded by a water level difference of 0.1m and is supported at the top and along the bottom by horizontal supports (figure b). Once the gate is in final position the pins can be inserted through the gate without contact (if sufficient play is provided $s_1 > 0$). When the water level difference over the gate then increases the horizontal supports must be compressed to allow contact between the gate and the pin (figure c). The required additional compression (du_2) of the supports is related to the play (s_1) between the pin and the gate at the moment the pins are inserted. The horizontal supports must thus be flexible and must be able to allow the required deformations ($du_{tot} = du_1 + du_2$) without increasing the loads on the horizontal supports significantly. When the gate is then unloaded, the gate should return to its original position as the deformations are elastic and there should be no contact between the gate and the pin even if there is a residual water level difference of 0.1 m the play at retreat should be equal to $s=s_1$

Assumed Operation Forces:
The required operation forces under normal loading have been estimated at approximately 50kN, considering drag due to movement through water, inertia and friction of the hydro feet. Even though the above measures mitigate the accidental operation loads, extra provision shall be taken as a safety measure, therefore the operation system will be designed to supply a operational load 550kN which amounts to 50kN per pin.

Structural design:
In order to determine the approximate dimensions of the wagon structure and to determine the operation forces on the wagon support, a simplified structural model has been assumed and rough design calculation made using basic mechanical formulae. For the wagon's support use the of hydro feet has been assumed. Other options are possible (wheels, rollers etc.) but these all involve heavily loaded moving parts and the friction coefficients are in

the same order[34]. However this is a possible optimization for future research, and the choice of how the wagon is supported doesn't change the essence of the design.

The criteria that have been used (listed below) are operation based and it is assumed that these criteria are governing over strength and local stability (torsion, buckling etc.) req. of the steel structure. However basic stress checks have been done.

- The vertical displacement of the pin tips must be less than 0.05m (assumed vertical play)
- The support loads F_{s1} and F_{s2} must remain positive (up ward reaction force) in order to maintain positive pressure on hydro feet. Therefore the total weight F_g must be sufficient and ballasting may be required.

The simplified model has been presented below, in this case the use of hydrofeet has been assumed.
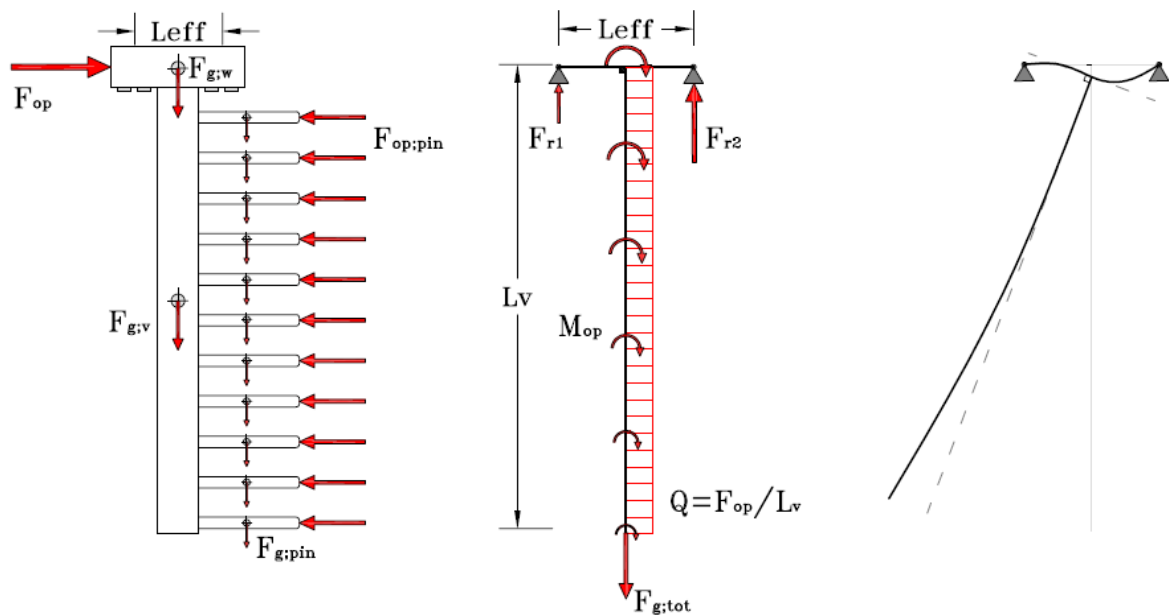
Figure 68: Simplified structural model of the wagon structure

Note: The operation forces can work the other way when retracting the pin, however the moment due to the eccentric weight of the pins then works against the moment caused by the operation forces and is thus more favorable. Adding counterweights to reduce the moment will thus only be favorable when inserting the pins, and only adds to the total weight. Therefore it has not been considered here, though further research should investigate this option in more detail and determine if it may be more economical.

Results

In the table below the results of the calculations are presented and it can be seen that vertical displacements of the pin tips is well within the required tolerance (0.05 m). In order to keep positive pressure on the supports, ballasting of the wagon is required; this can simply be done by filling part of the structure with sand. Although the weight of the wagon structure is significant, 554 ton, it can still be installed/removed using the Panama Canals floating crane, as the weight can be reduced to 340 ton at 13 m from the lock by decoupling the pins (bolted connection) and lifting the structure in parts.

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[34] VAN BEEK A., (2009), Advanced Engineering Design, Lifetime performance and reliability, Technical University Delft, Delft

Table 20: Design of the pin operation system

Effective Support Length	L_{eff}	6.5	m
Length of vertical member	L_v	34	m
Assumed operation force	F_{op}	550	kN
Weight of pins	$F_{g;pin}$	1937.64	kN
Maximum bending moment vert. member	M_{maxv}	21510.92	kNm
Steel cross section area of vert. member	A_{sv}	0.6	m²
Weight of vertical member	$F_{g;h}$	1554.30	kN
Maximum bending moment hor. member	M_{maxh}	21510.92	kNm
Steel cross section area of hor. member	A_{sw}	1	m²
Weight of horizontal member	$F_{g;h}$	1177.50	kN
Requiered ballast weight (sand)	$F_{g;b}$	2500	kN
Maximum vertical load on Hydrofeet*	$F_{op;v;max}$	3725.93	kN
Minimum vertical load on hydrofeet*	$F_{op;v;min}$	-141.21	kN
Vertical deflection of pin tip	δ_{pin}	0.01	m
Total weight of wagon and pins (steel)	G_{stot}	475.99	ton

Operation equipment

Every lock cycle, the pins have to be moved in and out of the lock gate structure. In order to do this, hydraulic cylinders will be used, as it concerns linear movement over a short distance. The pistons will be attached on both sides of the wagon, and are situated above the lock structure in order to provide easy maintenance and inspection. To prevent horizontal miss alignment of the pins, the cylinders can be computer controlled to assure equal stroke and a straight path of the wagon and pin structure. Of course some tolerances are accounted for and it is assumed that they will be sufficient. If further research points out that the cylinders cause excessive miss alignment of the pins (see figure below), horizontal guidance of the wagon can also be installed.

The specifications for the hydraulic cylinders have been given below.
- Maximum operation force: 550 kN
- Normal operation force 50 kN
- Stroke 5-7 m, additional stroke in order to fully retract the pins.

15   GATE STRUCTURE DESIGN, MODULE DESIGN

This chapter presents the design of the gate structure, which is essentially the structure that retains water when in closed position and transfers the forces that work on it to the Pin Support System. The Sliding Arch Gate will transfer the forces through arch action, mainly loading the cross section in normal forces, (see chapter 13). The gate structure has been assumed to be build up from 11 modules (see 15.2.2) each 3m high and that the basic design of the modules is identical and the structural design will consider one representative module, loaded by the governing forces. However, due to operational considerations the design of some of the modules must be adapted slightly. These adaptations to the design will be treated separately however no additional structural design calculations will be made. Below, the content of this chapter is presented:
- In paragraph 15.1 an overview the gate structure is given, showing how the gate is built up by the modules and presenting the basic module design.
- In paragraph 15.2.2 the assumed modular gate design is discussed.
- In paragraph 15.2 the general module design is presented and the structural design of the module is evaluated. For the calculations considering the structural design see Appendix 5
- As the gate must remain stable during transition and the modules are not supported independently the modules must be connected. This connection has been supplied by post tensioned vertical stiffeners and the design is presented in paragraph 15.3.
- The design of the bottom module is presented In paragraph 15.4. This module must be adapted to provide the horizontal and vertical guidance systems of the gate (see chapter 17)
- The design of the top module, in which the pump chambers of the hydrofoot system is located is presented in paragraph 15.5.
- Finally in paragraph 15.6 it is shown how buoyancy chambers are integrated into the gates design.

15.1 Criteria for the gate structure

As mentioned above the prime criteria for the design of the gates structure <u>is that it must retain water when the gate in closed position and transfer the loads, described in chapter 13 to the Pin Support System</u>. Other criteria governing for the gate and module design are listed below:
- Provide connection to the support pins. In order to transfer the loads to the pin supports the gate must
- Provide buoyancy (chambers) to reduce the vertical forces on the hydrofeet
- Provide room for the pump installations of the hydrofeet
- Provide access to the mechanical installations within the gate.
- During transition, when the gate can also be loaded due to a small water level difference of 0.1m <u>the gate must remain stable and deformations of the gate should remain limited</u> in order to prevent miss alignment with the support connections at the other side of the lock.

15.2 Gate structure design overview

In the figures below a general design overview of the gate structure design is given and has been made according to the above criteria and assuming modular gate design. In the following paragraphs the specific details and the basic module design are treated in further detail.
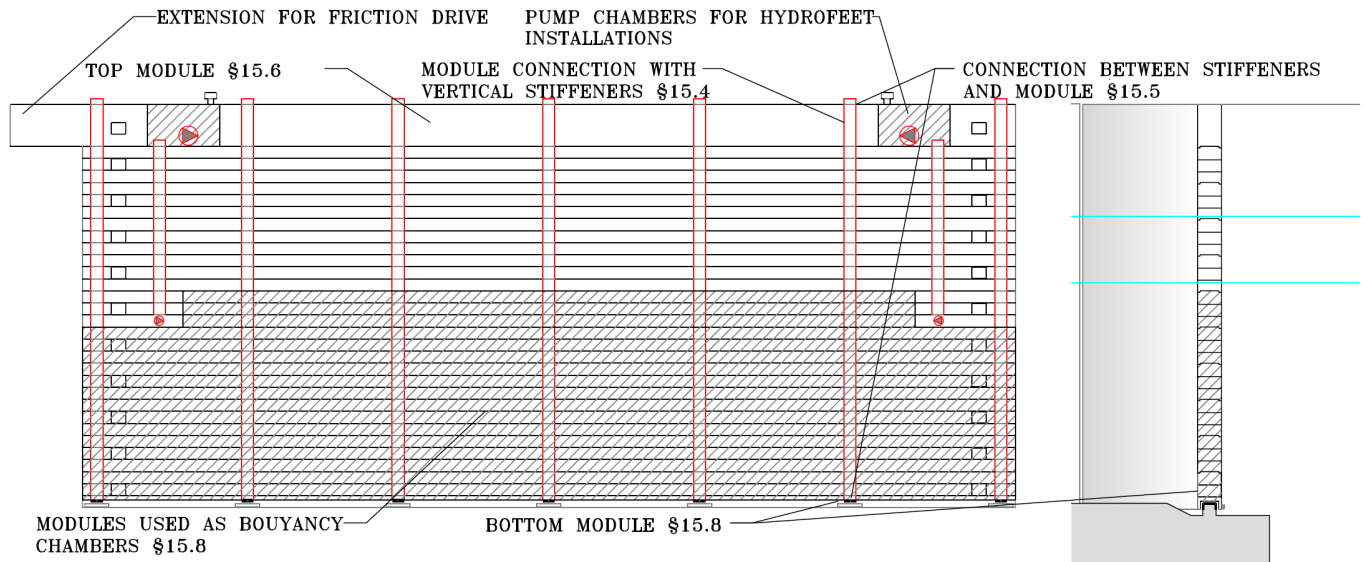
a. Projected Front view and general cross section
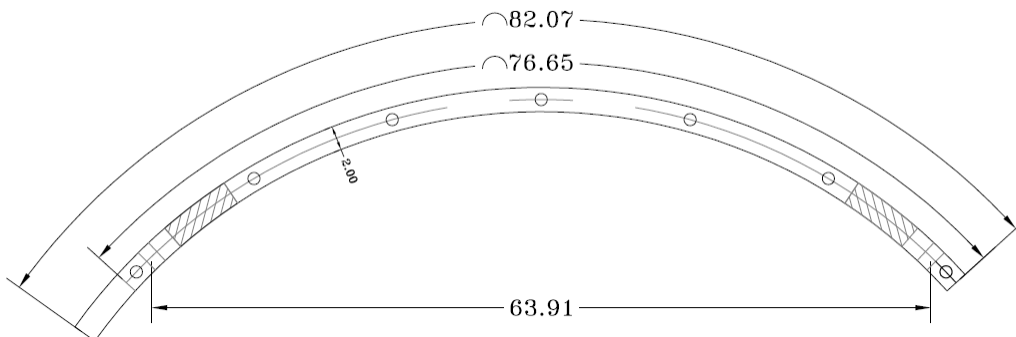
b. Top view

Figure 69: Gate structure overview

15.2.1 Basic module design

In order to fulfill the above functions the module will be designed with a rectangular cross section built up from a number of steel plates, as shown in the figure below. The inside cavity of the gate can be used to either serve as buoyancy chamber, installation room etc, provided some adaptations to the design will have to be made. In order to reach the hydrofeet, which are situated at the bottom of the gate, and to provide a stiff connection between the modules for when the gate is in transition, hollow vertical stiffeners will run through the modules over the total height of the gate structure. These vertical stiffeners will only be connected to the bottom and top module by bolts, allowing easy removal of the hydro feet and a relatively quick dismantling of the gate. In order to assure water tightness of the modules and to provide a smooth connection between the module and the vertical stiffener, steel lining tubes will be welded in the module, through which the vertical stiffener can be inserted. For more details on the connection between the modules see paragraph 15.4.
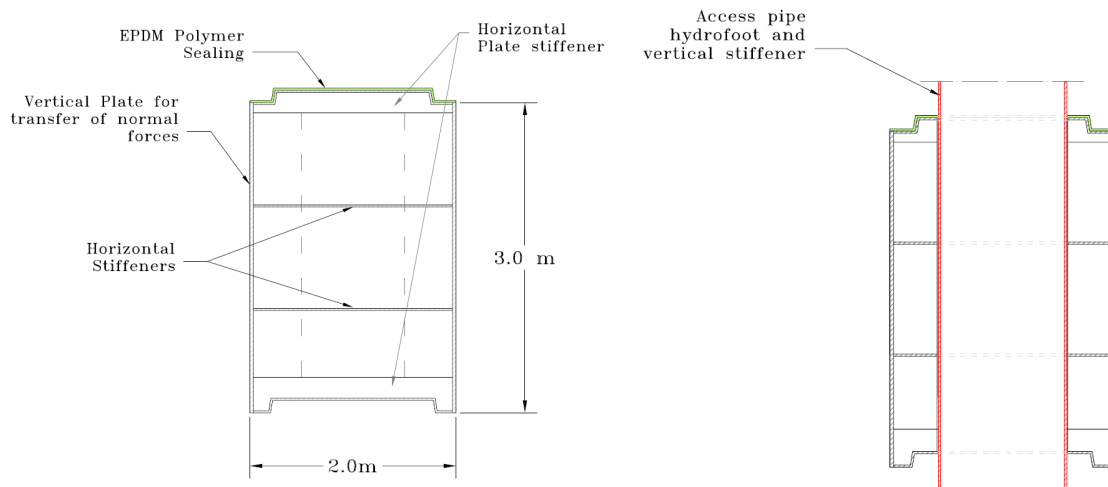
Figure 70: General cross section of gate module,

The outer vertical and horizontal plates are the main structural components, and in case the module is used as a buoyancy chamber, these will be loaded by local hydraulic pressures (see Figure 71). In order to reinforce the outer plates, the horizontal plates are supplied with stiffeners in transverse direction. The vertical plates will be designed to transfer the majority of the normal load, as the horizontal plates cross sections are locally reduced due to the passage of the vertical stiffeners and the vertical plates will supply the connection to the pin supports (see Figure 75). The vertical plates will thus be considerably thicker than the horizontal plates, and will be less dominated by the local hydraulic pressures. This makes it possible to reinforce the plates with horizontal stiffeners, running through the whole cross section of the gate, which from a fatigue loading point of view is more desirable then transverse stiffeners with weld running perpendicular to the normal stresses in the plate. The reasons why the vertical plates will be used to supply the connection to the support pins are given below:
  − By introducing the normal forces from the gate close to the supports of the pins, the bending moments and deformations of the pins is strongly reduced.
  − By keeping the contact area limited to the thickness of the vertical plates the variation of the contact pressure along the supports length (thickness of plate) will be minimal. Maximizing the efficiency of the support.
  − No complex load path and welded support structures are required, which is favorable considering the fatigue design of the module.

The minimum width of the gate modules has been assumed at 2m, a practical value taking into consideration:
  − The installations required for operating the hydrofeet, see paragraph 17.1.3.3.
  − Width required to provide sufficient buoyancy.
 Optimization of the design could lead to a more slender gate structure and thus less water loss.

15.2.2   Discussion on the application of modular design

In the concept design phase, it has been assumed that the gate structure should be modular, built up vertically by a number of arched members. However this has a significant impact on the gates design and a discussion on applying modular design has been presented in this paragraph.

The initial reasons for assuming modular gate design have been listed below:
  − The gate has to be lifted in and out of the gates recess, as the required length and radius of the gate structure are too large to allow the gate to be turned out of the recess to be floated away, even if the gate would be able to float in a stabile manner. Therefore it was assumed; specifically for the PCEP case study, that the available (floating) heavy lifting crane of the canal authorities should be able to lift the gate out. In this case modular design is required and the maximum weight of a module is 300 ton (considering a reach of 20m), see paragraph 11.3. This also forms the basic assumption that the gate need to consist of 11 modules keeping the module weight just under this limit.
  − The ease of fabrication is significantly improved when applying modular design:
      o The modules for the lock gates allow for series production

- o The smaller and more handelable dimensions of the modules make construction less complicated and expensive. Also the specifications of the construction yard / dock are less extreme.
- – Transportation
- – Exchangeability: Considering the large amount of lock gates required for the PCEP (16 in total), with comparable dimensions and load conditions the modules can be designed to be exchangeable. Meaning that spare gate modules can be stored nearby, and can be quickly interchanged when one or more modules are damaged or require maintenance.

In addition to the above: when considering possible larger scale applications (larger span / larger head), the weight of these advantages increase and may even become governing.

However during the design phase the following implications, caused by applying modular design where found:
- – When applying modular design, and using the same basic module design for the whole gate structure the total weight of the gate structure becomes significantly heavier due to the following:
  - o Hydraulic pressures on horizontal plates
  - o Over-design of the modules in the upper segment of the gate
- – In order for the gate to remain stable and to give the gate stiffness during translation the modules have to be connected.
- – Number of pins required are more or less determined by the number of modules. This may not be the optimum number of pins, considering the design of the Pin Support System and the load transition.
- – Possible failure of a pin during retaining has not been taken into account. In case this occurs the module interconnections must transfer the loads to the adjacent modules in order to prevent failure of the gate. This will have to be investigated in future research.

If the gate where to be designed as a continuous structure, this would result in:
- – A lighter gate structure, see above
- – A (floating) heavy lifting crane capable of lifting approx 2000-3000 ton at a reach of approx. 20 m would be required. Such cranes do exist however there are only a few of such cranes and it is questionable if they even fit in the lock. These cranes are generally very expensive to hire and will probably bring about high start up costs as they may have to travel hundreds or maybe even thousands of miles. It also would require planning far in advance for the crane's availability, which makes this option unusable for emergency use incase of unexpected repair and maintenance.
- – In relation to the above, maintenance may have to be preformed inside chamber, req. larger recess dimensions and thus more water consumption
- – In case of a possible pin failure, the continuous structure will redistribute the load transition much easier. However, it should still be checked.

Concluding form the above the application of modular design for the Sliding Arch Gate is in no sense binding and may even not be the optimum solution at this scale. It is also possible to construct a gate as a continuous structure and also the number of modules can be varied according to the available heavy lifting equipment available. However to make a choice between applying modular design or not should be based on a economical study, considering not only the weight of the steel structure but also issues as:
- – Manufacturing
- – Transportation
- – Probabilistic modeling considering the risks of possible pin failure.

It is apparent that when considering smaller scale lock gates, the continuous gate structure would be preferable as the gate structure will be lighter, more handelable and easier to construct. However when considering larger scale applications, possibly even beyond the scale of the PCEP it is questionable if maybe applying modular design is more economical and possibly even inevitable. Therefore modular gate design has been assumed in order to pioneer its possibilities. The actual optimization of the gates design considering the application of modular design and the possible number of modules is left for future research.

15.3 Structural module design

In this paragraph the structural design of the representative gate module has been presented, checking the basic cross section design presented in the previous paragraph. The weight of the module and that of the gate will be determined, checking if the assumption of dividing the gates structure into 11 modules to allow the modules to be installed / removed by crane is realistic. First the loads on the module will be presented after which the critical

cross sections of the gate will be determined and will be checked according to the Euro Code 3, considering fatigue loading and ultimate stress checks.

15.3.1 Loads

In chapter 13 a model has been presented with which the normal forces, shear forces and the bending moments in the gate structure have been determined. However, when considering the cross section of a module, there are also local hydraulic pressures, working on the outer plating of the module, that must be taken into account as the module may be used as a buoyancy chamber. These loads are the main input for the modules cross section design and are given below:

Loads due to the arch action
The loads on the module cross section, due to arch action have been given in chapter 13 in Table 16.

Local loads due to local hydraulic pressure
The module can be used as a buoyancy chamber and can thus be subjected to hydraulic pressures from all directions, as the inside pressure will be equal to the atmospheric pressure. The submerged module, used for buoyancy could also be pressurized in order to relive this load, however loss of pressure could lead to failure of the module and thus of the gate as a whole, and will not be considered. The local pressures on the module are given below for load case 1 and load case 5.

Load case 1, Fatigue design:
For Load Case 1, which considers fatigue loading of the gate structure, the cyclic pressure variation ΔP on the vertical and horizontal plates must be determined. On the left hand (upstream) side the max operation water depth during retaining is 29.14 m and the minimum water operation depth is found during transition, 18.3 m. On the right hand (downstream) side the maximum depth occurs during transition, 23.8 m and the minimum depth when retaining water, 8.91 m. Resulting in the following local pressures (figure a):

a. Local hydraulic pressures during LC1 [kN/m²]   b. Local hydraulic pressures during LC5 [kN/m²]
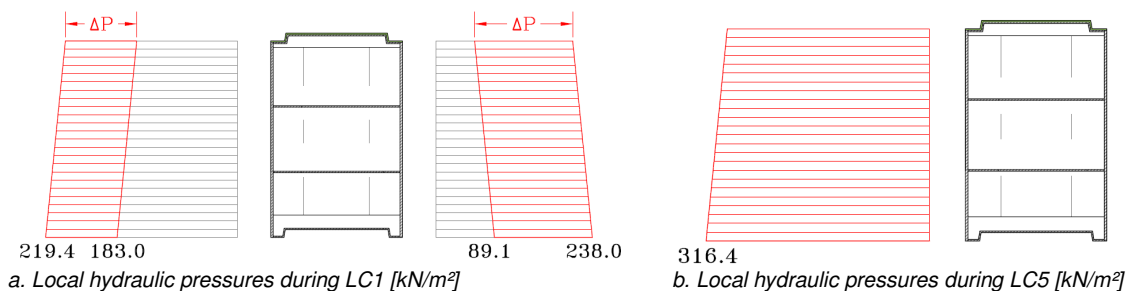
Figure 71 Local hydrostatic loads

Load case 5, Ultimate Strength design:
During maintenance closure, there is only water on one side of the gate with a maxim retaining height of 31.64 m (figure b).

15.3.2 Cross section definition

The gate module can be divided in three distinct sections where the internal stresses of the gate differ significantly:
  − Section A: Is the main section of the gate.
  − Section B: Is the transition section near the pin support, where the normal forces, transferred by the vertical plates, are lead over the rectangular hole required for the pin support. In this disturbed part of the cross section high stress concentrations will occur see paragraph 15.3.3.
  − Section C: Is the back section of the gate, providing the connection to the pin support. Taking the support pressures into account and the disturbed cross section above the pin hole, the vertical plates will be the thickest here

The general cross section design, as presented in Figure 70, will not change, however the plate thicknesses of the vertical plates (t_{vA}, t_{vB}, t_{vC}) will vary according to the expected stresses per section. For results see Table 21.
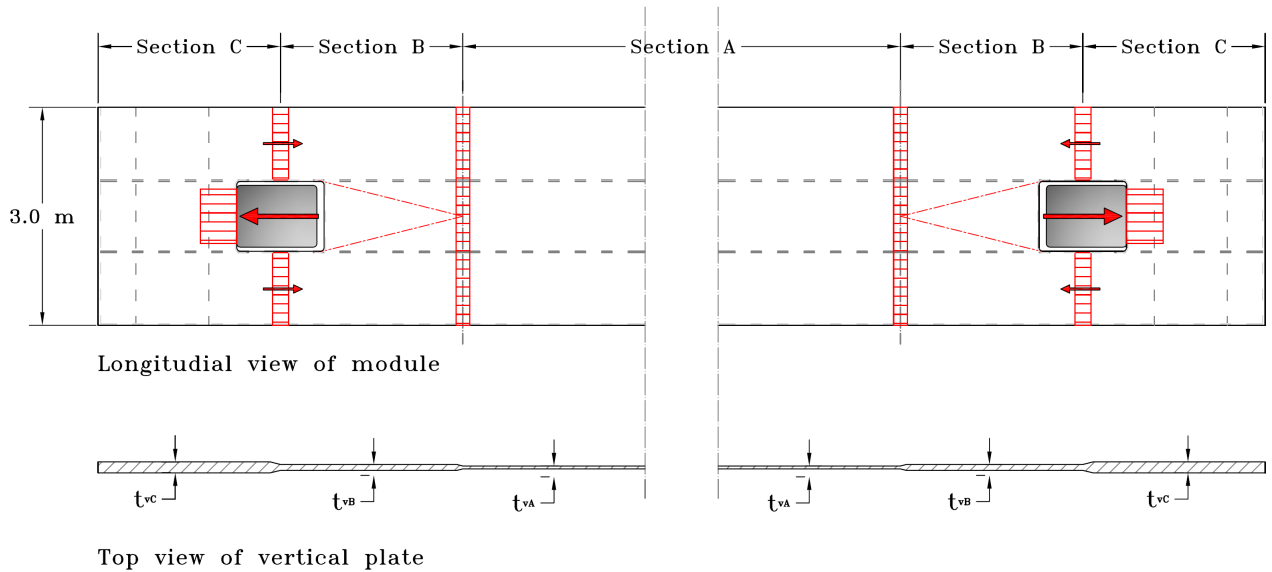
Figure 72: Module Section Definition

15.3.3 Fatigue design, Load Case 1

During the design life of the gate, the gate is expected to undergo 450000 lock cycles, which for the gate structure means moving to closed position, retaining water and moving back into opened position. The gate structure and therefore the modules will be subjected to cyclic loading and fatigue phenomena must be taken into account. In the case of cyclic tension stresses, tiny hair cracks form around stress hotspots in the structure. These can either be welds, holes, non uniform stiffness distributions, impurities[35] etc. The sharp crack creates stress concentrations larger than in the original notch. The fatigue crack propagates when stresses vary and there is some tension in each stress cycle to open the crack and thereby opening producing new area. At some point the crack size is large enough to raise the stress intensity at the crack tip to the material fracture toughness and sudden catastrophic failure will occur[34].

The relation between the cycle stress and the number of cycles to fatigue failure is very much based on empirical research and there are many factors of influence, some of which must be determined from tests. The Euro Code 3 'Design of Steel Structures' provides specific design rules for designing steel structures subjected to fatigue loading. Taking into account the material properties of normal constructions steels, stress concentrations for numerous design details, size factors, etc. One of the most important and hard to determine: the stress concentration factors and size factors have been accounted for by dividing standard construction details into detail classes for which the endurance limits have been determined.

When checking the fatigue capacity according to Euro Code 3, the following unity check must be verified:

$$UC = \frac{\sigma_S}{\sigma_R \cdot \gamma_{mf}} \leq 1.0$$

In Which:

σ_s : Cyclic stress in the steel, [N/mm²] determined as the von misses stress, considering the stresses due to the normal forces and bending moments in the gate and the bending stresses and shear stresses due to the local hydraulic pressures.

γ_{mf} : Material factor assumed 1.15 [-]

σ_R : Fatigue stress, [N/mm²] which is determined by:

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[35] WARDENIER J., (2009), Hollow Sections In Structural Applications, VSSD, Delft
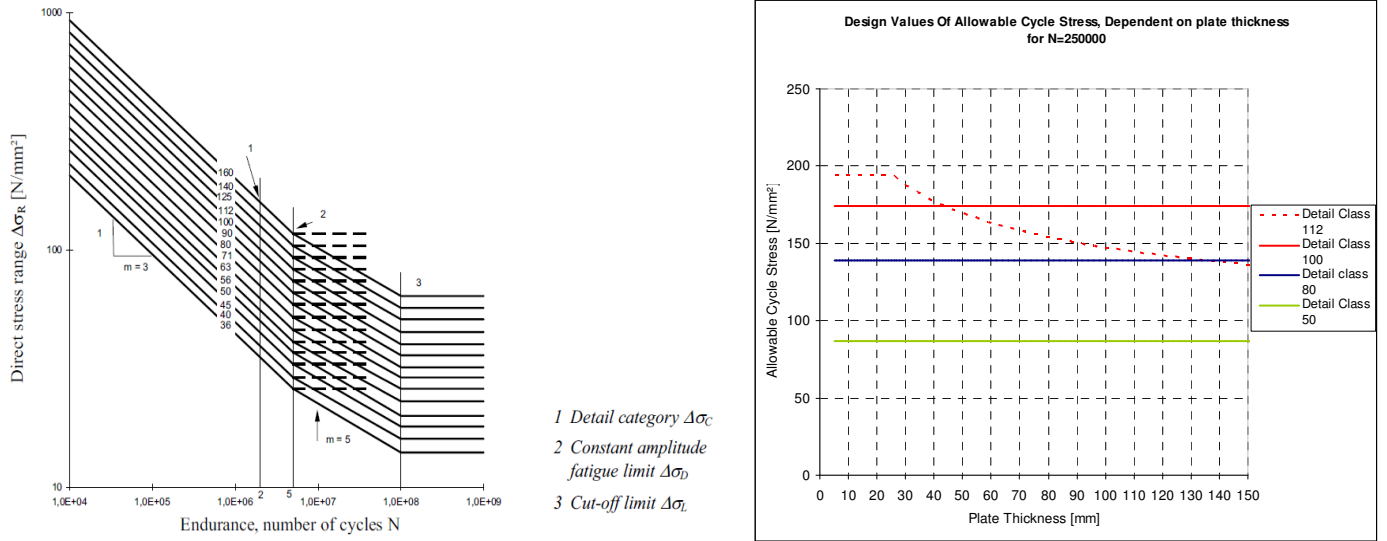
Figure 73: Fatigue design according to Euro Code 3

$$\sigma_R = e^{\frac{-Ln(N_f) + Ln(N_e) + m \cdot Ln(\sigma_e)}{m}}$$

In Which:

N_f : Number of cycles to which the module is subjected. In case of the maximum operation conditions the number of cycles may be reduced to $N_f = 250000$ cycles, see paragraph 11.3

N_e : Endurance limit $N_e = 2 \times 10^6$ cycles

m : Slope of the S-N curve, see figure above.

σ_e : Endurance stress at N_e 2×10^6 cycles, [N/mm²]:

$$\sigma_e = \sigma_c \cdot k_s$$

In Which:

k_s : Size factor [-]

σ_c : Detail category [N/mm²]

The exact calculations can be found in Appendix 5, however the determination of the detail classes is given below:

Detail classes:

The module has been considered as a welded built-up section, made from hot rolled steel plates and welded manually from at least one side.

- Due to the length of the gate, it is assumed that the module will be constructed from multiple plate sections welded together. The transverse butt welds of the steel plates, if carried out from two sides belong to detail category 112, this is higher then the general detail category but for but welds, a size factor must be taken into account and will become governing for larger plate thicknesses.
- The vertical plates in section B and C are distorted by the opening required for the pin to pass trough. The Euro Code does not prescribe such details; however the influence of the opening is comparable to a bolted connection with normal clearance holes between two plates loaded in tension, which belong to detail category 50. This is a significant reduction of the endurance limit and will be assumed to give a good approximation of the influence of the opening in the vertical plates.
- The horizontal plates have stiffeners in perpendicular direction to the stress, which is unfavorable for fatigue design as a notch (weld penetration) is present along the whole cross section loaded in tension. Such detail belongs to detail category 80.

15.3.4   Ultimate limit stress, Load Case 5

Load case 5 considers the maintenance closure of the lock structure, whereby the gate must retain over its full height. This is considered to be the ultimate limit state for the gates design and will only occur a few times during the life of the gate. Therefore no fatigue has to be taken into account, however due to the increased head over the gate the stresses are significantly higher. In order to check if the structure does not fail the following unity check must be satisfied according to the Euro Code 3:

$$UC = \left(\frac{\sigma_{xd}}{\sigma_{yd}}\right)^2 + \left(\frac{\sigma_{zd}}{\sigma_{yd}}\right)^2 - \left(\frac{\sigma_{xd} \cdot \sigma_{zd}}{\sigma_{yd}}\right) + \left(\frac{\tau}{\sigma_{yd}/\sqrt{3}}\right)^2 \leq 1.0$$

This method has been used to check cross sections A,B and C and the calculations can be found in Appendix 5. However for the support pressure of the pins the following limit state has been assumed, which considers the shear stress directly next to the support:

$$UC = \frac{\sigma_{sup}}{\sigma_{yd}/\sqrt{3}} \leq 1.0$$

15.3.5 Results

Table 21: Results of module design; General cross section dimensions

General cross section dimensions			
Vertical plates:			
Plate thickness section A	$t_{v;A}$	0.035	m
Plate thickness section B	$t_{v;B}$	0.09	m
Plate thickness section C*	$t_{v;C}$	0.15	m
Horizontal plates:			
Plate thickness	t_h	0.02	m
Stiffeners			
Spacing	c.t.c	0.2	m
Height	h_{st}	0.2	m
Thickness	t_{st}	0.012	m
Horizontal stiffeners:			
Plate thickness	$t_{h;st}$	0.015	m

* Plate thickness is extremely thick and may give complications considering production and weldability. The design of the back section and the connection area with the pin could be optimized; however this will require complex FEM modeling and is recommended for further research. For the operational design of the Sliding arch gate, this indicative figure is assumed to suffice.

Table 22: Results of module design; Overall module dimensions

Overall module design			
Length of section A	L_a	64.65	m
Weight of section A	G_a	1868.96	kN
Length of section B	L_b	3	m
Weight of section B	G_b	108.82	kN
Length of section C	L_c	3	m
Weight of section C	G_c	151.19	kN
Total length of gate	L_g	76.65	m
Module weight*	G_{mod}	2421.91	kN
	M_{mod}	243.53	ton

* Excluding endplates, compartimentations and vertical lining tubes.

As can be seen in the table above, the module weight is well under the 300 ton limit of the floating crane. However the vertical lining tubes and additional weight due to operation equipment hasn't yet been taken into account, but it is assumed that the total weight will not exceed 300 ton.

15.4 Connection between modules

When the gate is in transition, the gate modules have to be connected in order to assure the stability of the gate while it is moving and to limit the deformations and miss-alignments of the modules for the connection to the pin supports. During translation the gate is subjected to the following loads:

- Operation forces introduced at the top of the gate, required for moving the gate, see paragraph 17.3.2.
- Loads in radial direction caused by the water level difference over the gate, assumed to be 0.1 m (in either direction), see paragraph 11.3. This load has assumed to be governing for the connection between the modules.
- Loads due to different deformations of the modules, are only caused by the wave loads, as the deformations due to normal forces are negligible. These displacements can easily be evened out as the stiffeners apply point loads on the module, to which arches easily deform. Therefore the forces in the stiffeners will not be significant when retaining.
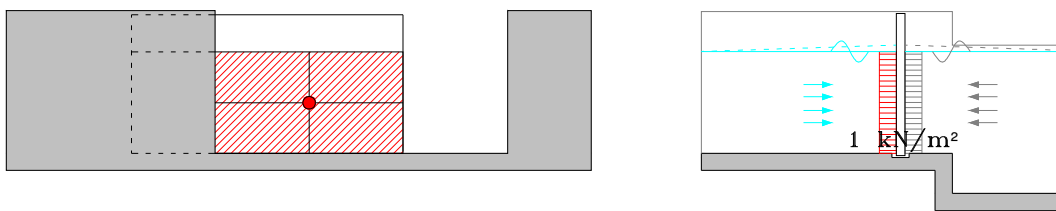
Figure 74: Radial load due to water level difference over the gate, while gate is in transition

In the figure above, this radial load has been illustrated. The loads will be transferred to the horizontal supports along the bottom and at the top of the gate. The red dot represents the resultant of this radial load at half the depth, which causes a bending moment (My) around the x-axis of the gate. In order to assure (external) equilibrium, the moment over the gate will be counter acted by the horizontal reaction along the bottom and at the top of the gate. The gate modules will therefore have to be able to transfer shear forces and bending moments between the modules in order to assure internal equilibrium of the gates structure as shown in the figure below:
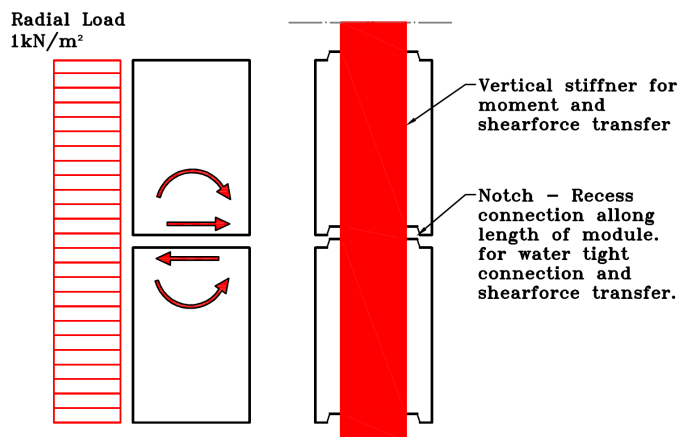
Figure 75: Force interaction between modules

As can be seen in Figure 75, the modules will be designed with a notch – recess connection, which is similar to a Lego brick connection, and will be able to transfer shear forces continuously along the length of the gate. An EPDM lining will be attached to the notch, assuring a water tight connection between the modules. In order to transfer the bending moments, vertical stiffeners will be inserted through the gate structure via lining tubes in the modules. As such these stiffeners can run over the full height of the gate and can be connected to the top and bottom modules such that the modules cannot separate in vertical direction and that lifting forces due to buoyancy chambers in the gate can be transferred.

Considering the hydro foot installations which form the vertical supports of the gate structure, see paragraph 17.1, the vertical stiffeners can be combined to also function as access shafts to the hydro foot, providing room for the supply pipes and easy removal / maintenance of the hydro foot installations, as the entire stiffener / access shaft

together with the hydro foot can be disconnected and removed, see paragraph 15.5. A total of 7 hydro foot installations will be applied, resulting in 1 vertical stiffener per 11.5 m, the stiffener will made of a tube section with a diameter of 1.0 m and a plate thickness of 0.02 m, and will be assumed to be sufficient. The connections have been designed qualitatively. Rough calculations have been made using a Finite Element Model and from this it became apparent that the forces to be transferred between the modules are relatively small and it is therefore assumed the connection as described above is sufficient. Though, detailed modeling and optimization of the connections is recommended for further research, requiring complex Finite Element modeling of the gates structure and its mobile supports. Some optimizations that may be found are:

- Minimizing the dimensions of the notch – recess connection, such that the horizontal plates are continuous, with local thickenings to supply the connection
- The number of stiffeners and supports (hydrofeet), optimizing the weight of the gate and installation design.

15.5 Connection and removal of the vertical stiffener:

As mentioned in the previous chapter, the vertical stiffener doubles as an access pipe to the hydrofoot and can be removed without dismantling the whole gate, in order to provide easy maintenance/replacement of the hydrofoot. The vertical stiffener will also be post tensioned, in order to press the modules together, adding the structural integrity and to provide a water tight closure between the modules, compressing the EPDM lining. The connection must be easy to decouple and should provide the possibility to post tension. Therefore the vertical stiffener will be connected to the bottom and top module only, allowing detachment form the inside of the pipe, and post tensioning from the top. This could be done by a simple bolt connection from the inside of the access pipe at the bottom of the gate, with fixed inner thread attached to the inner lining tube (nut welded to lining tube). At the top, also a bolt connection can be used to post tension the vertical stiffener, with fixed flanges attached to the top module and the vertical stiffener.
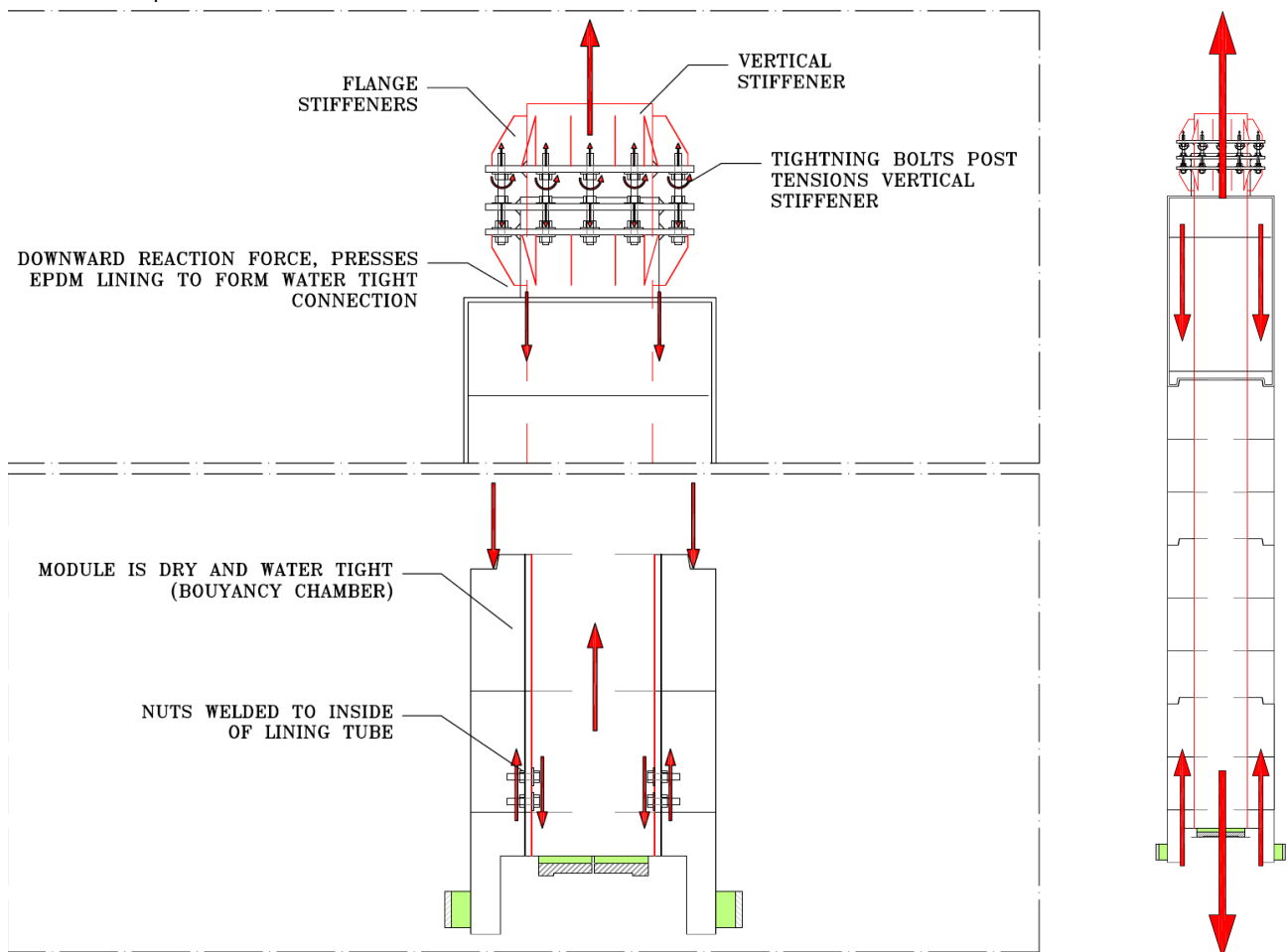
Figure 76: Connection of vertical stiffener to the gate structure

15.6 Top Module

The top module will be used for locating the pump installations of hydrofoot system which is treated in paragraph 17.1.3.3. There will be two pump chambers situated one at each end of the gate (see Figure 69). The pump chambers will be approximately 6m long and require the full height of the module. The horizontal stiffeners will therefore not be present in the top module and due to the significantly reduced loading of the top module this will not harm the structural integrity of the gate. The pump chambers must be water tight and accessible from above such that the pumps can easily be installed and replaced when required. In order to assure the water tightness, end plates will be welded in the cross section, the same as used for the buoyancy chamber, see paragraph 15.8. A water tight hatch will be installed at the top of the gate and air vents situated on top of the module, to supply sufficient air to the pumping chamber when the pumps are in operation. In the figure below the design of the top module has been presented:
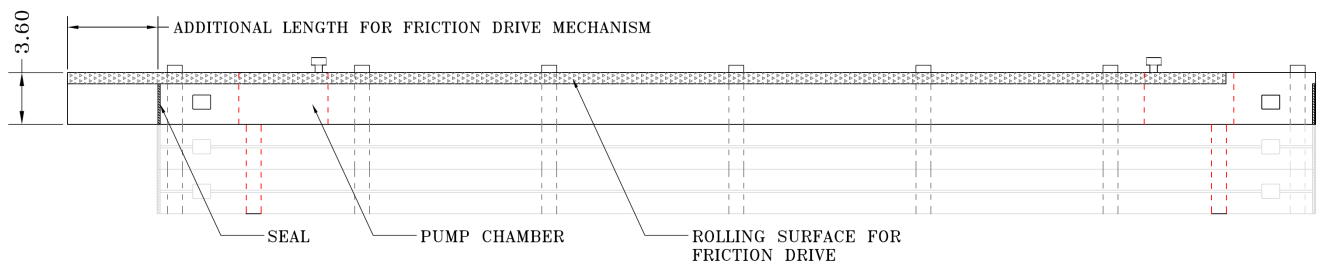
Figure 77: Lay-out of top module

15.7 Bottom Module

The bottom module of the gate structure provides the horizontal and vertical guidance of the gate. The specifications of the horizontal and vertical guidance systems have been determined in chapter 17 and in paragraph 17.1.4 siltation and debris problems are discussed. The required adaptations to the module design have been presented in the figure below:
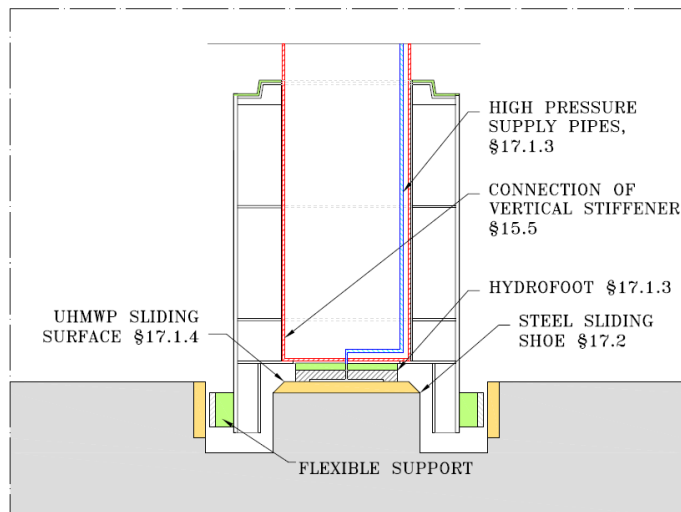
Figure 78: Design of the bottom module

It must be noted that the horizontal supports, which are only present at the location of the vertical stiffeners may exert significant forces on the side panel. It has been assumed that these forces can be transferred to the vertical stiffeners, by stiffening plates, however will have to be confirmed in further research.

15.8 Buoyancy Chambers

In order to relive the vertical guidance system, a number of modules will be used as buoyancy chamber. Theoretically if sufficient buoyancy is applied the gate could be made approximately weightless during transition. However the amounts of buoyancy is limited due to floatation criteria during flooding and while the gate is retaining water. The maximum buoyancy can be calculated from the (dry) weight of the gate minus the upward buoyant force due to the displacement of the gate (without buoyancy chambers) if it would be fully submerged (during a flood). Note, that as the pump chambers are water tight, they add approx 72m³ to the displaced volume.

Table 23: Specifications of buoyancy chambers

Maximum buoyancy and downward force during operation			
Maximum buoyancy:			
Total weight of the gate*	F_g	28996.12	kN
Displacement (without chambers)**	$V_{dis;s}$	441.71	m³
Max. allowable buoyancy force	$F_{v;b}$	24554.63	kN
Max allowable volume bouy. chamb.	$V_{;bouy;max}$	2441.97	m³
Number of modules used for buoyancy	n	5.79	-
Downward force during operation d =18.3m:			
Displacement during operation	$V_{dis;op}$	2582.90	m³
Downward vert. force	$F_{v;op}$	2994.20	kN
Downward force during operation d =23.8m:			
Displacement during operation	$V_{dis;op}$	2623.20	m³
Downward vert. force	$F_{v;op}$	2619.38	kN

* This is the total weight of the gate including vertical stiffeners, lining pipes, endplates and intermediate plates. The pump installations ect. have been estimated at 100kN.

End plates and compartimentation:
To make the modules water tight, endplates should be welded on the modules which will function as buoyancy chamber and in order to reduce the risks of an accidental leakage compartimentations can be made using intermediate plates. These intermediate plates however, may only be welded to the horizontal plates and the horizontal stiffeners. Due to the fact that welding these plates to the vertical plates would reduce the fatigue resistance of the vertical plates significantly from detail class 100 to detail class 80 which is a 20% loss in strength. A flexible resin (kit) can be used to provide a watertight, non structural connection to with the vertical plates. The intermediate compartimentations will be made at the location of the vertical stiffeners, thus adding to the overall stiffness of the gate by means of the intermediate plate.

16   LOCK HEAD STRUCTURE

In this chapter the design of the lock head structure is presented. Due to time limitations, only an illustrative design has been made, giving an idea of the dimensions and quantities. Detailed designing and calculations will therefore have to be made in further research. The main criteria for the present design and for future research have been presented in 16.1. The basic design of the lock head structure has been presented in 16.2. For which the dimensions and design of the lock head have been roughly estimated and general design features have been adopted from the design of the current lock heads and lock walls of the Panama Canal Expansion project. Finally the flow of forces is given and the force transition to the foundation is discussed.

16.1 Criteria for the lock head structure

In the final stage of the flow of forces (see Figure 50), the loads which have been introduced by the pin supports have to be transferred to the foundation through the (concrete) lock head structure. This is the prime function of the lock head structure and the other main functions / criteria have been presented below:
- Provide a recess where the gate can be stored.
- Provide room for operation equipment.
- Transfer loads to the foundation.
- Allow operation of the lock gate.
- Allow access to the gate for personnel, machinery and cranes etc. for maintenance, installation and removal of gate.
- Provide passage for ducts of the filling and emptying system.

16.2 Basic design of the lock head structure

According to the criteria stated in the above, a basic design of the lock head structure has been made and is presented in the figure below. Some important design aspects have been discussed after.
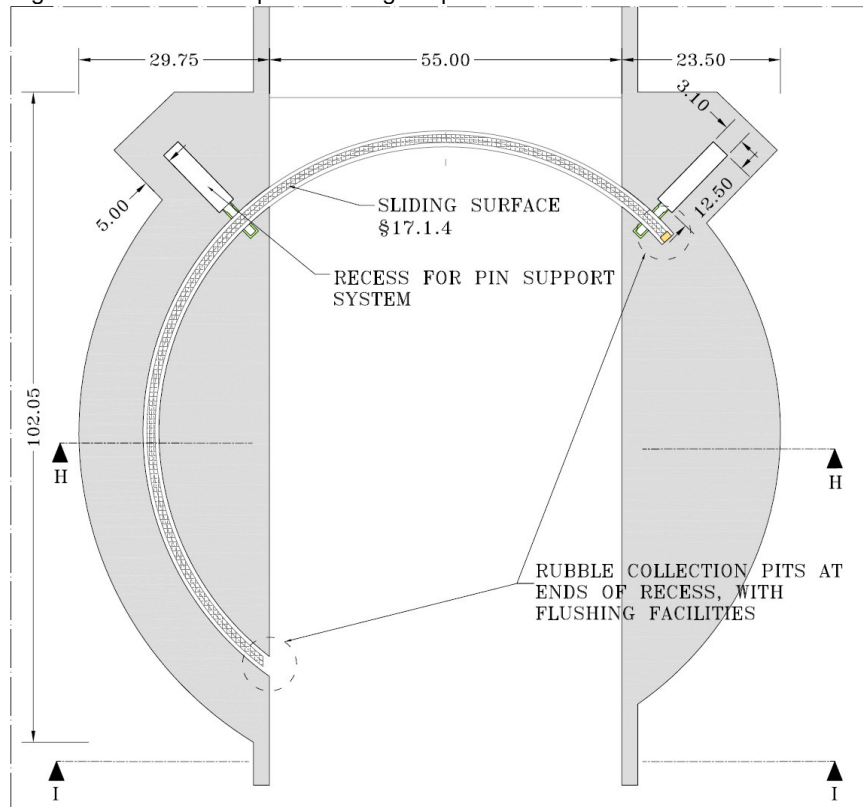
Figure 79: Top view of lock head structure
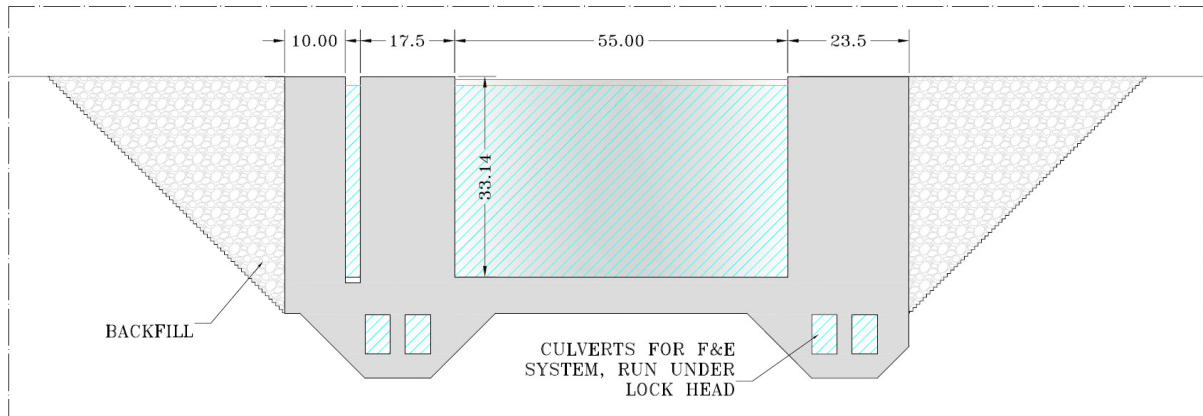
Figure 80: Cross section H-H of the lock head structure
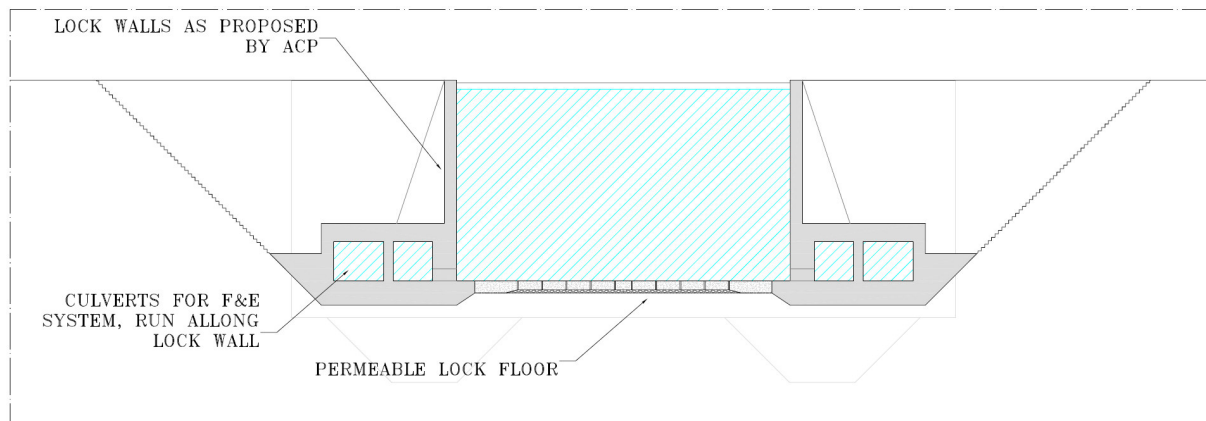
Figure 81: Lock wall design as proposed by ACP, cross section I-I

Gate recess:
- The gate recess has been designed to store the gate when in open position, keeping it out of the lock profile and protected from possible ship collision, waves currents etc.
- To limit water consumption the recess is assumed to be 0.5m wider then the gate, meaning 25% of the cross section is open and allowing water to move along the gate when it is moved.
- In accordance with the above, it has been assumed that the gate structure doesn't have to be fully accessible when inside the recess. For maintenance and inspection the gate can be lifted out of the recess or inspected by divers when in closed position. If further research shows it is more economical to be able to inspect and possibly to perform maintenance in the recess the recess dimensions can be enlarged. This however presents a trade-off with water consumption. For this master thesis project limited water consumption is preferred, as inspections and maintenance requirements are assumed to relatively low as there are no submerged moving parts.

Pin support recess:
- The recess of the Pin Support System has been designed large enough to allow lifting-out of the pin support structure incl. the pins.
- Room has been provided for the installation of the Pin Support System and the alignment of the pins, see Chapter 12.

Other features:
- The shape of the lock head structure has been design to be almost symmetrical in over the lock axis. This has been done to keep the inward resultant forces aligned, see next paragraph.
- The water pressure under the lock head structure and under the lock floors, has been assumed to be equal to the water pressure that would occur if the water level would be equal of that in the chamber. Therefore the design does not include adaptations to prevent floating. This assumption has also been accounted for in the concept design of the PCEP by ACP. As filters have been placed through the lock floor and no provisions against floating have been taken into account in the current design.
- The ducts for filling and emptying system, required for changing the water levels in the lock chambers, can be routed under the lock head in order not to weaken the structure. The ducts could also be lead around the lock head chamber, but they have to drop to the level of the downstream chamber anyway and the level at which they run under the lock head is the same level as required for the downstream chamber. This has also been done for the PCEP project and the duct dimensions etc. have been derived from conceptual design drawings supplied by ACP.
- Other facilities and buildings related to the lock gates operation such as electrical installations, compressors, transformers etc. do not necessarily have to be integrated in the lock head structure design and could also be positioned on the surface (or) adjacent to the lock head structure.

17   OPERATION EQUIPMENT

This chapter presents the design of the mechanical systems which are required to operate (move) the gate structure. They are responsible for the stability/guidance of the gate structure, and its propulsion. The specific criteria for each system have been presented in the according paragraph:

-    In paragraph 17.1, the design of vertical guidance system, responsible for transferring the vertical loads of the gate and minimizing friction and wear, is presented.
-    The horizontal guidance system will be presented in paragraph 17.2. It is not only responsible for guiding the gate but also for transferring the loads due to the water level difference during translation.
-    Finally the operation forces required to move the gate are determined and the design of the actuation system, which provides the movement of the gate, and given in paragraph 17.3.

17.1 Vertical guidance system

Since the gate is too slender to float during transition the gate will have a downward resultant force due to the weight of the gate structure. The vertical guidance system supports the gate structure in vertical direction whilst the gate is in transition. From the concept design presented in Chapter 9, it was concluded that hydrostatic bearing would be used for the vertical support of the gate, in order to decrease friction and wear phenomena to a minimum (a major issue with large Rolling Gates) and to prevent moving / mechanical parts under water.

17.1.1 Basic theory of hydrostatic thrust bearings

General
The basic principle of hydrostatic bearings is based on injecting a fluid under high pressure between two bearing surfaces, creating a thin fluid film which separates the bearing surface. The pressure supply is constant and therefore the full film lubrication is maintained also between stationary surfaces. And as the bearing surfaces are fully separated any fluid can be used. The friction of a hydrostatic bearing, in thus not determined by the friction between the surfaces, but is determined by the viscous shear of the fluid film.
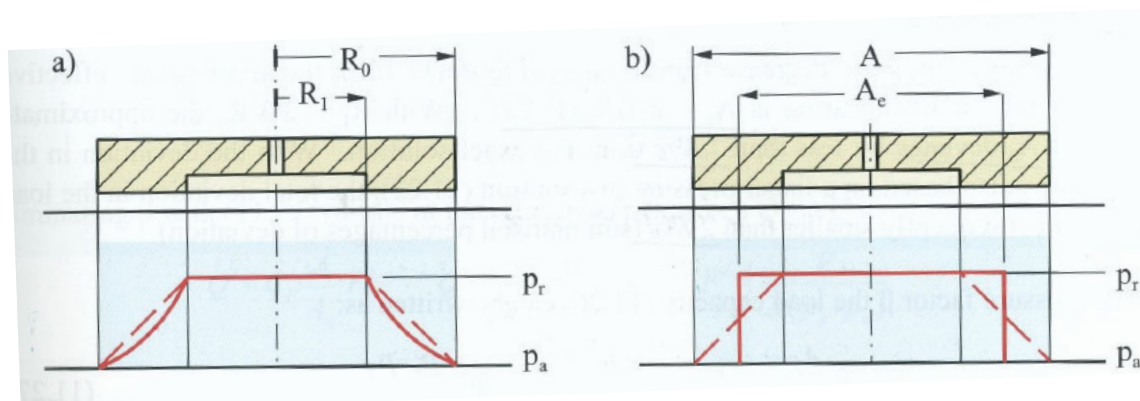
Figure 82: Pressure distribution under a hydrostatic bearing[34]

The load capacity of a hydrostatic bearing is determined by the integrating the pressure distribution over the bearing area. In order to increase the load capacity, hydrostatic bearings are often suited with one ore more pockets, as the pressure drop inside the pocket in negligible, if the pocket is sufficiently deep (see figure above). This results in a greater area where the pressure is equal to the maximum film pressure and thus in a larger load capacity. The reason why the pressure decrease inside the pocket is minimal is due to the relatively low flow velocities apposed to the flow thru the thin fluid film. In the area without the pocket the pressure decreases linearly to the atmospheric pressure.

For preliminary design calculations of hydro static bearings with pocket the following general formula can be used:

$$F_v = (p_r - p_a) \cdot A_{eff}$$

In which:

F_v : Bearing load capacity [N]

p_r : Reduced film pressure [Pa,N/m²]

p_a : Atmospheric pressure [Pa,N/m²]

A_{eff} : The effective bearing area over which a constant pressure p_r can be assumed [m²]. The effective area can be determined for different shapes and sizes hydro static bearing. However for circular hydrostatic bearings with R1 > 2/3 R0 the following approximation can be used for A_{eff}.

$$A_{eff} = \pi \left(\frac{R_0 + R_1}{2} \right)^2$$

Bearing stiffness

If the supply pressure to the hydrostatic bearing would be constant (at any discharge Q) the bearing load capacity (F_v) would be independent of the film thickness (h). This means that any small variation in F_v would result in a disproportionate change in the film thickness (h) and the bearing would have zero stiffness. For practical use, certain stiffness is required, as loads are generally never constant. In order to give the bearing stiffness, the pressure in the film (p_r), and load capacity must be made dependent of the film thickness (h): if the load increases, the film thickness becomes smaller and the pressure increases and thus a new equilibrium is obtained. To achieve this stiffness a number of measures can be taken:

- Flow restrictor*: reduces the down stream pressure (by viscous or inertia forces), dependent on the flow thru the restrictor. Thus: if the load increases and the film thickness becomes smaller, the flow reduces and the downstream pressure (and film pressure) increases, to a new equilibrium.
- Constant flow pump: increasing flow resistance will increase the pressure supplied by the pump.
- Non parallel film: results in a pressure gradient which is dependent on the film thickness and can be achieved by shallow pockets or tapered pockets.

In accordance with further design, only the use of a restrictor will be discussed in the following.

Flow restriction can be acquired through a locally strong decrease of the flow area of the supply pipe. This results in accelerated flow through the restrictor, where, dependent on the Reynolds Number, the pressure is reduced due to viscous shear forces (laminar flow, low Re-number) or by inertia forces (turbulent flow, high Re-number). A combination of both is also possible, however the calculation of the forces becomes very complex and designing the restrictor such, that one of the two is predominant, is generally done. A restrictor where vicious forces are predominant is called a capillary restrictor and if inertia forces are predominant it is called an orifice restrictor.

When applying a flow restrictor, the film pressure p_r, can be found by equating the flow through the restrictor and the flow through the film, where the flow trough an orifice restrictor is found with:

$$Q_r = C_d \cdot A_o \sqrt{\frac{2(p_s - p_r)}{\rho}} \qquad A_o = \frac{\pi}{4} d_o{}^2$$

In which:

Q_r : Flow through the restrictor [m³/s]

C_d : Constriction coefficient, approximately 0.65 [34]

A_o : cross section of the orifice passage [m²]

d_o : diameter of the orifice passage [m]

p_s : is the supply pressure, assumed to be equal to pump pressure [Pa,N/m²]

ρ : the density of the fluid [kg/m³]

And the film flow is equal to:

$$Q_f = \frac{h^3 \cdot (p_r - p_a) \cdot C_f}{\eta}$$

In which:

Q_f : Flow through the film [m³/s]

h : Film thickness [m]

C_f : film factor, approximated by: [van beek]

$$C_f = \frac{\pi}{12} \frac{1+\gamma}{1-\gamma} \ , \ \ \gamma = \frac{R1}{R0} \geq \frac{2}{3}$$

η : Viscocity of the fluid [N/m² × s, Pa×s]

17.1.2   *Application of hydro feet for lock gate usage*

Hydro static bearings have successfully been used for the vertical guidance of lock gates in the Netherlands (Oranjesluis) and Great Britain (Mersey Docks)[36] and are also know as Hydro Feet.

In both cases the gates where normal (rectangular) Horizontal Translation Gates and hydro feet where applied to avoid the large inspection and maintenance costs of rolling wagons. The 4 lock gates at the Mersey docks, where actually first fitted with conventional rolling carriages, but due to excessive wear of the wheels and tracks, hydro feet where applied. In case of the Oranje Locks, the lock gates where originally designed with hydro feet, and extensive research and tests have been done by Bouwdienst Rijkswaterstaat, IHC Lagersmit and TuDelft, in order to optimize the design of the hydro feet and its required installations for lock gate application. The application of the hydro foot installations at the Oranje Locks has been very successful, the knowledge collected by the extensive research will be used for the design of the hydro feet of the Sliding Arch Gate. The basic lay-out of the installations and design of the hydro feet will also be applied for the Sliding Arch Gate and are depicted below:

Multi pocket thrust bearings
The hydro feet used for the Mersey and Oranje Locks, support the lock gates in vertical direction whilst these are in transition. During the translation of the gate, there is generally no water level difference over the gate, however due to unforeseen circumstances small water level differences can occur due to waves, currents ect. This can cause the gate to slightly tilt during translation and therefore the hydro feet have been design with four pockets each with its own restrictor to give the hydro feet rotational stiffness. If the hydrofoot would only have 1 pocket with 1 restrictor, the film pressure would decrease significantly if the bearing is rotated slightly, causing an increased film thickness on one side, allowing the pressure to 'escape'. The application of multiple pockets will result in increased pressure on the side where the film thickness is decreased and vice versa (see figure below). By situating a rubber hinge between the 'rigid' gate and the hydrofoot, the bearing can align itself due to this righting moment and continue to deliver sufficient upward force to support the gate.
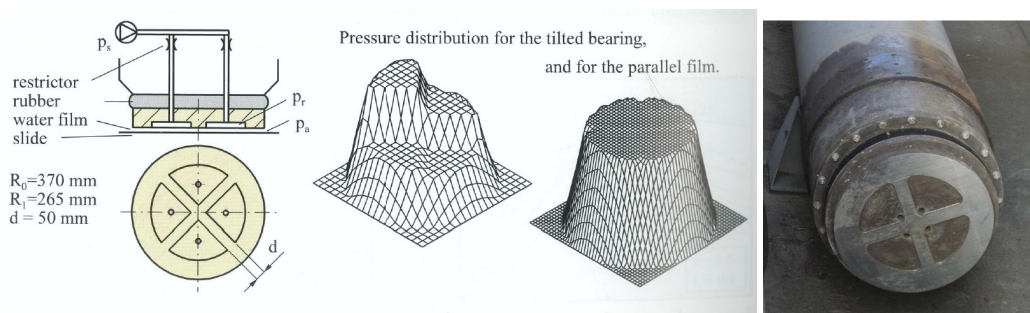
Figure 83: Pressure distribution of a tilted bearing [34] [37],

Hydrofenders:
Hydrofenders have been developed by the TUDelft and Rijks Waterstaat, and form the heavy duty alternative for hydro feet. The bearing surface is not round like that of the hydrofoot, but rectangular allowing much larger bearing loads. They can also be designed as single pocket bearing and the pump pressure can be significantly reduced, allowing PE pipe work and much more silent (submerged) pumps[39]. Therefore Hydro Fenders could also be considered for application of the sliding arch gate, however this should be investigated in further research

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[36] VAN TOL R.A.G., (2009) *Hydrostatische lagers dragen deuren Nieuwe Oranjesluis,* Article retrieved from PIANC Locks report DVD, (2009)

[37] PIANC WG29, (2009), *Project Review, Oranje Locks, Amsterdam (NL),* Retrieved from PIANC Locks report DVD

Basic layout of hydrofoot installation

According to the design of the hydrofoot installations of the Oranje Locks, a basic hydrofoot installation consists of the following components, where all the mechanical installations are situated inside the lock gate:

1. Intake chamber with trash rack
2. Submerged pump
3. Pump chamber
4. Filter unit
5. High pressure pump
6. Flow restrictors
7. Access cylinder
8. Hydrofoot
9. Sliding surface
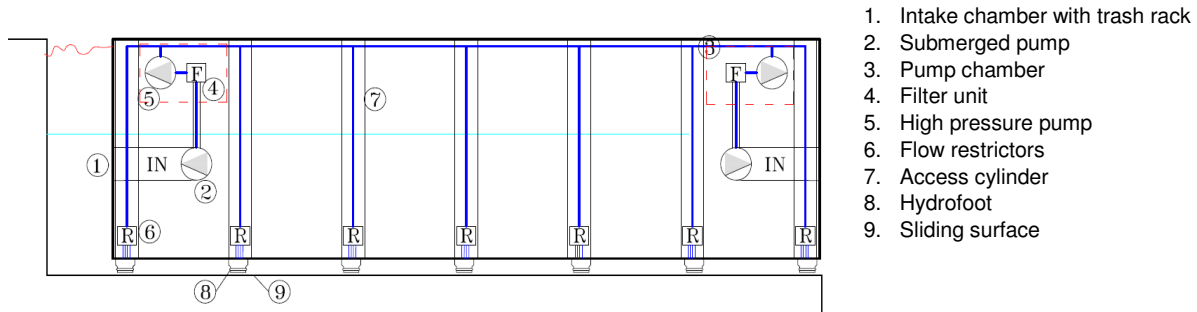
Figure 84: Hydrofoot installation lay-out

The lock gate was designed with 2 hydro feet, each carrying an operational load of 250kN. For operational continuity and reliability, the two pump installations (1 / 7) where installed, of which only one at a time was in operation feeding both the hydrofeet. This full back up installation allows maintenance to be carried out on one installation while the gate remains operational and also reduces the risk of system failure.

The water is drawn in through the intake chamber (1), where a trash rack prevents large debris to enter. A submerged pump (2) then pumps the water up to the pump chamber (3), which is situated at the top of the gate enabling easy access for inspection, maintenance and installation. Here the water is filtered in order to prevent blocking of the flow restrictors. The filtered water is then pressurized by a high pressure pump up to the required supply pressure (22bar) and the water then flows thru the stainless steel high pressure pipes to the flow restrictors, where the main supply pipe is divided into four smaller pipes (one for every pocket) each with one restrictor for every in order to give the hydrofoot rotational stiffness. The pipes then travel down the access shaft to the hydrofoot. The access shaft not only allows inspection and maintenance of the pipes and the hydrofoot, but also allows removal of the hydrofoot without the gate having to be lifted up. The access shaft can be disconnected and lifted out of the gate together with the hydrofoot, incase of replacement or repairs. The hydrofoot is, as described in the previous, connected to the shaft by a rubber hinge to allow alignment of the hydrofoot in case the gate is tilted, or to adapt to slight unevenness of the sliding surface. The sliding surface is made of Ultra High Molecular Weight Poly Ethylene (UHMWPE) which supplies an even surface for the hydro foot and reduces drag. Due to the high wear resistance and relatively low friction coefficient, the gate can also be operated even if hydro feet are out of operation, though higher operation forces are required.

Evenness requirements:

The film thickness between the hydrofoot and the sliding surface should be kept as small as possible as the pressure in the hydrofoot pockets decreases with the 3rd power as the film thickness becomes larger. However there are practical limitations concerning the minimal value of the film thickness. Because the smaller the film thickness becomes the more even the sliding surface must be in order to prevent pressure losses or contact between the hydrofoot and the sliding surface. *"On the large scale of a lock–gate, a hydrostatic bearing typically requires sliding surfaces with a surface waviness smaller than 0.1mm/m. However, the track cannot be manufactured easily with a surface waviness smaller than typically 0.5mm/m. This means that contact between the bearing and track will be inevitable"[38].* The maximum evenness that can be obtained is dependent on the construction of the sill and the UHMWPE plates which that are mounted on it. Regarding the large lock structure and the size of the UHMWPE plates, construction tolerances play an important role and for the Oranje Locks a minimum film thickness of 0.12 mm was considered a practical limit regarding the obtainable evenness and allowable contact between the hydrofoot and the sliding surface. However, it must be mentioned that at the start op operations small unevenness can be scraped by the much harder and wear resistant steel hydrofoot to eventually form an even surface, ideally formed by the hydrofoot itself. Therefore increased friction at the start of operations can be expected, which was also the case for the first Dutch application of hydrofeet at the Oranje Locks. Monitoring of the friction and wear due to hydrofoot operation has been performed. It became apparent

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[38] VAN OSTAYEN R.A.J., (2002), *The Hydro-Support: An Elasto-Hydrostatic Thrust Bearing with Mixed Lubrication*, Proefschrift, Technical University Delft, Delft

that, at the start of operations there was increased friction due to imperfections of the sliding surface, the friction coefficients measured at the start op operations was approximately f=0.01, which reduced to 0.001-0.003 with in a few years of operation[39].

Table 24: Specifications of hydro feet Oranje Locks

Specification of hydro feet, Oranje Locks			
Number of hydrofeet		2	-
Operation load	F_{op}	250	kN
Number of pockets		4	-
Outer radius	R0	0.37	m
Inner radius	R1	0.265	m
Supply pressure	p_s	22	bar
Film pressure	p_r	9	bar
Discharge per hydrofoot	Q_{op}	9.72	m³/s
Film thickness	h_{op}	120	μm

17.1.3   *Hydro foot installation design, Sliding Arch Gate*

The design of the hydro foot installation is rather arbitrary, assuming most of the governing parameters, in accordance with hydrofoot expert *ir. D. Ros*, and according to the design of the hydrofoot installations applied at the Oranje Locks in Amsterdam[23][36]. An optimized design has not been made as there are many variables to consider, and although optimizations could be found, the basic principles and the scale of the installation will not change significantly.

Therefore the design should be considered as indicative, giving an estimation of the following parameters:
  – Hydrofoot dimensions
  – Required flow
  – Required supply pressure
  – Pump capacity
  – Pump dimensions
  – Pipes and other installations
  – Required power and energy consumption

17.1.3.1   **Loads on hydro feet**

The load that must be carried by the hydro foot installations is determined by the downward force during transition, which is caused by the weight of the gate. In order to relive the hydro foot installations part of the modules will be used as buoyancy chambers. However the amount of buoyancy added, is limited as the gate needs a certain downward force to prevent floatation whilst retaining water, or in case of a flood event. According to the above buoyancy restrictions the following values for the total vertical operation load have been found:

Table 25: Vertical operation froces LC6A&B

Vertical Operation Forces	
Operation water depth	$F_{v;max}$
23.8 m (max)	2619.38 kN
18.3 m (min)	2994.20 kN

Under normal circumstances, the vertical load will be approximately evenly distributed between the hydro feet, however when the gate is loaded in radial direction due to a water level difference during translation, it is possible that the gate may tilt slightly and due to the arched shape of the gate a number of the hydro feet will be lifted slightly. This may reduce the upward forces delivered by some of the hydro feet and the remaining hydro feet will therefore have to carry an increased bearing load. Determining how much the gate will tilt and how the vertical load will be distributed over the hydro feet is rather complicated as the stiffness in vertical directions of the adjoined modules plays an important role in the plate like reaction of the gate to the hydraulic forces, and due to the non linear relation between the film thickness and the upward force delivered by the hydrofeet.

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[39] ROS D., (2006), *Deel 1: Ondersteuningsprincipes, monitorings resultaten en praktijkervaringen*, Article from: Land+Water, ½ 2006

Therefore it has been assumed that maximum bearing load per hydrofoot is equal to one third of the total vertical operation load. Resulting in the following bearing loads per hydrofoot, <u>assuming the application of 7 hydro feet:</u>

Table 26: Design values of bearing loads on a single hydrofoot

Design values of bearing loads on a single hydrofoot		
	Rep. value	
$F_{v;op}$	427.86	kN
$F_{v;max}$	998.33	kN

17.1.3.2 Hydro foot design

The hydro feet to be used for the Sliding Arch Gate have been designed using a number of parameters derived from the Oranje Locks, and some assumed parameters. The design is only indicative and optimizations may be found in further research. The input parameters for the hydrofoot calculations have been given below, the actual calculations can be found in Appendix 6. A short explanation dimensionless ratio's has been given after. <u>The hydro feet have been design as circular single pocket hydrostatic bearings.</u> Accurate calculations of multi pocket bearings are significantly more complicated and require FEM modeling, and according to *[VAN TOL][36]* a good estimation of the design can be obtained by designing a multi pocket bearing as a single pocket bearing.

Input:
The input parameters for the hydrofoot calculations have been given below, the actual calculations can be found in Appendix 6. A short explanation dimensionless ratio's and minimal film thickness has been given after.

Table 27: Input parameters for hydrofoot design

Input parameter for hydrofoot design			
Pump pressure***	Pp	30	bar
Design load***	F_{vmaxd}	998.33	kN
Dimension less pressure ratio**	β	0.7	-
Dimensionless radius ratio*	γ	0.716	-
Minimal film thickness*	h_{min}	1.2×10^{-4}	m
Restrictor constriction coeff **	Cd	0.65	-

* Parameters derived from hydro foot design of the Oranje Locks[40]
** Parameter assumed according to suggested design values from *[VAN BEEK][34]*
*** Parameters assumed based on

Dimensionless pressure ratio:
The dimensionless pressure ratio, is the ration between the effective pressure before and after the flow restrictor. It represents till what extent the bearing is loaded to its maximum capacity, and how stiff the bearing will react:

$$\beta = \frac{p_r - p_a}{p_s - p_a} = 0.7$$

If the β becomes equal to 1.0 the film pressure is equal to the supply pressure and cannot increase any further and the bearing stiffness becomes zero, which will result into the film thickness to decrease to zero if the load on the bearing is increased any further. According to *[VAN BEEK][34]*, a practical value of β lies in the interval 0.4 < β<0.7 for the design load, to assure sufficient bearing stiffness. In case of the maximum bearing ($F_{max;d}$) load a value of 0.7 will be used.

Dimensionless radius ratio:
The dimensionless radius ratio is the ratio between the outer radius and the pocket radius and has been assumed to be the same as used for the Oranje Locks:

$$\gamma = \frac{R1}{R0} = \frac{0.265}{0.37} = 0.716$$

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[40] ROS D., (1993), *Sluisdeuren glijden straks op flinterdunne waterfilm, Deel 1*, Bouwdienst Magazine, May 1993

Minimal film thickness:

The minimal film thickness has been assumed to be the same as the film thickness used for the Oranje Locks, in order to keep the related evenness requirements realistic, as the evenness is limited to the construction accuracy. This assumption has been made in accordance with dr. ir. R. v. Ostayen, PHD on hydrofoot design, and ir. D. Ros.

$$h_{\min} = 1.2 \cdot 10^{-4} m$$

Results:

The design calculations, presented in Appendix 6, have resulted in to the following values for the hydro feet design for the Sliding Arch Gate:

Table 28: Results of hydrofoot design

Results of hydrofoot design			
Outer radius	R0	0.468	m
Pocket radius	R1	0.335	m
Effective area	A_{eff}	0.424	m²
Pump pressure	Pp	30	bar
Average film pressure	Pr	21.55	bar
Requiered flow (at F_{max})*	Qf	19.42	m³/s
Film thickness*	h	1.2×10^{-4}	m
Restrictor diameter	do	0.016	m

* Values are dependent on the active bearing load

Variation of the film thickness and flow with varying loads:

In the graphs below the relations of the film thickness, the film flow with the bearing load are depicted. As can be seen, the film flow increases significantly, when the loads on the bearing decrease. This is due to the fact the film thickness increases as the load decreases and the film flow is determined by order h³. Eventually the film flow reaches a maximum level, as the flow through the restrictor cannot increase any more. However this means that when the hydro feet are totally unloaded, or when the operate under normal circumstance $F_{op} < 427.9$ kN, the required pump discharge is much higher, and thus the required pump power, as the pump pressure stays the same.
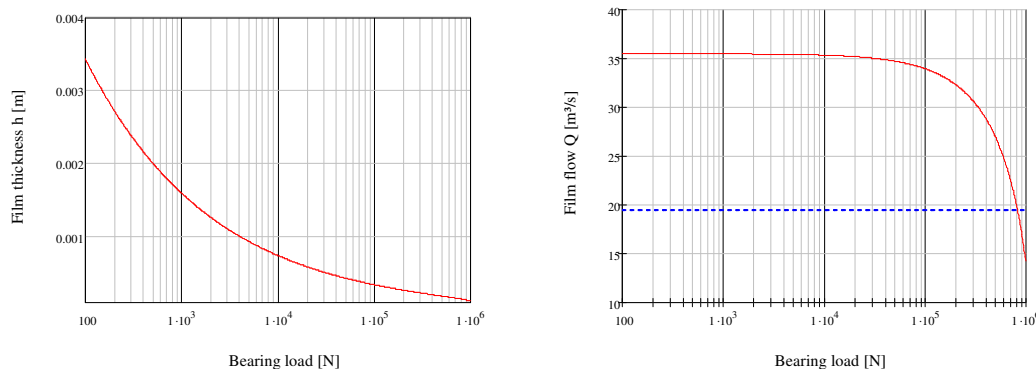
Figure 85: Film thickness and film flow as function of the bearing load

In order to prevent excessive energy consumption, required pump capacity, and to supply every hydro foot with an even amount of water, flow regulation valves can be installed in the supply pipes to each hydro foot. The discharge through the pipes to the hydrofeet will become constant, independent of load variation and equal to the flow required for the design load, as shown by the blue dashed line in the figure above. The regulation value will have to be installed before the restrictor unit, which will still be required, in order to allow independent pressure distribution between the pockets, giving the bearings rotational stiffness.

17.1.3.3   Hydro foot installations

Now the basic specifications of the hydrofeet have been determined, the required installations and lay-out will be specified. As can be seen in the figure below the lay-out of the hydrofoot installation is almost the same as that of the Oranje Locks.
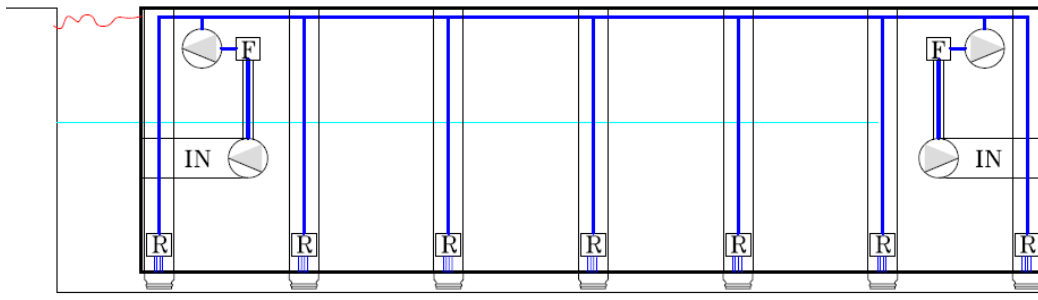
Figure 86: Hydrofoot installation lay-out

Pump Chambers:
The pump chambers will be situated in a dry compartment in the top gate module which can be accessed through a hatch at the top, also allowing removal and installation of the pumps. The design of the top module will thus differ from the other gate modules. In order to supply sufficient space for the pump and the other installations, there will be no horizontal stiffeners, allowing the full module height to be used for the installations. This will not have any structural implications as the loads working on the top module are significantly less then the design loads (of the bottom module).

Intake:
The intake of the pump installation will be situated in the first module beneath the lowest operation water level, to prevent air getting sucked into the system. The end plate of this module, which will also be used for buoyancy, will be moved inward and a trash rack situated at the end of the module.

Submerged pump:
For the submerged pump an access shaft will be installed through the top modules of the gate, similar to the access shafts (and vertical stiffeners) of the hydro feet. This allows the submerged pump to easily be replaced and maintained. The supply to be delivered by the submerged pump is approximately $7 \times 20 = 140\text{m}^3/\text{hour}$ with at pressure head of approximately 15-20m. Such pumps are relatively compact; diameter of approximately 0.3m and are light enough to be lifted using a chain tackle.

Pressure pumps:
There are two pump installations each with enough capacity to supply all the hydrofeet. This means that each pump should have a capacity of approximately 140 m³/hour with an output pressure of 30bar. Pumps that match these requirements, multi stage centrifugal pumps, are relatively compact, and can easily fit inside the gate. According to the specifications of SIHI Pumps[41], an adequate pump including electro motor would have the approximate dimensions of L × B × H, easily fitting into the module and allowing enough space to move around the pump.

Pipe work:
The pumps are connected to the main supply pipe with an intermediate valve, which can be closed in case the pump is not working or if pump is removed. The main supply pipe can then run over the top of the gate, keeping it accessible and branching off at every hydrofoot. This way the same supply pipe can be used for both the pumps. After every branch-off there is a valve which can be closed when the hydro foot is in maintenance or needs to be removed. Then a flow regulating valve controls the flow to the hydrofoot and restrictor unit. The restrictor unit and the splitting into 4 smaller pipes need situated in the hydrofoot access shaft, near the bottom, in order to prevent dynamic complications (according to expert judgment dr. ir. R. v. Ostayen).

Access shaft:

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[41] SIHI, (2008), *Modular multistage pumps, SIHI^multi, type MSL, MSM*, Product Catalogue, Retrieved from: www.sihi.com

The access shaft of the hydro foot will, as described in paragraph 15.4 will not only give access to, and allow removal of the hydrofoot, but will also act as vertical stiffener of the gate.

17.1.4 *Sliding track of the hydro foot installation*

Sliding surface and friction forces:
Similar to the design of the hydro foot installation of the Oranje Locks, the hydrofeet will translate over a UHMWPE surface. This sliding surface isn't necessarily meant to reduce drag during normal operation. But is rather to allow relatively low friction and wear incase of hydrofoot outage or incidental contact. In this case, when due to unforeseen circumstances the hydro feet do not function, the gate can slide directly over the UHMWPE surface. This will result in a higher (but still relatively low) friction coefficient of f = 0.15 in stead of 0.0015, but due to the good wear resistance of UHMPWE the gate can still be operated without significant damage to the sliding surfaces, though at lower speed and only a limited number of cycles.
In the beginning of operation, the hydro feet also may have to wear into the sliding surface, before minimal friction is achieved. Therefore, taking into account possible hydrofoot outage and increased friction at the start of operations the operation equipment must be taken into account. And the gate must be able to be moved considering a friction coefficient of 0.15.

Elevated sliding surface
In order to reduce the risk of sediment or debris damaging the steel and/or UHMWPE sliding surfaces the sliding surface will be elevated and placed on a concrete sill (extra safety measure), as can be seen in the figure below. However research by Rijks Waterstaat has shown that hydrofeet are practically insensitive to rubble and debris even if jammed under the bearing surface. In addition the flow from the hydro feet will wash away any small sediment laying on the sliding surface, and larger parts will be pushed off by the front end of the gate's structure. The horizontal guidance system will support on the out sides of the gate, in order to allow a continuous seal along the gate face, essential for providing a water tight connection. This will cause a kind of gutter, where sediments and debris may pile up and in order to prevent damage or jamming of the gate, high pressure jets can be installed at both ends of the gate. Small debris will thus be blown away, and in order to remove larger debris, collection pits can be placed at the end of the recesses which can be flushed by opening a valve. In addition, it is recommended to shape the front of the gate such that pushing large debris through the gutter will not cause jamming.
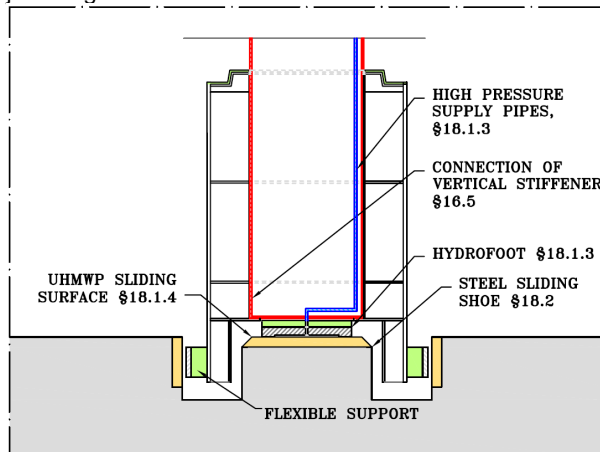
Figure 87: Sliding surface of the Slinding Arch Gate

Effects of a damaged sliding surface:
It is realistic to presume that the sliding surface may, at some point in time, become damaged, due to stones or heavy objects landing on the sliding surface etc. According to ir. D. Ros, former engineer at the Bouwdienst Rijkswaterstaat, involved with the development of the hydrofoot, extensive tests where preformed with damaged sliding surfaces; scratches, gauges and barbs didn't seem to significantly effect the hydrofoot's (long-term) friction. This can be explained to the multi pocket design of the hydrofoot where pressure loss in one pocket is compensated by increased pressure in the other pockets due to a decrease in film thickness. Also possible barbs or peaces sticking out would be scraped even again by the steel hydro foot, only causing a temporary increase in friction. In case of the Sliding Arch Gate, where 7 hydrofeet are present, the other hydrofeet can easily

temporarily take over the load bearing if one hydrofoot loses pressure due to large damaging of the sliding surface.

Possible replacement of sliding surface:
If somehow the sliding surface does becomes significantly damaged, or excessive wear has occurred, the sliding surface must be able to be replaced. The UHMWPE sliding surface will be build up from plate segments, with toothed joints in order to prevent pressure loss (as applied for Oranje Locks). The plate segments can be connected to the concrete sliding sill by a sunken bolt connection near the side of the plate. Thus the bolt holes will not affect the hydrofeet performance and divers can dismantle the sliding surface. Then the segments can easily be brought to the surface, requiring minimal lifting facilities as the UHMWPE has about the same density as water, and can be replaced accordingly.

17.2 Horizontal guidance

When the gate is moved form opened to closed position or vise versa, the horizontal guidance system guides the trajectory of the gates movement such that it arrives at other side of the lock, aligned with the recess. Not only must the horizontal guidance system guide the movement of the lock gate it must also transfer possible horizontal forces due to waves, currents etc. that can occur while operating the gate. This paragraph considers the design of this horizontal guidance system. First the criteria are listed after which two alternatives are considered, one using hydrofeet and the other using sliding shoes.

17.2.1 Criteria

The prime criterion of the horizontal guidance system is to provide guidance and stability during movement of the gate. The gate can be loaded by small water level differences, resulting in a radial surface load over the exposed gate plane. This load has been assumed at 1 kN/m², taking into account possible currents, waves etc. To provide stability and to be able to transfer the loads the gate must at least be supported horizontally at the top and along the bottom of the gate and must be able to transfer these loads (presented in Figure 88) while gate is moving. In addition the following criteria also should be taken into account when designing the horizontal guidance system:
   − Limit additional installed power of the operation equipment.
   − The supports must have sufficient deformation capacity to allow the gate to come into contact with the pins.

Horizontal loads during transition:
As the gate moves further out of its recess, the area which is loaded increases and thus during the transition of the gate (form opened to closed position) the resultant force of this radial load increases as can be seen in the figure below:
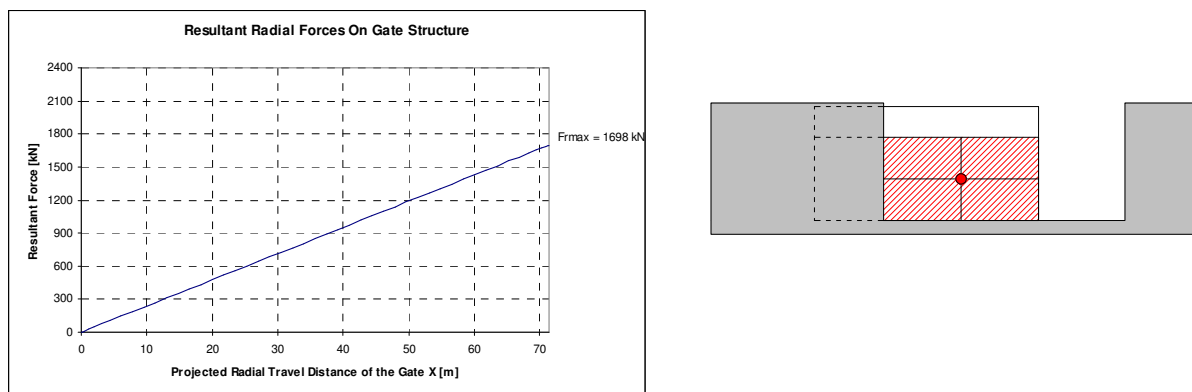
Figure 88: Resultant radial forces on gate structure during transition

17.2.2 Horizontal support along the bottom of the gate

For the horizontal support at the bottom of the gate, two alternatives have been considered:
- o Using hydrofoot installations for horizontal guidance
- o Using steel sliding shoes, on an UHMWPE sliding track.

Although the hydrofoot system almost eliminates friction due to radial loading and additional requirement for the actuation system are minimal, the horizontal support system using hydrofeet will not be considered for further design due to the following reasons: (Calculations of the hydrofoot system can be found in Appendix 6)
- – The additional required pumping power (226.3 kW) and the related energy consumption per gate operation (135.8 MJ), are significantly higher then additional required power of the actuation system and its energy consumption in case of the sliding shoes.
- – The efficiency of the hydrofeet is very low, as they must always be in operation even if the radial load is not present.
- – Hydro feet are required on both sides of the gate as the radial load can work from either direction, this results in significantly more pipe-work and extra required installations.
- – In case of hydro foot outage, the friction forces will be equal to that of the steel sliding shoe, therefore the maximum required forces to be delivered by actuation system are approximately equal, and the installed power of the actuation system will be the same.

Steel sliding shoes, on an UHMWPE sliding track.
If the horizontal guidance system would use steel sliding shoes on an UHMWPE surface, the friction forces would become significantly higher in comparison to the hydrofoot system. These friction forces have to be over come by the actuation system, resulting in larger operational forces and installed power. Assuming a friction coefficient of 0.15 the required maximum operation force, to be delivered by the actuation system, is equal to:

$F_{op;req}$ = 1698 [kN] × 0.15 = 255 kN

This is a significant addition to the normal operation forces which are approx 155kN, see Figure 93. To estimate the energy consumption per lock cycle, the work done by the actuation system is calculated using:

$$E = \int_0^X F_r(x)dx$$

In which:
E   : Work done by the actuation system, total energy [J]
$F_r(x)$: Is the resultant of the radial force as function of the gate displacement [kN]
X   : The total travel distance of the gate [m]

This, results in an energy consumption of 9.1 MJ per gate operation, which is considerably less then the energy consumption required when using the hydro feet for the horizontal guidance. Also, in contrast to the hydrofeet, the additional required force will only have to be delivered, if a water level difference over the gate is present, which under normal circumstances isn't the case.

As the two surfaces are in contact (not separated by water film like hydrofoot) the wear of the UHMWPE sliding surface must be taken into account. The permissible amount of wear is limited, due to the tolerances of the support system. If the wear is too large the support system may not be able to operate, as the gate may be out of line due to the excessive wearing of the sliding surface.
In order to check if the wear of the UHMWPE sliding surface is acceptable, the wear has been calculated assuming the maximum radial load and the full life time number of cycles (n = 450000), and using the general wear formula.
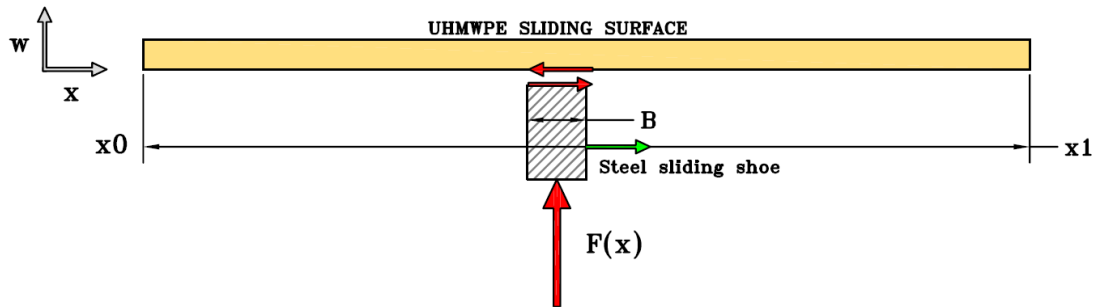
Figure 89: Mechanical scheme of a sliding shoe

Where the wear of the sliding surface has been calculated using:

$$V_{wear} = k \cdot L \cdot F$$

In Which:

V_{wear} : Amount of removed material [m³]
k : Coefficient, for UHMWPE k = 2.7×10^{-15} [m²/N]
L : Sliding distance [m]
F : Bearing force [N]

When considering a varying load F(x) which is move n times along a distance x0 – x1 the left hand side of the equation can be rewritten as:

$$V_{wear} = N \cdot \int_{x0}^{x1} k \cdot F(x) \cdot dx$$

And the removed material volume can also be written as:

$$V_{wear} = \int_{x0}^{x1} w(x) \cdot h \cdot dx$$

w(x) : Wear depth as function of x [m]
h : Width of the sliding surface (perpendicular to the plane shown in figure X), h is assumed to be equal to h = 0.3 [m]

Equating and canceling the integral gives:

$$\int_{x0}^{x1} w(x) \cdot h \cdot dx = N \cdot \int_{x0}^{x1} k \cdot F(x) \cdot dx$$

$$w(x) = \frac{N \cdot k \cdot F(x)}{h}$$

The total amount of lock cycles during the life time of the lock gate is equal to 450000 lock cycles. Assuming the horizontal guidance system will be loaded equally in each direction by the radial loads, each of the sliding surfaces will be loaded by 225000 cycles, each consisting of 2 passages (opening an closing) which amount to a total of 450000 passages. Calculating the wear depth along the length of the bearing surface and assuming the radial load to be maximum every cycle (which is very conservative) this results in a maximum wear depth of 0.014m, see figure below. This wear depth is considered to be acceptable, if the thickness of the UHMWPE is sufficient, and the tolerances between the support and the gate structure have been taken into account. The sliding surface thickness of the horizontal guidance system is therefore assumed to be equal to that of the vertical guidance system and is equal to 0.07 m, which is more than sufficient.
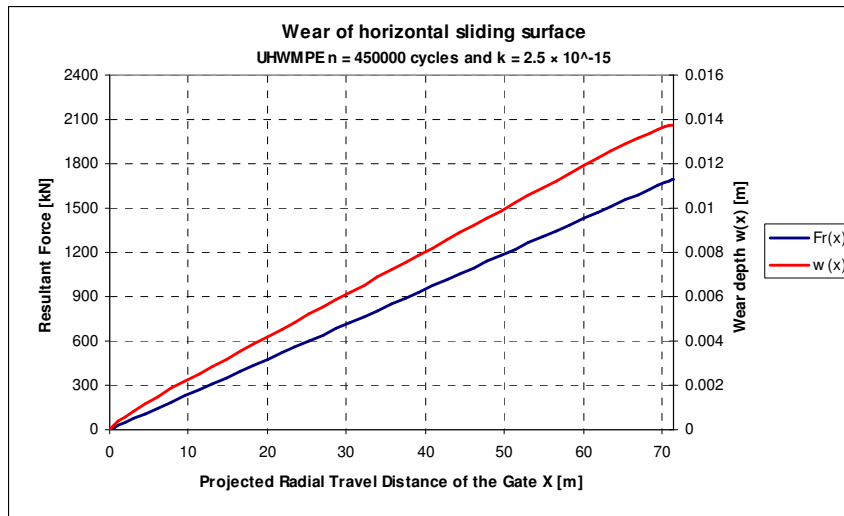
Figure 90: Wear of the sliding surface

17.2.3 Support at the top of the gate

The horizontal support at the top of the gate, required for its stability during transition, has been integrated into the actuation system, see paragraph 17.3.

17.2.4 Horizontal gate protection strips

When the gate moves through its recess, accidental contact between the gate and the concrete lock head structure could be possible, as the gap between the recess and the gate is only 0.25 m. In order to prevent the coating of the steel gate structure to be damaged, the gate modules will be fitted with protections strips. Similar strips are also applied with conventional Rolling Gates and can be made of UHMWPE or Azobé [6].

17.3 Actuation system

The actuation system is responsible for moving the gate structure and overcoming forces related to the movement of the gate: friction, drag and inertia forces. An indicative design of the actuation system is presented in this paragraph. Firstly the criteria are presented after which an approximation of the operation forces is given. A number of alternative actuation systems have been considered and finally an indicative design has been presented of the chosen actuation system; a friction wheel drive, determining the rough dimensions and installations required.

17.3.1 Criteria

The prime criterion of the actuation system is to supply controlled movement of the gate, moving it from opened to closed position, aligning the gate with the Pin Support System and vise versa. In addition the following criteria also should be taken into account when designing the actuation system:
  - In order to move the gate the operation forces related to moving the gate must be overcome.
  - Operate the gate structure in approximately 4 minutes.
  - Supply controlled movement of the gate.
  - Provide horizontal support of the gate.
  - Allow easy access and replacement possibilities.

17.3.2 Approximate operation forces

The operation forces have been calculated to determine the order of magnitude to which the actuation system should be designed. In doing so, the following forces have been taken into account:
  – Loads in tangential direction caused by the movement of the gate due to drag and Inertial forces.

- Friction forces in tangential direction caused by the horizontal and vertical guidance systems taking into account:
    - Loads in radial direction due to differential pressure, see Figure 88
    - Vertical loads due to weight of the gate, see Table 26. Including additional friction incase of hydro foot outage.
- The minimum and maximum operation depths during transition.
    - The maximum depth of 23.8 m will result in higher drag, inertia forces and friction caused by the horizontal guidance system.
    - The minimum depth 18.3 m will result in the highest vertical load and friction caused by the vertical guidance system (governing in case of hydrofoot outage).

As the design is indicative, the following assumptions / simplifications have been made:
- The calculations have been made assuming the gate plane to be straight and thus neglecting the curvature. The curvature significantly complexifies the calculations to be preformed, and only an approximation is required to determine the order of magnitude. Although the projected gate length has been taken into account, this simplification may cause an underestimation of the operation forces. As the angle at which the operation forces are introduced will result in additional horizontal loads on the lower supports (horizontal guidance system) and that it is unfavorable for the gates stability during transition; though this should be investigated further in future research.
- It has been assumed that in the accidental case of hydro foot outage, and the gate must be operated with increased friction, there will be no differential head over the gate.
- It is assumed that, when taking into account the extreme operation forces due to hydrofoot outage or a differential head over the gate, the increased friction forces at the start of operation, due to the wearing-in of the hydrofeet are accounted for. This is confirmed by tests preformed by Rijkswaterstaat and real-life measurements of the operation of the Oranje Locks. And it has been found that the friction at the start of operation will be approximately 0.06 and after 3000 cycles approximately 0.001 [40], while the friction incase of hydro foot outage is approximately 0.15.
- Only moving the gate from opened to closed position has been taken into account, it can be expected that moving the gate in opposite direction, will result in similar operation forces.
- As the recess is in open connection with the lock, recess drag has been neglected. This phenomena normally occurs due to water build up or draw down, due to the movement of the gate in and out of the recess. Causing a differential head over the gate front and increased current between the gate and the recess wall.

Forces due to drag and inertia forces:
In order to determine the operation forces due to drag and inertia, an operation scheme has been assumed, consisting of three phases:
- Acceleration phase; in which inertial forces are dominant, and drag forces gradually increase, taking into account the acceleration of the gates mass and the added water mass.
- Constant speed phase; in which drag forces are dominant as the gate travel with constant speed.
- Deceleration phase; in which inertial forces become dominant again but work in opposite direction, against the gradually decreasing drag forces.

a. Acceleration phase   b. Constant speed phase   c. Deceleration phase
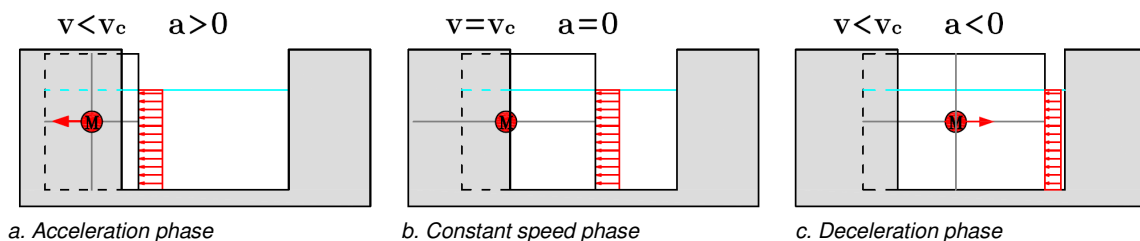
Figure 91: Operation phase of gate movement

Many different operation schemes are possible, and optimization may be found, fine tuning the operation with the performance of the actuation system, and more complex analysis of the operation forces. For the calculations of the approximate operation forces the operation scheme is assumed and is presented in the graphs below together with the results. The actual calculations can be found in Appendix 7:
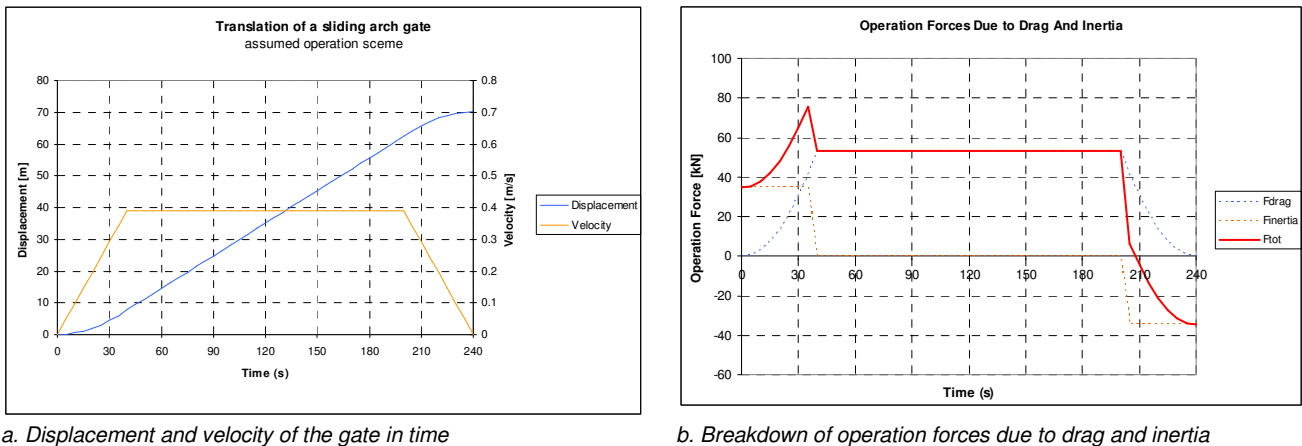
a. Displacement and velocity of the gate in time   b. Breakdown of operation forces due to drag and inertia

Figure 92: Gate operation and forces due to drag and inertia

Forces due to friction:

When considering the extreme forces to be delivered by the actuation system in order to overcome the friction forces caused by the horizontal and vertical guidance systems, two load situations have been distinguished:

- Differential pressure over the gate Load Case 6A&B: In paragraph 11.3, the resultant radial force, caused by the differential head over the gate of 0.1m has been assumed for designing the horizontal guidance system. Taking into account a friction factor of 0.15 the additional operation forces have been calculated and are presented in Figure 93.

- Hydrofoot outage Load Case 7: if the hydrofoot installations fail, it should still be possible to be able to move the gate, in order to reduce down time of the lock, whilst repairs are being preformed. This, however, will cause a significant increase in friction forces, as the lubricating water film is no longer present between the steel hydrofoot and the UHMWPE sliding surface. The friction factor of steel on UHMWPE is approximately 0.15 [mat web]. Considering the vertical load of the gate during transition presented in Table 30 the additional operation forces have been calculated and are presented in Figure 93 :
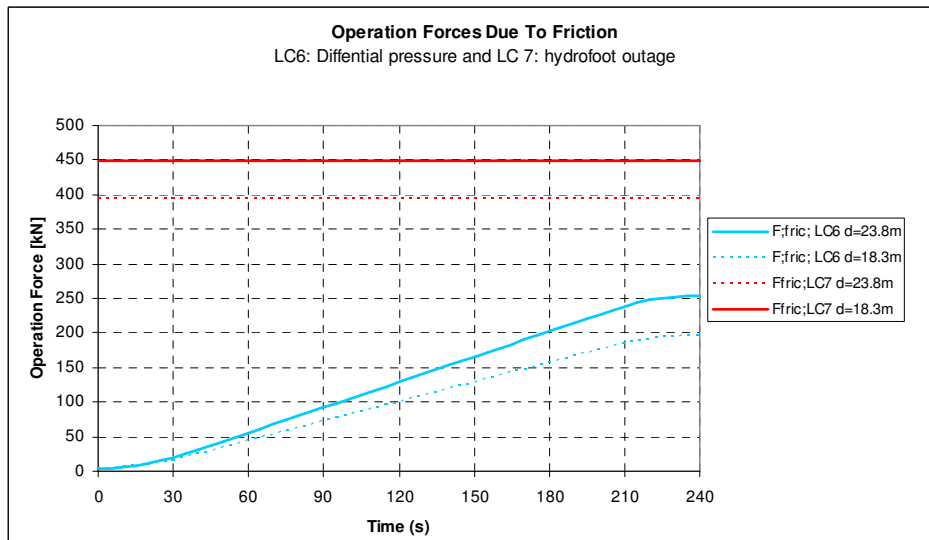
Figure 93: Operation forces due to friction, differential pressure & hydrofoot outage

Total operation force:
Adding the friction, drag and inertial components the total operation forces have been presented in the figure below.
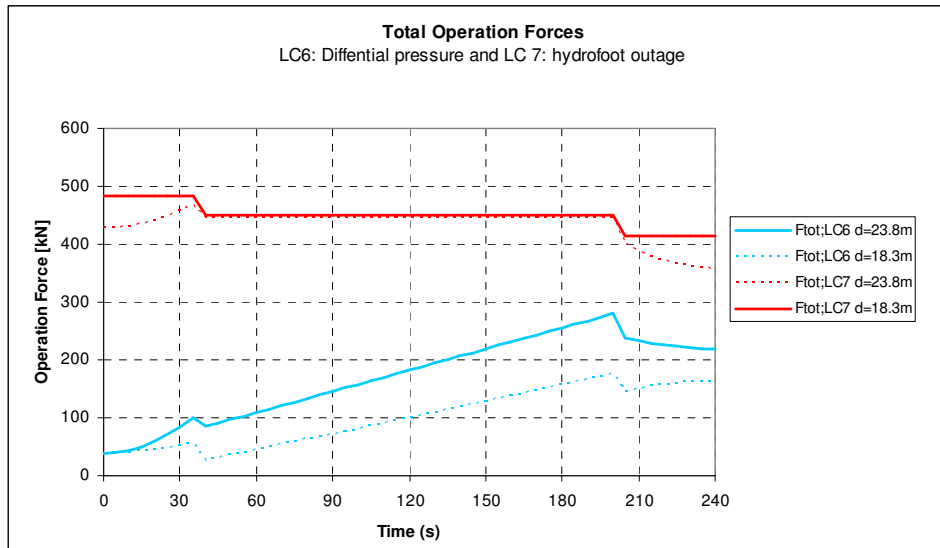
Figure 94: Total operation forces

17.3.3 Lay-out and design of the linear friction wheel drive

Basic principle:
In consultation with experts form DHV and civil/mechanical expert ir D. Ros (MRCONSULT B.V.) a linear friction drive mechanism has been chosen to provide the gates motion. The basic principle of such a mechanism (presented in figure below) is pressing two rollers against a member, opposite of each other. By turning one or both of the rollers, the member is then move along its normal axis. The movement is provided by the friction between the roller and the member, such the torque in the wheel is transmitted as a normal force to the member. The larger the force required to move the member, the harder the rollers must be pressed against it, in order to

provide sufficient friction (traction) to prevent slipping and the following must hold: $F > \dfrac{M}{R \cdot f}$
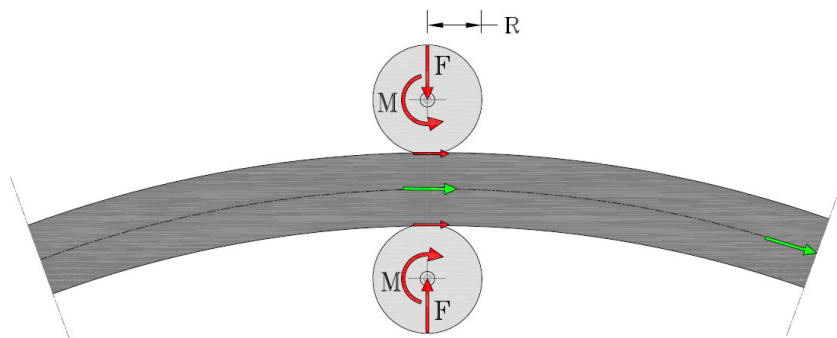
Figure 95: Basic principle of a friction drive mechanism

Common practice [42]
Friction wheel drives are commonly used for the actuation of large Ferris wheels, one of the most well known examples being the London eye, which diameter is 135 m. Also the Great Wheel of Beijing (Ø198 m) uses a hydraulic friction drive unit, capable of delivering a drive force of 900 kN, more then double the required force to operate the sliding arch gate. These large mechanisms use multiple drive units, and reinforced rubber or

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[42] HITCHCOX A. (2008), *Hydraulics power the Great Wheel of Beijing,* Article Retrieved from, www.hydraulicspneumatics.com, 7-12-2011

polyurethane wheels to provide sufficient traction. In case of the Great Wheel of Beijing, the wheels are pressed on the circular rim by means of hydraulic presses.

Hydraulic motors are used to supply smooth and well controllable movement. The hydraulic control supplies all motors within an assembly group with the same flow, a simple means of synchronizing the torque at the respective wheels, which is important for low wear and smooth motion. The hydraulic cylinders, pressing the wheels against the rim, can also be controlled, increasing pressures in humid or rainy conditions. The advantages of using hydraulics are obvious for this application. Hydraulics combine extremely high power density with low maintenance requirements and produces smooth, slow motion with low heat generation.

a. the London eye, Europe's largest Ferris wheel
Ø = 135 m

b. Friction drive mechanism

Figure 96: Friction drive mechanism of the London Eye Ferris wheel, [wikipedia]

Application for the sliding arch gate:
The application of a (hydraulic) friction drive unit, like described above, for the sliding arch gate, seems suitable, as the conditions under which it would operate and the forces to be applied are similar. Major differences being a more maritime environment, which would likely only enhance the use of hydraulics and the relatively short duration usage, 2 (operations) × 4 minutes every hour (assuming a lock cycle takes approximately 1 hour.

The main advantages of a friction drive mechanism for the sliding arch gate are:
- Friction drive also supports the gate in horizontal direction, without having to adapt the design
- Rubber steel contact, provides a 'soft', low wear connection. In addition wear remains confined to the rubber wheels, which can also be designed to withstand substantial wear.
- Smooth controlled movement, as mentioned above.
- Very suitable for moving curved objects in a circular path
- Simplified operation: No rails, cables, carriages etc.
- Easy access, if required whole unit can be disconnected form the lock head and removed
- Fixed mechanism, actuation system does not move along with the gate.

Although drive mechanisms exist that can deliver even larger forces, little is know about the exact design of such a mechanism and the design is therefore only illustrative. If further research does somehow show the mechanism is not suitable then also other actuation system can also be considered:
Apart from the friction drive also other alternatives have been considered:
- Toothed gear mechanism: Similar to the friction drive but then with gear instead of wheels. Has a higher load capacity, but more wear and maintenance sensitive
- Locomotive: Locomotive on two sides required. Curved tracks and high loads, especially radial loads due to differential pressure, may result in wear problems. Less smooth and controlled movement of the gate
- Electro magnetic propulsion, as mentioned will cause significant energy consumption.

Lay-out and required installations

Little or no other references and design guidelines have been found in order to make a more accurate design, considering dimensions, number of wheels power etc. Therefore an illustrative design has been made along the lines of the design of the friction drive units of the London Eye and the Great Wheel of Beijing.
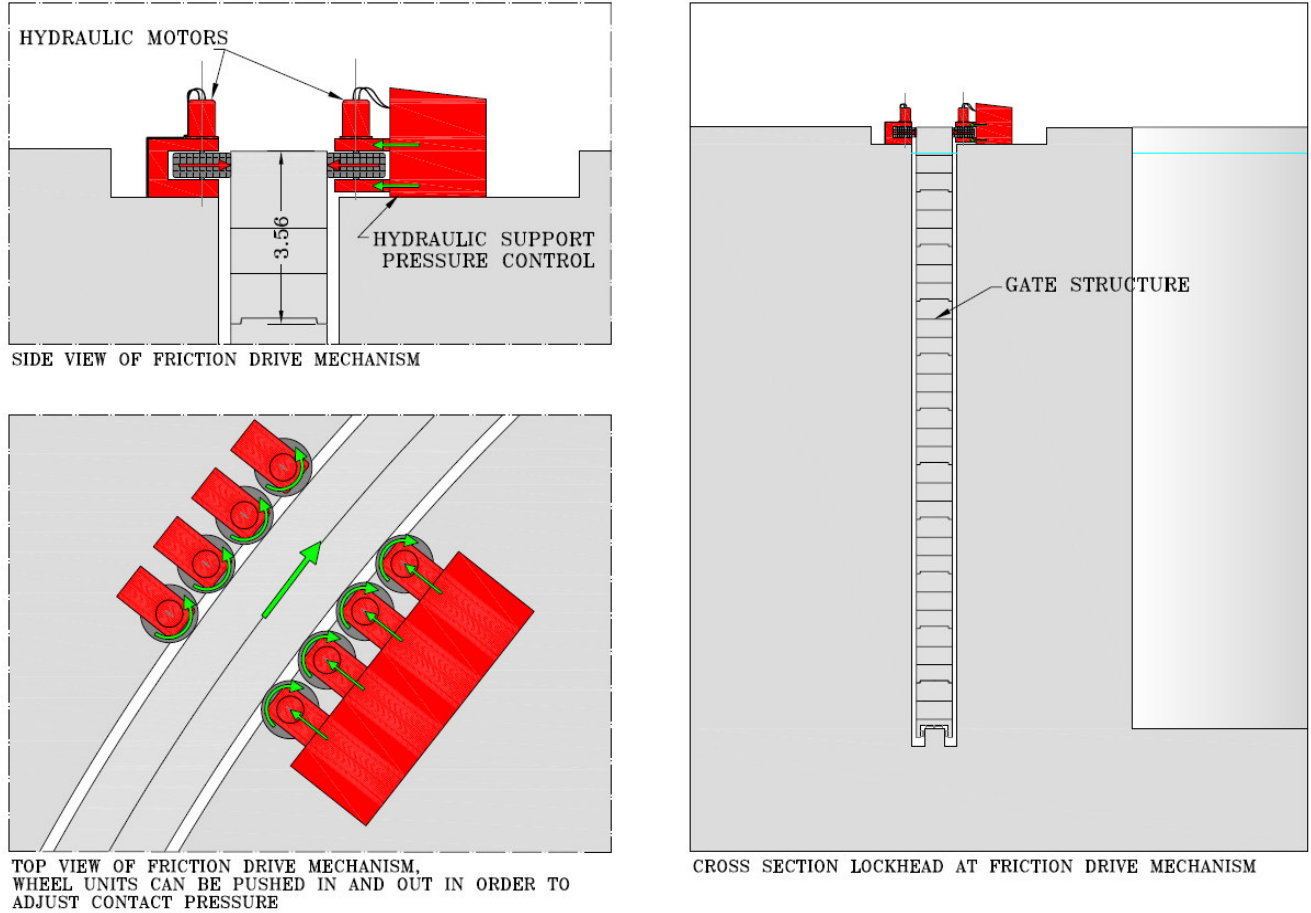
Figure 97: Hydraulic Friction Drive Mechanism

Remarks and assumptions on design and lay-out

− The number of wheels presented in the figure above is arbitrary and has been assumed according to the design of the large Ferris Wheels presented in the previous. The four sets of wheels can be powered by two different units, of which one can function as back-up system. However a detailed mechanical design should be made.

− The hydraulic press units that regulate the contact pressure between the wheels and the gate structure only have to be situated on one side of the gate. Considering the available space they have been situated on the inside, and here also the hydraulic pressure supply unit can be situated, which supplies the presses and hydraulic motors.

− A walk bridge over the recess can provide easy access to the hydraulic unit. Also the hydraulic lines can run over this bridge in order to supply the hydraulic motors on the other side.

− The top module has to be a bit higher in order to supply a rolling surface for the wheels. And the top part of which, will be reinforced with stiffeners in order to transfer the contact loads. Also, in order to maintain wheel contact of all the wheels, the top module should be extended. As can be seen in the figures chapter 12.

− The steel rolling surface can treated with aluminizing coating which has excellent bonding properties and provides excellent wear and corrosion protection and also promotes traction. Incase the obtained traction is not sufficient the steel surface can also be profiled.

− The top module has to be extended in order

18   COSTS AND VALIDATION

In the previous chapters the design of the Sliding Arch Gate has been worked out, considering the most governing boundary conditions from the Panama Canal Expansion Project (PCEP). However, in order to draw a conclusion on the validity of part [3] of the hypothesis: that new/innovative concepts could prove to outperform up-scaled conventional technologies, the gate's design and its performance should be evaluated.

This chapter will therefore give a comparison of the gates performance with conventional technologies considered for the concept design of the PCEP (Rolling and Mitre Gates) and will evaluate the general performance of the Sliding Arch Gate according to the future requirements of lock gates, stated in chapter 7. The evaluation is not necessarily geared towards proving the new/innovative Sliding Arch Gate will perform better or not, as more in depth research considering optimization and whole lifecycle costing is required to reach consensus on this. But it will rather focus on whether or not further research is useful, and if the new concept could prove to outperform conventional technologies.

- In paragraph 19.1 a general qualitative evaluation is given, considering the requirements for future lock gates as derived in chapter 7.
- In order to put the design of the Sliding Arch Gate into perspective, a quantitative comparison has been made with conventional technologies considered for the PCEP, in paragraph 19.2 considering the indicative construction costs and the effects of water consumption.
- Finally, in paragraph 19.3 consensus is reached on the validity of the new/innovative concept of the Sliding Arch Gate, and if the hypothesis can be justified. This paragraph therefore represents a conclusion on Phase 3 'Design and Validation' of this master thesis project.

18.1 General evaluation: Requirements for future lock gates

In chapter 7 'Field of innovation: Objectives and Requirements for future lock gates' it was concluded upon a set of primary and secondary requirements according to which the Sliding Arch Gate will now be evaluated. These requirements have been listed below:

Primary requirements:
4. The reliability and safety of operation is paramount and the design must be geared towards maximizing this.
5. The accessibility of the lock may not decrease (limited head clearance etc.)
6. Water consumption should be kept to a minimum

Secondary requirements:
4. Use of space should be kept to a minimum
5. Minimizing energy consumption must be take in to consideration
6. Minimize construction and maintenance costs.

Whole lifecycle costing
The whole lifecycle costs (WLC) have not been added to the list, only indicative construction/maintenance costs. Optimum design regarding the above will thus automatically lead to a lower a WLC. Further the WLC is almost impossible to determine or even hard to guess in such a low detailed phase and is very project specific.

Reliability:

Evaluation:
In chapter 7 the requirement of Reliability has been expressed as a low rate of break down, low maintenance interruption, high redundancy and adequate provision against flood events. The Sliding Arch Gate is evaluated below according to the design characteristics related to reliability (Chapter 7):
- Simplicity: Due to the Pin Support System, the operation of the gate becomes somewhat more complex, as there are now 3 systems (instead of 2) essential for the operation of the gate; actuation, guidance and supporting system. The Pin Support System is a never before applied technology for lock gates, and therefore present uncertainties about its performance
- Maintainability and inspectability: No moving/mechanical parts that are hard to access. Gate does not have to be removed. Only paint work.

- o Hydrofeet can be removed, by disconnecting the vertical stiffening pipe from the top and bottom module and can temporarily be replaced by a dummy (only for stiffening purpose) as the 6 remaining hydrofeet have sufficient capacity to operate without.
        - o Light UHMPWE sliding surface plates easy to inspect, remove and install by diver, due to bolted connection.
        - o Nylon sockets can be removed is required, though required maintenance is not expected
        - o Incase paintwork has to be preformed on the gate structure, the modules requiring maintenance can be removed and painted adjacent to the lock or at a special maintenance dock.
    - − Inspectability: Same as above, inspection of sliding surface can be preformed by divers.
    - − Redundancy and vulnerability:
        - o Pin Support System is the most vulnerable part, see above.
        - o Gate structure, due to its slender design is vulnerable to uneven, unsymmetrical loads, especially during transition. Therefore uneven wave loads and loads during transition have been taken into account. The modular design is a point of attention, though modules are stiffly connected.
        - o Hydrofoot installation:
            - ▪ Sliding surface: Excepted wear will only improve the performance of the hydrofoot system as the hard steel hydrofoot, scrapes the surface to its own operating optimum. If major damage where somehow inflicted, it will show in the operation of the gate, and specific plate can be replaced. A damaged sliding surface will not cause damage to other sub-system, as the gate is designed to be <u>able to operate without hydrofeet functioning if necessary.</u>
            - ▪ As a precaution measure, <u>the sliding surface has been elevated</u>, preventing debris and sediments accumulating on the sliding surface. The high volume flow through the hydrofoot will also wash sediments and debris of the sliding surface, and larger part will be pushed off the sliding surface by the front of the gate. Of course there is always a possibility of excessive debris, blocking the gates operation, but this applies to almost any gate type. However, here the elevated sliding surface diminishes this risk.
            - ▪ Inside the gate's structure there are two pump installations, which can operate the hydrofeet independently. Thus if one breaks down the other can take over, or if one is in maintenance the other can operate.
        - o The actuation system
        - o Flooding
            - ▪ The gate has been designed to withstand flood levels, as the retaining height during a flood is significantly less then during operation and the gate will maintain downward pressure when submerged.
            - ▪ The installation rooms of the hydrofeet are closed of with a water tight hatch, with air vents above expected flood levels, to keep pumps and electrical equipment dry.

<u>Comparison:</u>

Considering the above and comparing with technologies as Mitre Gates and Rolling Gates, for which both rely on permanently submerged moving parts and mechanical part subjected to significant wear phenomena:
- o Lower wheel carriage of the Rolling Gate
- o Hinge's of the Mitre Gate.

The Sliding Arch Gate does have potential to out perform these conventional technologies when considering the reliability requirement, or at least it can be assumed it will perform on a comparable level. <u>However, the complication of operation by the support system, should be thoroughly investigated in order to reach consensus on this</u>. As it adds an extra system which is essential to the gates operation, however it is designed such that it can be easily inspected and maintained and the sensitive/vulnerable part are all easy to access.

<u>Considerations:</u>

In search of improving the gate's performance given this requirement, the following considerations are listed:
- o It may be considered to increase the recess dimension slightly to allow painting and maintenance in the recess (also requiring bulkheads and pumps for emptying the recess), though this presents a tradeoff with optimizing water consumption.
- o Further research on the Pin Support System is required to optimize design and investigate if its performance can reach the reliability and safety standards.

Safety

Evaluation:

In chapter 7 the requirement of safety has been expressed as the resistance to failure, considering unusual / extreme loads and the reliability of safe operation. The Sliding Arch Gate is evaluated below according to the design characteristics related to safety (Chapter 7):

For the design of the lock gates safety is characterized by the following:

- Resistance to extreme / unusual loads: Accidental loads due to earth quakes, ship collisions, etc. have not been taken into account during the preliminary design of the Sliding Arch Gate. However, the gate has been designed considering fatigue loading under normal operation conditions. This limit state strongly reduces the permissible stresses in the structure for cyclic loading, and therefore the gate has much larger load capacity when considering (non cyclic) incidental loads. However, this should be checked, though it can also be stated that the gate can be designed to with stand even larger loads.
- Stability: Allowing certain deformations/local failure events without introducing progressive collapse.
  - o Deformation capacity: When considering unusual loads and especially impact loads, sufficient deformation capacity is required to absorb the energy. When considering ship impacts the (Tension) Arch Gate has great deformation capacity due to its low stiffness and high cross sections area, and can therefore absorb large amounts of energy without substantial increase of the normal forces in the gate considerably, when loaded by a concentrated (impact) load. However additional safety measures may be considered (see accessibility)
  - o Possible pin failure:
- Reliability: As described above.

Comparison:

The safety to failure can be assumed to be around the same level as that for conventional technologies, however it must be investigated if the modular design does not present unnecessary risks considering the failure of 1 pin during operation or if the redistribution of support loads can be handled by the module connections and support system.

Considerations:

In search of improving the gate's performance given this requirement, the following considerations are listed:

- o Ship collision investigation, determining possible redundancy to ship impact.
- o Investigation to possible effect of a pin failure, concluding on if the gate design should be modular or not.

Accessibility:

Evaluation:

In chapter 7 the requirement of accessibility has been expressed as the accessibility of the lock and it's connected reaches which can also be described as the capacity and availability of the lock. The Sliding Arch Gate is evaluated below according to the design characteristics related to accessibility (Chapter 7):

For the design of the lock gate the accessibility is characterized by the following:

- Operation speed of the gate: The time needed to operate the Sliding Arch Gate is between 4 and 5 minutes. The actuation system has been designed to operate the gate in 4 minutes and the Pin Support System will require approximately 30s – 60s to complete this operation. This is within the required operation time (5 minutes) presented by ACP and due to the low water displacements and low friction during normal operation conditions, the speed may be increased considering future design optimizations.
- Effects of the gates design on overall lock cycle time:
  - o Operate with small head
  - o Water consumption
- Head clearance: The head clearance is unlimited, and gate structure will not harm the accessibility of the lock more then the limitations presented by the lock dimensions itself.
- Additional safety measures: Although the gate has large deformation capacity; the water tightness may be harmed, due to the modular design, as a result of a ship impact. Therefore applying a double gate lay-out or other safety measures may be considered. However this consideration is very project specific as it is dependent on probabilistic design, taking into account traffic intensities, how ships are moved through the locks, possible consequences etc.

Comparison:
The Sliding Arch Gate does not effect the accessibility more then conventional technologies (rolling and Mitre Gates), and is even expected to out perform, considering:
- o Mitre Gates at such large scale may take longer to operate, due to the huge amounts of water displacement associated to rotating the miter leaf through the water. It is even questionable if this operation is even (realistically) possible considering possible water level differences over the gate due to waves, currents and turbulence during transition.
- o The Sliding Arch Gate will improve the lockage capacity of the lock system due to its reduced water consumption.

Considerations:
In search of improving the gate's performance given this requirement, the following considerations are listed:
- o Water consumption optimization
- o Gate speed optimization

Water consumption:
Evaluation:
In chapter 7 the requirement of minimizing water consumption has been expressed by the lost lock area or passive volume. In the figure below an indication is given of the lost area, considering single gate application and the boundary conditions considered for the design of the Sliding Arch Gate. In order to relate this figure, estimates of the lost area for rolling and Mitre Gates have also been presented. These estimates have been made according to the conceptual design of the PCEP by ACP.
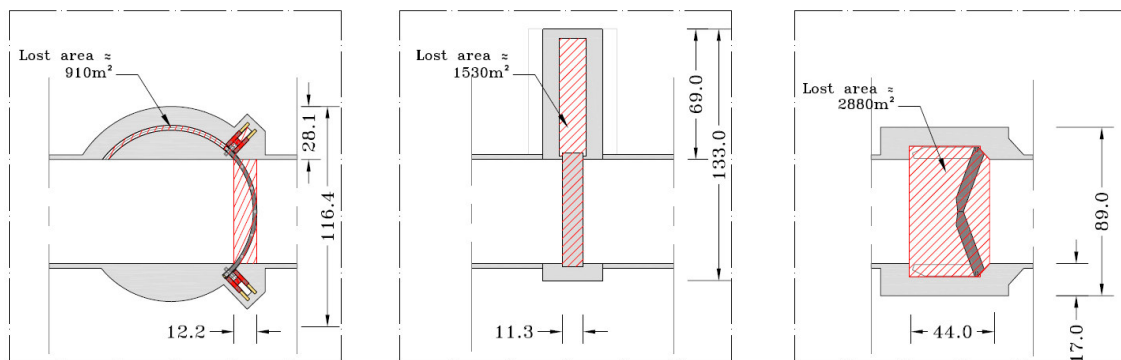
Figure 98: Water consumption of the Sliding Arch Gate, compared to conventional technology

It has not been achieved to eliminate water consumption; however significant improvements compared to conventional technologies (rolling and Mitre Gates) have been made. A Vertical Lift Gate will still remain the ideal solution when considering water consumption, however the limitations of its applicability due to its limited head clearance governs the overall performance and has not been taken into account for comparison.

The reduction of water consumption, compared to Rolling Gates, can theoretically improve the locks capacity by approximately 2.1%, which is equal to 7.7 days of operation per year. This could either be used for preventive maintenance improving the reliability, or increasing the number of transits to increase revenues. Which incase of the PCEP could means millions of dollars annually (see next paragraph)

Considerations:
In search of improving the gate's performance given this requirement, the following considerations are listed:
- o Optimization of water consumption by increasing the gates radius (less curvature), however this presents the following tradeoffs:
    - o Increasing the radius will increase the use of space
    - o Loads on the gate structure and lock head structure will increase
- o Optimization of water consumption by decreasing gate width
    - o Only limited reduction possible, considering gate deformations and structural implications.

Use of space:

Evaluation:

In chapter 7 the requirement of minimizing the use of space has been expressed by the space used by the lock head structure adjacent to the lock, or the lengthening of the total lock complex. For illustration see Figure 98.
- o Minimal length increase of the lock structure.
- o Use of space adjacent to both sides of the lock:

Comparison:

In if and how space related requirements are limited, strongly differs per project:
- o In some cases the length should be kept as short as possible (not only considering water consumption) and the use of Mitre Gates is ruled out.
- o In other cases the space used adjacent to the lock is governing, like for the Ijmuiden project where there is limited room available on either side of the lock, ruling out the application of Rolling Gates, as they use considerable amount of space on 1 side of the lock. Whereas the Sliding Arch Gate uses a comparable width but then distributed on both sides of the lock, which may prove limiting incase there is no space on one side and abundant space on the other.

Considerations:

In search of improving the gate's performance given this requirement, the following considerations are listed:
- o By varying the radius of the gate structure, some slight changes can be made. However when reducing the required length by increasing the radius, the use of space adjacent of the lock increases and vice versa.

Energy consumptions

Evaluation:

In chapter 7 the requirement of minimizing energy consumption has been expressed by the amount of energy required for the operation of the lock gates and the influence of the lock gate design on the total consumption of energy by the lock. For the design of the lock gates the energy consumption is characterized by:
- – Required operating equipment: The use of hydrofeet does not (significantly) influence the friction compared to rolling friction of carriages [36]. Thus energy consumption by the actuation system in not decreased, and the hydrofoot installations do increase the total energy consumption. Also incase of hydrofeet failure, the actuation system has been designed to operate with increased friction, and is thus over designed and may not operate at optimum efficiency.
- – Displaced water volume: As the gate is slender and 'cuts' through the water the water displacement will be minimal and therefore also the drag forces and inertial forces of the added water mass. Also the lighter gate structure will reduce inertial forces
- – Water consumption: As described above.

Comparison:

It is can be assumed that the energy consumption of the Sliding Arch Gate will be higher then that of a Rolling Gate. As the friction caused by the hydrofeet is in order of the friction of carriages of Rolling Gates and the hydrofeet require extra pump capacity.

Considerations:

In search of improving the gate's performance given this requirement, the following considerations are listed:
- o Apply back-up actuation system which can be used incase of increased friction, optimizing efficiency. Though cost benefit analyses should be preformed.

18.2 Application for the Panama Canal Expansion Project

In order to put the design of the Sliding Arch Gate into perspective, a quantitative comparison has been made with conventional technologies considered for the PCEP. First the adaptations to the design of the Sliding Arch Gate are discussed, which are required to compare the Sliding Arch Gate to the current double lock gate lay-out design. Then comparison is made considering the indicative construction costs and the economic consequence water consumption.

18.2.1 Adaptations to the design

In order to compare the Sliding Arch Gate to the conventional technologies considered for lock gate design by ACP (rolling and Mitre Gates), some adaptations must be made:

- Double lock gates: Considering continuity of operation and safety, the lock complexes of the PCEP have been fitted with double lock gates. Thus in order to make a realistic comparison considering the PCEP the design of the Sliding Arch Gate must also be adapted to a double gate configuration. This can be done by increasing the gates radius, in order to fit the Pin Support System in the inside support segment of the lock head structure, see Figure 100. Also the end of the recess of the downstream gate must able to be closed off, if the downstream gate is out of operation and only the inner gate is used. The increased radius will lead to larger normal forces in the gate structure, and must be designed accordingly (same holds for support system and lock head).

- Retaining negative head: In case of dry lock maintenance, all three lock chambers must be emptied entirely. To allow this the upstream and downstream gates must be able to retain water over their full height, which incase of the downstream gate means it must retain a negative head. In case of the Sliding Arch Gate, using the Pin Support System retaining a negative head is possible though the following adaptations of the design of the down stream gate should be made/checked:
  - o The buckling stability of the arch should be checked. This may possibly lead to an increased gate width, in order to provide sufficient stiffness.
  - o The vertical plates of the gate modules near the support may have to be thickened (section B, figure Figure 72) considering the support pressures.
  - o Flow of forces in the lock head structure should be checked if additional reinforcement may be required concerning splitting forces due to the compressive support load and bending moments in the lock head.

In the figure below an impression is given of the Sliding Arch Gate applied for the PCEP.
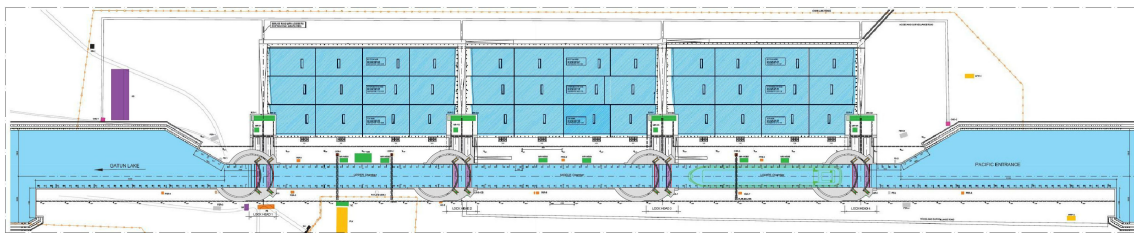
Figure 99: Impression of the Sliding Arch Gate applied at the Pacific lock complex for the PCEP

18.2.2 Rough construction cost estimation

In the tables below, rough cost estimates have been made for the Sliding Arch Gate and Rolling Gate, at lock head 3 considering the boundary conditions applied for the design of the Sliding Arch Gate. The results are only indicative, to determine if the costs of the Sliding Arch Gate are in the same order of magnitude as that of conventional (applied) technology. The cost estimations have been made assuming the following.

- Unit prices according to ACP[26] date. 2002.
- Cost of operation equipment is roughly the same, and maintenance costs significantly reduced.
- Gate structure of the Rolling Gate determined according to figures used by ACP.
- Costs concerning excavations, seals overburden etc. are small and will be approximately equal considering both alternatives.
- Average rebar percentages over the whole lock head structure are assumed to be equal.

Table 29: Cost estimation of Rolling Gate and Sliding Arch Gate

Estimaiton of constructions costs Rolling Gate						
	Quantity		Unit price		Total	
					[$]	
Gate structure						
Weight Rolling Gate 2×	7887.99	ton	6173*	$/ton	48.69	mln.
Lock head						
Reinforced concrete	143274	m³	120	$/m³	17.19	mln.
Rebar						
Percentage	0.95%					
Rebar volume	1356.00	m³				
Total	10644.57	ton	875	$/ton	9.31	mln.
Total Rolling Gate				$	**75.20**	**mln.**

Estimation of constructions costs Sliding Arch Gate						
	Quantity		Unit price		Total	
					[$]	
Gate structure						
Gate structure 2×	5911.54	ton	6173***	$/ton	36.49	mln.
Operation equipment Pin Support						
Steel structure pin and wagon 4×	1903.93	ton	6173*	$/ton	11.75	mln.
Hydraulic press	8	pcs		$/pcs	1.00	mln.
Lock head						
Total reinforced concrete	273360.0	m³	120	$/m³	32.80	mln.
Reduced length of lock wall	146.0	m	95538.1**	$/m	-13.95	mln.
Rebar						
Percentage	0.95%					
Rebar volume	2587.18	m³				
Total	20309.34	ton	875	$/ton	17.77	mln.
Total Sliding Arch Gate				$	**85.87**	**mln.**
Total Rolling Gate				$	**75.20**	**mln.**
Difference				$	**10.67**	**mln.**
					14.19	**%**

Estimated cost of Rolling Gates, including manufacture, operation equipment, transport, installation and testing.
*** Determined from ACP bill of quantities, considering 30m segments. Excluding costs for excavation, backfill ect. as these have also not been considered for lock head.*
**** Due to the modular design and the related ease of manufacture and series production this unit price could be reduced, though further research must prove so.*

18.2.3 Water consumption: Possible economic consequences

In the figure below the water consumption of a double lock gate lay-out for the Sliding Arch Gate, a rolling and a Mitre Gate are illustrated. After, the possible economical consequences of water loss, due to lock gate design, are put into perspective by quantifying these according to two different approaches: One focusing on the water saving aspects and one purely on capacity based aspects. In the following paragraph a conclusion is given, discussing the necessity for implementation of water loss aspects into whole life cycle costing of lock gate designs. It must be remarked that the quantifying approaches are illustrative and have been made in hind-sight of the proposed design made by ACP. When taking into account these aspects in the initial design stage, many more factors play a role, and the results only give an illustration of the possible economic consequences.
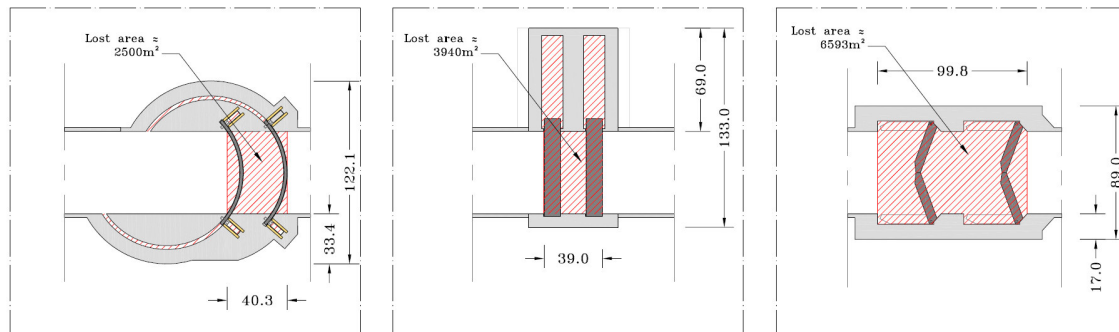
Figure 100: Water consumption for double lock gate lay-out

In the figure above it can be seen that also for a double lock gate lay-out as required for the PCEP the Sliding Arch Gate still gives a significant reduction of water loss. Considering the effective lock area to be 55m×488m the relative water loss becomes:

Table 30: Relative water loss, double lock lay-out as proposed by ACP

	Lost Area [m²]	Relative water loss
Sliding Arch Gate	2500	8.5%
Rolling Gate	3940	12.8%
Mitre Gate	6593	19.7%

From a water saving perspective [26]:
In order to reduce the water usage of the new lock complexes of the PCEP, reutilization basins will be built that can save up to 60% of the water used for locking. In order to build these reutilization basins an investment was required of approx $620 mln. Taking this into consideration, 1% of water saving is worth about 620/60 = $10.33 mln dollars, considering investment costs into water saving.
When considering that the Sliding Arch Gate uses 4.2% less water this could expressed as a possible saving of 4.2%×10.33mln = $44.37 mln, which is significant. Reducing the estimated extra investment of the Sliding Arch Gate.

From a capacity perspective [26]:
Looking from another perspective, and considering the possible increased capacity due to lockage time required for filling and emptying the lock chambers, one can conclude that reducing the area that needs to be leveled every lock cycle, linearly reduces the lock cycle time. Thus a lock gate design which decreases the locking area by 4.3% (without reducing the effective area used transferring ships) could theoretically increase the lock capacity by approximately 2.1%, considering that the time required for filling and emptying is approx 50% of the lock cycle time[10]. Accounting that the new set of locks has a maximum capacity of 270 mln PCUM ton annually, which is projected to be reached in 2032 considering the expected growth rate in Figure 101. And considering an approximate fee of $12.01 p.ton. A capacity increase of 2.1% could theoretically increase revenue by 0.021× 270×12.01 = $68.1 mln annually.

The commercial life cycle of the gate structure is 50yrs, and are therefore expected to operate until 2064, 32 years after the third lane has reached its maximum sustainable capacity. The increased capacity could therefore possibly result in 32×68.1= $2179 mln extra revenues, during the design life of the gate structure, dwarfing the increased construction costs of the Sliding Arch Gate, even if the extra initial investments are discounted, considering an interest rate of 6%: 2179-10.67*1.06^{50yr} = $1983 mln.
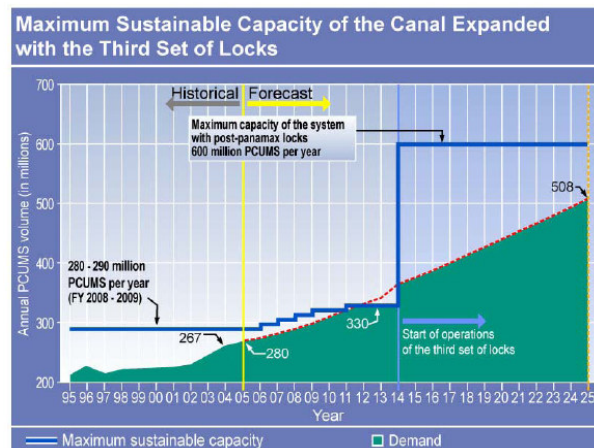
Figure 101: Projected capacity and demand growth of the expanded Panama Canal [14]

In addition, regarding also the direct investment costs of $5.25 billion to double the canals capacity, each percent capacity increase is approximately worth $52.5 mln and a 2.1% increase is therefore worth approximately $110.25. mln This would also justify an average, additional investment cost of 110.25/8 = $15 mln. per lock head.

Putting this into perspective of the additional investments of the Sliding Arch Gate ($10.67 mln), this reduces to: $10.67 mln – $15 mln = -4.33 mln.
Hence the Sliding Arch Gate becomes more economically attractive considering these investments.

18.3 Validation

In order to put the design of the Sliding Arch Gate into perspective, a quantitative comparison has been made with conventional technologies considered for the PCEP, taking into account the indicative construction costs and the effects of water consumption.

From the indicative construction costs, it appeared that the initial investment to construct the considered lock head using the Sliding Arch Gates would be approximately 10.5% higher then that for Rolling Gates, a $7.87mln difference. This figure, is however a rough estimate, and does not take into account costs involved in the further development and prototype testing of the Sliding Arch Gate. Further research and optimizations may change the economic picture either way, though can be assumed that the costs are in the same order of magnitude.

However, the Sliding Arch Gate reduces the water consumption of the new Panama Canal locks with approximately 4.3%, due to the decreased 'wet' area required for the lock gate operation. The possible economic consequences of water loss due to lock gate design have been investigated, and appear to be significant, to say the least, saving possibly an investment of $44.37 mln in water saving utilities. However, when considering a possible increased operational capacity of 2.1% (7.7 full operation days per year) due to reduction of the filling and emptying times, the economic consequences are much greater, equalizing possible investments of approximately $110.25 mln and adding $2179 mln in extra revenues during the 50yr design life of the gate structure as the expanded canal is expected to reach is maximum capacity in 2032.
Putting these numbers into perspective with the total initial investments in the lock gate and lock head structure:
  − The possible investment reduction of $44.37 mln, considering water saving measures amounts to 7.5% of the total investment of lock gates.
  − The possible investment reduction of $110.25 mln., considering capacity increase, approximately 1.5 time the extra investment required for applying Sliding Arch Gates.
  − The extra revenues minus the initial discounted investment, considering an interest rate of 6% amounts to $2179-10.67*1.06^{50yr} = $1983 mln.

The above presented quantitative figures are very specific for the Panama Canal's situation, regarding a capacity driven design, rather then a dimension driven design, which holds for most large maritime locks. For example; Ijmuiden, Berendrecht, Le Havre and Mersey Docks to name a few. Though for a number of possible future projects (listed below), with similar situation to the PCEP, and which fit the field of innovation (large, high head locks) the same considerations do hold.

- Possible 4th lane expansion of the Panama Canal
- The Thai Canal
- Expansion of the great lake locks
- Some large inland waterway locks, where large ships navigate lower reaches of inland waterway systems.

In addition, a more general evaluation has been presented considering the performance according to the future requirements of lock gates, derived in chapter 7. It appeared that the Sliding Arch Gate does not under-perform compared to conventional technologies and even may even outperform conventional technologies considering
- Water consumption
- Accessibility
- Use of space (in specific conditions)

However the performance considering, reliability and safety are largely dependent on the operational performance of the pin-support system and further research and testing will have to prove the reliability and safety are within acceptable levels. For the pioneering design of the Sliding Arch Gate it has been attempted to diminish the risks involved in using the 'complex' support system by:
- All moving/mechanical parts are easy to reach and situated above water
- Preventive measures for blocking
- Whole Pin Support System can be lifted out and replaced by cranes.

Conclusion:

From the above it can be concluded that, although the Sliding Arch Gate requires higher construction costs, <u>it does have the potential to outperform conventional technologies</u>. This would probably become more apparent when determining the whole life cycle costs. Especially when considering large high head locks, that must transit large maritime (or comparable) vessels, where capacity driven design prevails and water saving measures are required. <u>Therefore part [3] of the hypothesis: that new/innovative concepts could prove to outperform up-scaled conventional technologies has been justified.</u> And additional research is recommended considering:
- Performance based optimizations of the gates design
- Probabilistic modeling in order to investigate if the required reliability and safety levels can be met

The detailed list of recommendations, concerning further research is given in chapter 20.

Further an unexpected eye-opener, considering the design of lock gates for large high head locks, was the possible economic consequences of additional water loss due to lock gate design. Which become more imminent when considering larger scale locks, as filling and emptying times increase together with issues considering water saving, of which the counter measures (reutilization basins) also increase the filling and emptying times. The figures presented on the previous pages, were only an indication, but proved to be so significant that a proper investigation considering these economic consequences is recommended, as the real economic and environmental picture is much more complicated. It can be stated that this aspect may not be neglected when designing large high head locks. Also when considering the design of locks at this scale and economic importance, other alternative measures to enhance water saving and capacity increase may also become interesting:
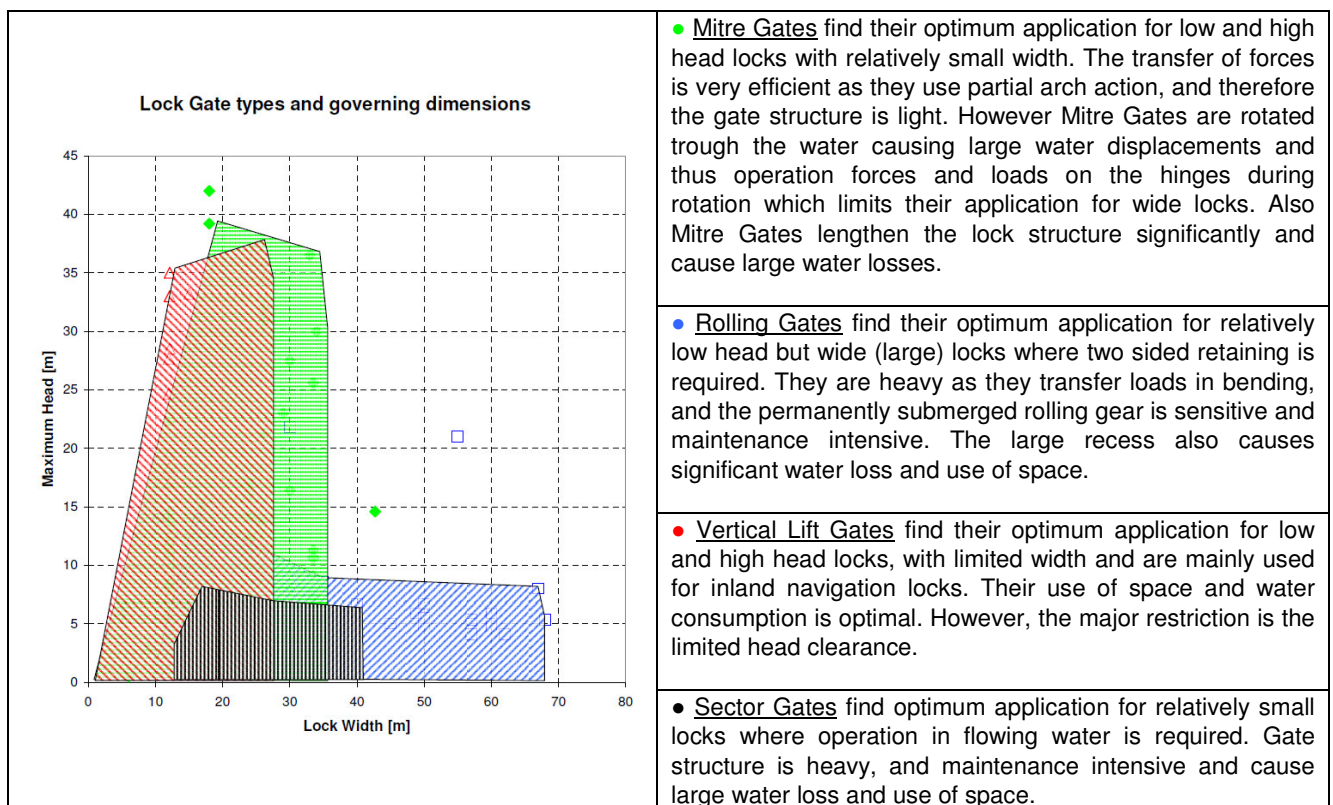- Pumps
- Variable lock chamber size
- Other…

19   CONCLUSION

This master thesis project has researched the need and possibilities of innovative lock gate design for future large, high head locks. Lock dimensions are increasing together with their water, time and energy consumption. And until now limited research has successfully pioneered new & innovative lock gates as alternative for traditional gate designs being scaled up. The goal of this master thesis project was to develop an innovative gate design that diminishes the drawbacks of current technologies being scaled up, caused by the increasing dimensions of locks and fitting the future requirements for large lock design regarding efficiency and performance.

Hypothesis**:** Lock dimensions are increasing [1], efficiently scaling up traditional gate designs is finite [2] and new/innovative concepts could prove to outperform up-scaled conventional technologies [3].

Considering the results of this master thesis project, the following conclusions has been drawn, eventually leading to the justification of the hypothesis and the following final conclusion:

I.   A historic research and a data analysis have been preformed, analyzing over 220 of the worlds largest locks throughout history. In total over 20 types of lock gate have been found and 4 main lock gate types have been defined; Rolling Gates, Mitre Gates, Vertical Lift Gates and Sector Gates. Each having a specific application area where their performance can be assumed to be near optimum, see figure below:

● <u>Mitre Gates</u> find their optimum application for low and high head locks with relatively small width. The transfer of forces is very efficient as they use partial arch action, and therefore the gate structure is light. However Mitre Gates are rotated trough the water causing large water displacements and thus operation forces and loads on the hinges during rotation which limits their application for wide locks. Also Mitre Gates lengthen the lock structure significantly and cause large water losses.

● <u>Rolling Gates</u> find their optimum application for relatively low head but wide (large) locks where two sided retaining is required. They are heavy as they transfer loads in bending, and the permanently submerged rolling gear is sensitive and maintenance intensive. The large recess also causes significant water loss and use of space.

● <u>Vertical Lift Gates</u> find their optimum application for low and high head locks, with limited width and are mainly used for inland navigation locks. Their use of space and water consumption is optimal. However, the major restriction is the limited head clearance.

● <u>Sector Gates</u> find optimum application for relatively small locks where operation in flowing water is required. Gate structure is heavy, and maintenance intensive and cause large water loss and use of space.

II.   From the investigation into the future developments of the navigation infrastructures system it has been concluded that: A number of future projects will require lock gates that fall far outside of the application area of current technologies. One of the most well known of these future projects, the Panama Canal 3rd lane (see figure above), do not only require the up scaling of gate technologies in one direction but require large width <u>and</u> high head lock gates. <u>Confirming the first part of the hypothesis: 'Lock dimensions are increasing'</u>

III. The application of current technologies at this scale (large width <u>and</u> high) must be seen as 'unproven technology' and it is in no means to be assumed that up scaling conventional technologies to such an

extent will result in an optimal design. It is therefore concluded that <u>efficiently scaling up traditional gate designs is finite</u> and new/innovative concepts could possibly prove to be better suited for future large high-head locks. Confirming the second part of the hypothesis.

IV. The area of innovation, for which new/innovative concepts have been developed during this master thesis project, has been demarcated as the area not covered by conventional technologies; large, high head locks.

V. For the design of lock gates within the area of innovation, the future developments of the navigation infrastructure system will highlight the following requirements of lock gate design, geared toward reducing whole life cycle costs and reducing economic risks of the navigation infrastructure system:
   − <u>Reliability;</u> low rate of break down, low maintenance interruption, high redundancy and adequate provision against flood events
   − <u>Safety;</u> resistance to unusual loads, stability, reliability of safe operation.
   − <u>Accessibility;</u> the influence of the lock gate design on the <u>capacity</u> of the lock considering, restricted dimensions (head clearance), gate operation time, effects on filling and emptying times.
   − <u>Water consumption;</u> Volume of lost water every lock cycle due to inefficient use of the chamber area by the lock gate(s).
   − <u>Use of space;</u> Space required adjacent to the lock, or extra length of the lock structure required by the lock gate design
   − <u>Construction and maintenance costs:</u> Materials, volumes, constructability, maintenance requirements, transportability.
   − <u>Energy consumption;</u> Efficient operation systems, low loss of water

VI. The Panama Canal Expansion Project has been chosen as reference project, as it fits the area of innovation and is currently under construction. Supplying boundary conditions and a reference design to which comparison can be made.

VII. Considering the field of innovation and associated future requirements, a number of conceptual lock gate designs have been made. Of which the most 'promising' and 'technically challenging': *'the The Sliding (tension) Arch Gate'*. A new/innovative gate design that transfers the hydrostatic loads through arch action (tension) to the lock head structure, resulting in a slender gate design and slides in an out of the lock profile, using hydrofeet to eliminate friction and wear. This alternative was presumed to possess major benefits considering water consumption, reliability, accessibility and use of space. And in order to reach consensus on the validity of these presumptions, this gate was chosen for further research and design.

VIII. The design of the Sliding Arch Gate has been worked out to an operational level, and considering the governing aspects of design the following has been concluded:
   − The gate structure is arched and transfers the hydrostatic loads mainly through normal (tension) force to the supports. Resulting in a slender gate design, with a width of 2m spanning a 55m wide lock and retaining over 20m of water. The gate structure is build up from steel modules, which are connected by vertical stiffeners and can be disconnected in order to allow transport and assemblage of the gate.
   − The Pin Support System has been developed, to allow movement of the gate in the same direction as it has to be supported. Pins are inserted through the gate, and are supported in sockets in the concrete structure on either side of the recess. By doing so local moments in the concrete are avoided and the loads are transferred through tension by the reinforcement to the lock head structure and eventually to the foundation.
   − The lock head transfers the forces from the gate structure to the foundation. It is designed as a brace structure in order to equalize the large thrust forces which are a result of the arch action.

- − The recess dimensions have been kept to a minimum in order to promote water saving, ,made possible by the slender gate design. On each side of the gate there is a 0.25m gap, in order to allow water flow around the gate while it is moved.
- − Hydrofeet will be used to support the gate in vertical direction. Eliminating friction and wear, by creating a high pressure fluid film between the steel hydrofoot and the UHMWPE sliding surface. Separate pump installations (2) have been installed of which one is in operation an the other acts as back-up system.
- − Steel sliding shoes, which slide over UHMWPE sliding surface have been fitted along the bottom of the gate. These provide horizontal support and guidance during the gates movement.
- − A hydraulic friction wheel drive mechanism will provide the movement of the gate. It will supply smooth and controlled movement of the gate, and reduces wear and maintenance. It is powerful enough to be able to operate the gate without the hydrofeet functioning (full contact friction)

IX. The gates design and performance have been evaluated and compared to conventional technologies and the following conclusions, considering the future requirements and construction costs, have been made:

Conclusions on general performance (qualitative):
- − It appeared that the Sliding Arch Gate does not under-perform compared to conventional technologies and even may even outperform conventional technologies considering:
  - i. Water consumption
  - ii. Accessibility
  - iii. Use of space (in specific conditions)
- − The performance considering, reliability and safety are largely dependent on the operational performance of the pin-support system and further research and testing will have to prove the reliability and safety are within acceptable levels. For the pioneering design of the Sliding Arch Gate it has been attempted to diminish the risks involved in using the 'complex' support system by:
  - i. All moving/mechanical parts are easy to reach and situated above water
  - ii. Preventive measures for blocking
  - iii. Whole Pin Support System can be lifted out and replaced by cranes.

Conclusions on project specific performance (quantitative), The Panama Canal Expansion Project:
- − From the indicative construction costs, it appeared that the initial investment to construct the Sliding Arch Gates would be approximately 14.2% higher ($10.67 mln.)then that for Rolling Gates ($75.20 mln), a $10.67 mln difference.
- − However, the Sliding Arch Gate reduces the water consumption of the new Panama Canal locks with approximately 4.3%, due to the decreased 'wet' area required for the lock gate operation.
  - i. The possible investment reduction of $44.37 mln, considering water saving measures amounts to 7.5% of the total investment into lock gates.
  - ii. The possible investment reduction of $110.25 mln., considering capacity increase amounts to 18.7% of the total investment into lock gates. Almost double the extra investment required for applying Sliding Arch Gates.
  - iii. The extra revenues minus the initial discounted investment, considering an interest rate of 6% amounts to $2179-10.67*1.06^{50yr}$ = $1983 mln.

From the above it can be concluded that, although the Sliding Arch Gate requires higher construction costs, it does have the potential to outperform conventional technologies. Confirming part [3] of the hypothesis: that new/innovative concepts could prove to outperform up-scaled conventional technologies has been justified.

X. The major benefit of the Sliding Arch Gate; reduced water consumption and increased lockage capacity will only hold to its significance, concerning: Locks of which the design is capacity driven, where filling and emptying times are dominant for the whole lock cycle time, and/or for which water saving is related environmental limitations, like the Panama Canal Expansion Project (3rd lane). A number of expected future projects will present such conditions for example: 4th lane expansion of the Panama Canal, expansion of the Great Lake Locks, the Thai Canal.

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Final conclusion:

A number of future lock projects require lock gates of which the dimensions and loads fall far outside the application area of current technologies [1]. Simply scaling-up conventional technologies will not lead to optimal solutions [2], especially considering reliability and water consumption, which can significantly impact the locks capacity. New/Innovative Concepts like the Sliding Arch Gate can out perform up scaled conventional technologies [3] and compensate their initial investments by low/easy maintenance and increased lockage capacity, due to water saving. In case of the Panama Canal Expansion Project, this can possibly result in over a billion dollars in added revenues during the commercial life time of the gate.

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20   RECOMMENDATIONS FOR FURTHER RESEARCH

This master thesis project contains the pioneering work of a new/innovative lock gate; 'the Sliding Arch Gate', a design which has been worked out to an operational design level. In doing so many assumptions have been made and optimizations can be found to improve or justify its design. However the pioneering of the new technology formed the basis on which the final conclusion has been drawn. And it is shown that new/innovative concepts like the Sliding Arch Gate can possibly out perform up-scaled conventional technologies. Thereby, further research is justified and recommendations for further research are suggested in the following.

I.   For the concept development three alternatives have been considered. The sliding arch gate was presumed to be the most 'promising' and 'technically challenging'. However further research into new/innovated concepts is recommended and may provide other, even better alternatives.

II. The boundary conditions and design criteria, derived from the Panama Canal Expansion Project are limited to the making of a basic operational design. Therefore a detailed and optimized design should consider a full set of boundary conditions and design criteria, related to a specific project, especially considering accidental load conditions like earthquakes and ship impacts.

III. Modular design of the gate structure, proved to be technically feasible, and could be required if no extremely heavy lifting equipment is available. Limitation of the module weight and thus the number of modules was here determined by the available heavy lifting crane as a practical limit. Further research should investigate the economic feasibility of modular design taking into account:
   –   Manufacturing
   –   Transportation
   –   Probabilistic modeling considering the risks of possible pin failure.

IV. The structural design of the gate structure was basic, and limited to a fatigue and ultimate stress design according to the Euro code 3. It was assumed the modules react independently of each other. And that the 7 vertical stiffeners would provide sufficient rigidity while the gate is being moved. Detailed structural modeling using finite element methods should be performed for further design.

V.   The modules have been designed as built-up welded sections, made from steel plates. The plate thicknesses which have been determined from the structural design give an indication of the required cross section and weight of the gate. However the plate thicknesses are so large (0.12 -0.15m) that it is questionable if the assumed cross section design is optimal near the supports. Alternative methods of load transfer to the pins and cross section designs for the back sections (section B & C) of the gate should be considered, requiring complex modeling and an economically optimized design.

VI. The gates radius and width have been determined assuming practical values. Herein, optimizations can be found considering further decreases in water consumption. However this will present a trade-off with the use of space adjacent to the lock and gate structure weight and less favorable loading of the lock head structure.

VII. The Pin Support System is a never before applied technology for lock gates, and therefore present uncertainties about its performance. Further research on the Pin Support System is required to optimize design and investigate if its performance can reach the reliability and safety standards especially considering:
   –   A detailed / optimized design of the pin operation system
   –   An optimization of the number of pins together with the (modular) gate structure design
   –   The risk of malfunctioning due to the blockage of the pin system
   –   Possible effects on the gate structure in case of a pin failure
   –   Alternative, simplified methods of moving the pins.

VIII. The design of the lock head structure is illustrative and only major considerations for its design have been given. A detailed design of the lock head structure should be made determining in more detail the quantities required for such a structure and if a different methods of transferring forces to the foundation may not present better solutions (example: more slender lock head using anchors etc). The quantities

related to the lock head design (concrete and reinforcement) play a major role in determining the construction costs, therefore detailed design an optimization is recommended. In addition it is recommended to investigate the effects of applying such a structure considering less favorable soil conditions, as this will determine the feasibility for the possible application of the Sliding Arch Gate for medium – low head locks, which are generally subjected to poor soil conditions.

IX.   The operation equipment has been designed in order to illustrate how the gate can effectively be operated. Detailed mechanical design should optimize and better alternatives could be presented. Also the operation forces should be determined in more detail, taking the effects of the curvature into account considering the load interaction during transition.

X.   The previous points consider mainly recommendations concerning certain design aspects. However research should be done to optimize the performance of the gate as a whole.

XI.   Probabilistic modeling and possibly prototype testing should be done to investigate must if the required reliability and safety levels can be met. However this is not yet recommended as the design should first be worked out in more detail as suggested in the above.

XII.   It appeared that the economic consequences of water loss caused by inefficient lock gate design are so significant; they can play a governing role if they where to be taken into account in the whole life cycle costing of a lock gate design. Therefore proper research on these economic consequences is recommended, also taking into account the environmental picture which makes it much more complicated. In addition, due to the economic significance, other alternative measures to enhance water saving and capacity increase may also become interesting for further research:
- Pumps
- Variable lock chamber size
- Other…

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DOCUMENT HISTORY

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COLOPHON

APPENDIX 1: LOCK DATA ANALYSIS

APPENDIX 2: CONCEPT DEVELOPMENT

APPENDIX 3: ANALYTICALING MODEL OF THE GATE STRUCTURE

APPENDIX 4: PIN SUPPORT DESIGN

APPENDIX 5: GATE STRUCTURE DESIGN

APPENDIX 6: HYDROFOOT CALCULATIONS

APPENDIX 7: OPERATION FORCES