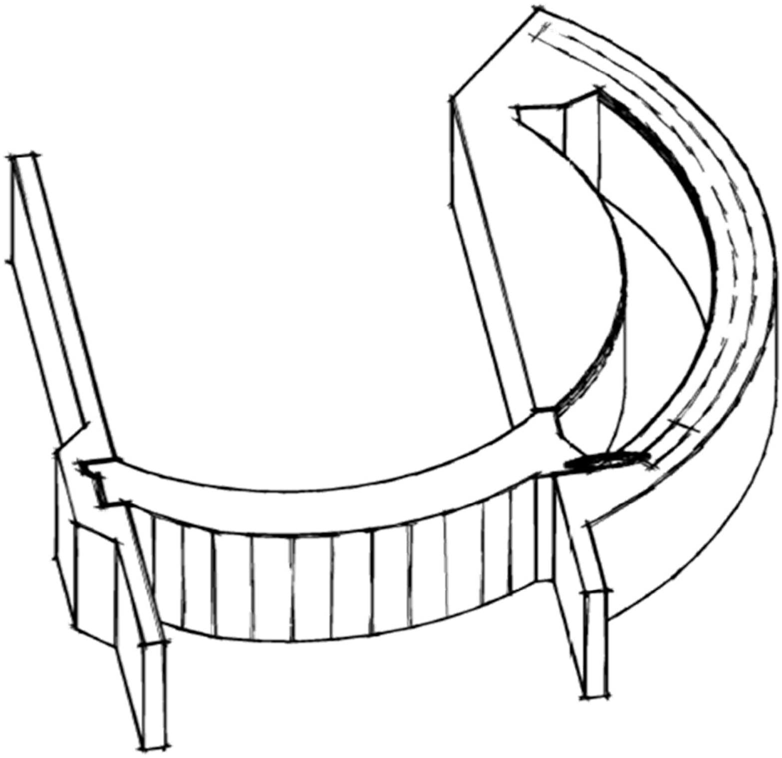
Innovative design for lock gates

Curved sliding gate

Case study: IJmuiden Nieuwe Zeesluis



Master Thesis Report by:

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Master Thesis
Specialization Hydraulic structures

Innovative design for lock gates

Curved sliding gate

Case study: IJmuiden Nieuwe Zeesluis

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Foreword

This Thesis concludes the master study in the track hydraulic engineering with the specialization of hydraulic structures in the Technical University of Delft. The work consists of a feasibility study, a preliminary design and an applicability evaluation for the innovative concept of curved sliding gate to be used in future lock complexes. This gate has been chosen to be the subject of this study because of its unique characteristics in comparison to conventional and common types of lock gates. Furthermore, the special requirements of the new lock in Ijmuiden made it an appealing case for this study to be carried out with the support of professional engineers in Iv-Infra. The concept has been developed based on certain criteria and by making use of a number of new technologies which helped broaden the area of applicability of these technologies into the lock structures.

The main idea for the initiation of this seven month work lies in innovation. As the lock complexes become larger in the course of time, the gates were being simply scaled up from the previous designs. Studies like this one, can introduce new solutions and alternatives for the designers so that they can perform safe and economical designs for large scale lock structures. It is in the intention of the author that the results of this work will be inspiring and further studies and experiments by next generation of researchers and professionals improve the current outcomes.

Finally, in acknowledgement of the people whom their support made it possible for this work to be done, I would like to thank my *mother, Zahra,* for her patience and her unconditional love, my *father, Esmaeil,* for his consistent encouraging and supporting attitude, *Samira*, my sister who was always there for me and never let me down and *Suzan*, my other sister for her non-stop help during all my education years.

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In the end, in appreciation of their support through the tough times of these years I am grateful of having them in my life: *Nima*, *Mardjan* and *Rasoul*, *Faraz*, *Reza*, *Yas* and *Herm-Jan*.

Delft,
31 July 2012
Sina Zel taat

Summary

Design of a lock gate for Nieuwe Zeesluis in IJmuiden becomes a challenge when the boundary conditions limit the choice for the conventional types of the gate. The available width of the lock does not allow a straight rolling gate to be considered as a possible alternative as it is in most similar cases. All the initial efforts of this study have been made in search of a new alternative to solve the space limit problem. After assessment of a number of feasible type of gates, finally, when the curved gate concept was introduced based on the concept of rolling gates and sliding gates, all the functional requirements of the design had to be met.

This study investigates in three different structural alternatives for the curved gate in the concept development stage as well as three different operating systems and two different supporting systems. Based on certain design objectives, a final concept is chosen and is developed into a preliminary design. The design objective have been defined based a simple criteria of achieving the most benefit with the lowest investment possible. In this manner it is tried to increase the functionality of the design for gate structure. These objectives are basically:

- Minimum use of movable devices
- Minimum necessity of maintenance
- Innovation
- Simplicity

The main challenge in the conceptual design is to find the optimum combination within the alternatives for the main compartments of the gate while every advantageous solution for a compartment, introduces a new problem in another. For making a better decision a framework is defined for the evaluation of the solutions and alternatives with the help of a score system which enables us to see which alternative is in line with the design objectives the most.

Furthermore, the study presents a rather detailed design of certain compartments such as operational equipment, guidance devices, tracks, hydraulic bearings and sealing system. Structural and stability checks are done for the extreme load conditions, loads during the special combined movement and construction of the gate. This results in a preliminary design which is integrated and consistent in satisfying all the functional requirements of the design.

The final and most important evaluation of the research study discusses the costs, safety, reliability and availability of the gate structure by means of a qualitative RAMS analysis accompanied by a cost comparison table. These two outcomes provide insight on applicability of the gate into the different situations but especially in this case study.

This report will discuss the approach and steps in which the idea was developed and it answers the feasibility and applicability questions by the help of final results and evaluations. It ends with presenting the conclusions of the work and giving a number of recommendations in the following areas:

- Design improvement by providing further details
- Further design investigation in structural behavior
- Room for experimental study
- Practical improvement by construction guidelines

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1 Introduction

1.1 Motivation

Due to continuous increase of international water transports, the need arises for constructing larger vessels. Consequently, the marine and inland infrastructures should be able to continue facilitating ship navigation efficiently. These rapid developments bring new challenges on structural design of these infrastructures and specifically lock complexes. As the lock complexes increase in size, they need to keep up serving the water transport system as they did before. In this manner, different components of a lock should be improved to hold their functionality and this improvement introduces extra costs when insisting on conventional designs. This is when the need for innovative designs and approaches comes into the picture. During the last years, several efforts have been made to design an innovative lock or lock component. One of the most influential efforts - from the structural point of view - is design of an innovative lock gate. Although innovative ideas are constantly being generated, not a vast number of those ideas have been developed to a practical level where it can be employed as a serious alternative in design. This study initiates from a specific space limitation which is described in problem definition.

The importance of this innovative design can be illustrated by looking into its economical and safety aspects. Along with development of waterways and associated infrastructures, the requirements grow for the consisting elements. When the demands get high from a structure, two approaches can be made. The first approach is to rely on the existing technology and repeat the design in the field where the most experience exists. This solution implies on spending the natural resources and increasing the costs of each single design for the new and improved requirements. This approach is safe and functional for time being but it is expensive and it becomes even more expensive as the demands grow more. The second approach insists on innovation, finding new solutions and exploring the possibilities outside the common practice. This approach is rather smart and effective in long run but it includes certain risks. Therefore it requires proper investigation in order to decrease the risks and improve the concept as the requirements continue to grow.

This study embarks on developing scientific knowledge for design of a gate - for wide waterways with large water head - which meets all the necessary requirements of a fully functional navigation lock. It is expected that providing reliable knowledge would lead to an economical design of a new and advantageous type of gate which has not been used in practice until now and making it a serious option in the future. This expectation can only be satisfied by meeting certain criteria. By the end of this study, the validity of this expectation is evaluated by making comparison among existing alternatives with similar boundary conditions.

1.2 Goal

Main question:

Two main questions are intended to be answered in this study. Primarily, the *feasibility* of an innovative design for lock gates and Secondarily, *competitiveness* and *applicability* of this innovative design in practice. Later in the research study, this design turns out to be a *Sliding Curved Gate*.

Problem definition:

In the project definition for the new sea lock in IJmuiden by Rijkswaterstaat, a new problem appeared in the boundary conditions of the lock complex which limited the design choices. Lack of enough space in the area resulted in insufficient width for the gate recess. Therefore, the designers began to search for any alternative which needs smaller width for the recess than the existing situation. Current research initiated when an innovative alternative was introduced which seemed appealing and was evaluated as advantageous. However, this innovative idea had to be rejected as in the case of most innovative ideas solely because it was not a proven technology. All the initial efforts of this study have been made in search of a new alternative to solve the space limit problem. The following steps in this graduation work are made to provide a reliable theoretical ground for this innovative type of gate.

Output and process:

Main output of this study is an evaluation on the practicality of the preliminary design. This design is build up from a conceptual design which itself is an enhanced principal solution which has been evolved on the basis of certain design objectives. Design objectives are defined according to the functional requirements and boundary conditions. Clients for navigation locks are constantly expecting growth in their profit and consequently they demand more efficient infrastructures which can only result in heavier and more intense requirements. In fact, this is where it all starts. Aiming at high profit introduces new problems which need new solutions.

Content:

Report starts with a brief introduction on locks and lock gates. Afterwards the main motivation of the research is defined and an evaluation of the existing types of lock gates is presented. Next, the new concept is introduced and the reader gets a general idea of the purpose of the study and becomes familiar with the motivations, process and challenges.

Chapter 3 describes the current study by defining the scope and boundaries of the design. It also focuses on the plans and methodology which links the research question to the solution establishment. Furthermore, a real case study in connection with the subject is briefly presented in that chapter.

In concept development (chapter 4), load conditions and relevant solutions and alternatives are discussed and decisions are made based on the design objectives. At the end of this chapter, all the choices among alternatives which are made on the basis of given arguments and calculations lead to a conceptual design.

Detailed calculations, design of main components, accurate structural analysis and total cost estimation of the design are given in the preliminary design chapter. This chapter provides a comprehensive description of the structure and the main equipment in a technical level. A general evaluation on reliability and availability of the structure and its role in the lock is done by the end of this chapter.

Finally, the results of the study are presented in the last chapter of the report. In this chapter, the conclusions of the study are discussed and recommendations are given for the future investigation.

Abbreviations and units:

In this report, the following abbreviations are used:

IJNZ	IJmuiden Nieuwe Zeesluis (New sea lock, Ijmuiden)
RWS	Rijkswaterstaat (Public Works and Water Management)

PIANC	The world association of waterborne Transport /infrastructure
UHMWPE	Ultra High Molecular Weight Poly Ethylene

All the units are SI except it states otherwise. The forces are in kN, and the moments are kN.m.

1.3 Report structure

Figure 1-1 summarizes the structure of the report. For each main title, two or three headlines are provided to give the reader an insight of the contents of the topics. Notice that the report structure is slightly different with the overall approach and the framework in which the work is carried out.

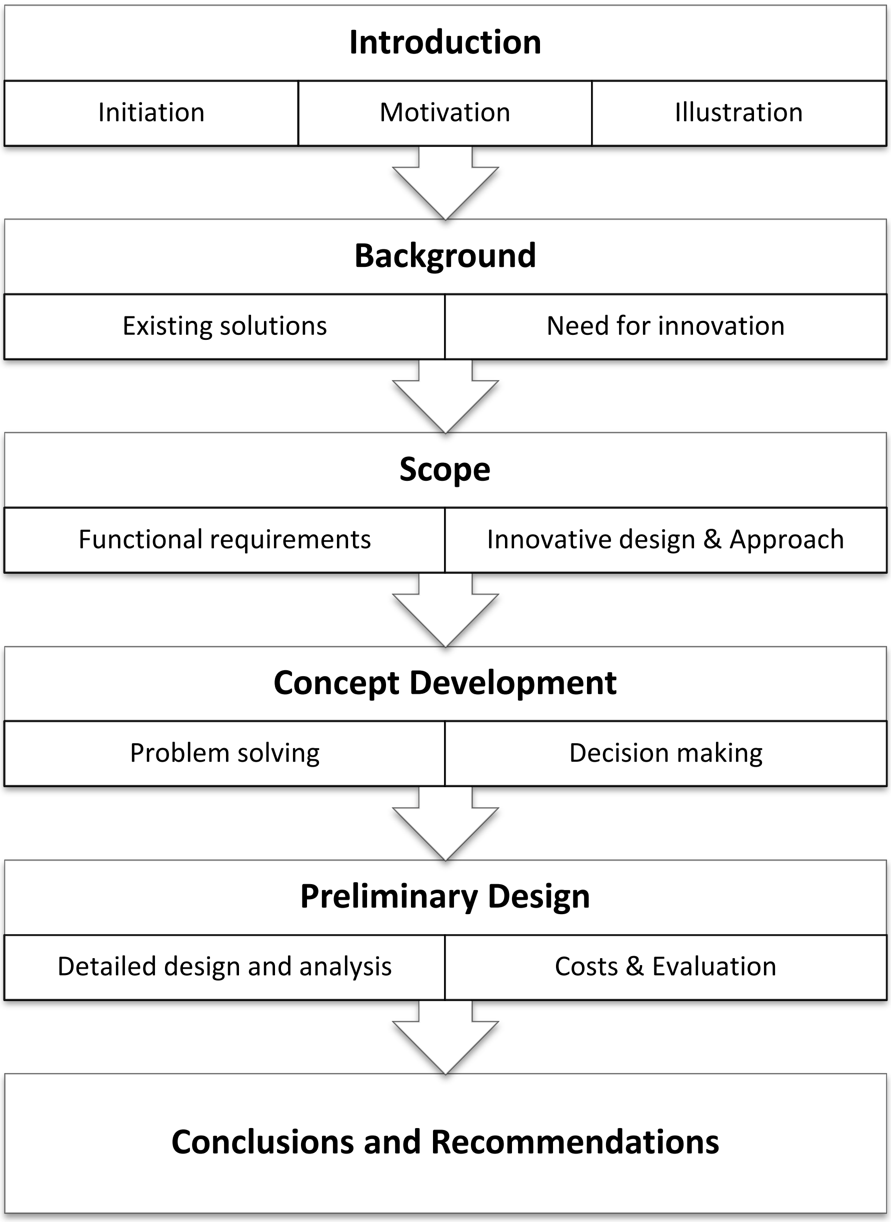


Figure 1-1: Report structure

2 Background

2.1 Common and conventional approach

2.1.1 Locks

A lock is part of the sluice family, it consists of an enclosed chamber in a waterway used to transport vessels from one to another water level (1). The main functions of a lock, are defined by Dutch Ministry of Transport, Public Works and Water Management (2) as:

- Navigation
- Water retaining
- Water management
- Crossing dry infrastructures

Locks can serve as infrastructures with different purposes. Since the focus of this study is navigation locks, wherever the word “lock” is mentioned, it implies on this type of locks. Other types of locks are (1):

- Dewatering gate
- Stop lock
- Guard lock

Navigation lock connects two sections of a waterway (river, sea or channel) with different water levels. The lock enables the transfer of the ship from one to the other section of the waterway while maintaining the water level difference between two sides. Navigation locks have also different types (such as Lift lock, Inclined plane, Pente d'eau, The rotating wheel,…) which are proper for different geometric and topographic boundary conditions (1). While the design case study is a lock for common maritime navigational purposes, current study can be applied on different situations and for different type of navigation locks.

Figure 2-1 and Figure 2-2 show general lay-out of locks. Notice that different lock structures may have different lay-out and compartments which are not included in the following figures.

In this study it is tried to design a gate which can provide a high availability rate. Non-availability could have the following causes:

- Water levels above and below locking levels
- Too much (cross)wind, bad visibility
- Malfunction of installations, operating mechanisms and operating
- Collisions
- Maintenance (and renovation)

In this manner, the above points are considered in the process of design. Further criteria and requirements are introduced in chapter 3 of this report.

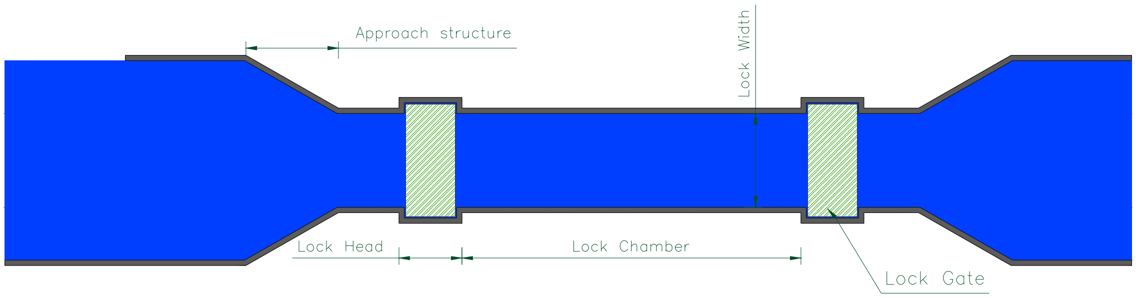


Figure 2-1: General Lock layout, Top view

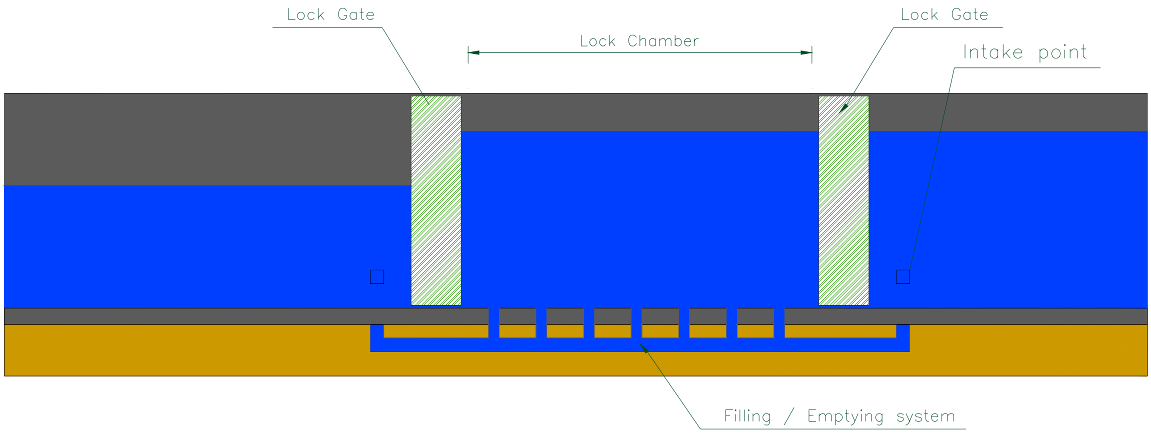


Figure 2-2: General lock lay-out, Side view

2.1.2 *Lock gates*

In this section, a number of current existing gate types are introduced and assessed afterwards.

2.1.2.1 Mitre gates

A frequently used type of lock gate (up to approx. 30 meters of lock-chamber width) is the mitre gate. Possible movement mechanisms are hydraulic cylinder, gear rack.

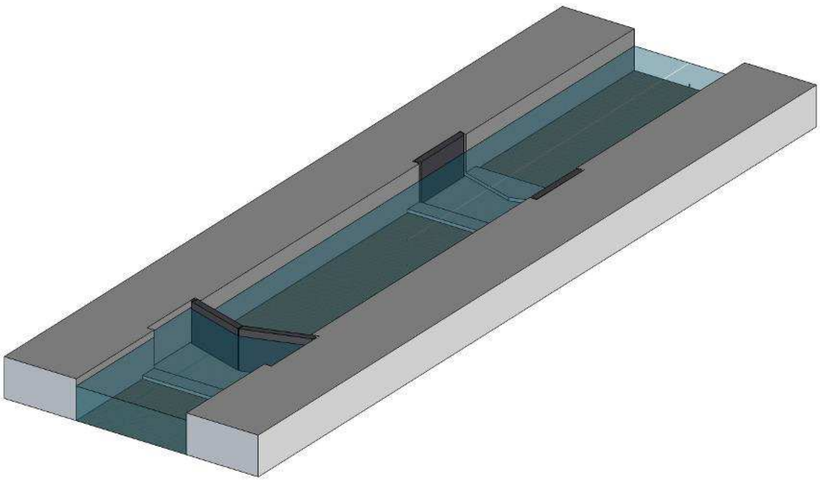


Figure 2-1 Impression of mitre gates

2.1.2.2 Straight rolling gate

The most frequently used type of lock gate in these dimensions is the rolling gate. Possible movement mechanisms are cable winch, tooth path.

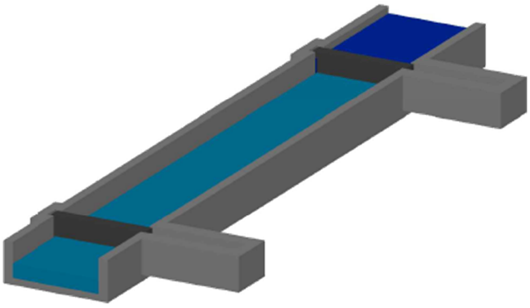


Figure 2-2 Rolling gate

2.1.2.3 Drop gate

A type of lock gate that is used on a small scale (and with smaller-sized locks) is the drop gate. In comparison to the lift gate, the gate does not move up but on the contrary, it moves down under the lock chamber. Possible movement mechanisms are cables, ballast water (floating construction) and hydraulic cylinders.

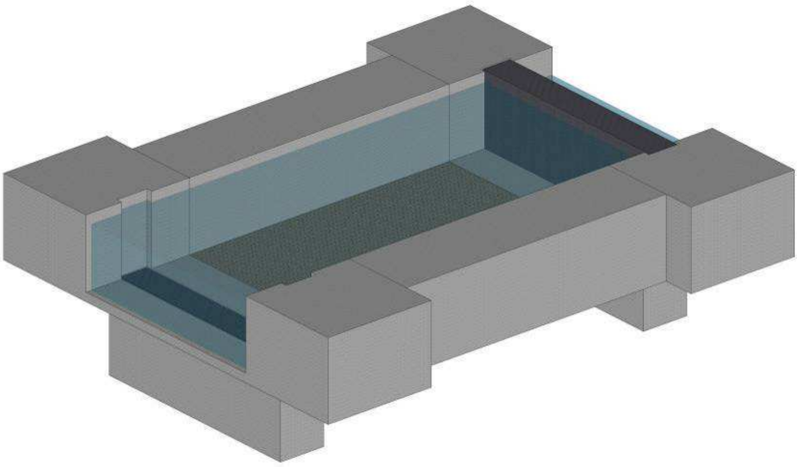


Figure 2-3 Impression of a drop gate

2.1.2.4 Segment gate

The segment gate was primarily used as a storm surge barrier (Ems barrier - Germany, Thames barrier - UK). Also, this type of lock gate, in smaller dimensions, is used in locks in Germany and Eastern Europe. The gate makes a rotational movement around a horizontal axis and rests in a casing in the lock floor when opened. Possible movement mechanisms are hydraulic cylinder and tooth path.

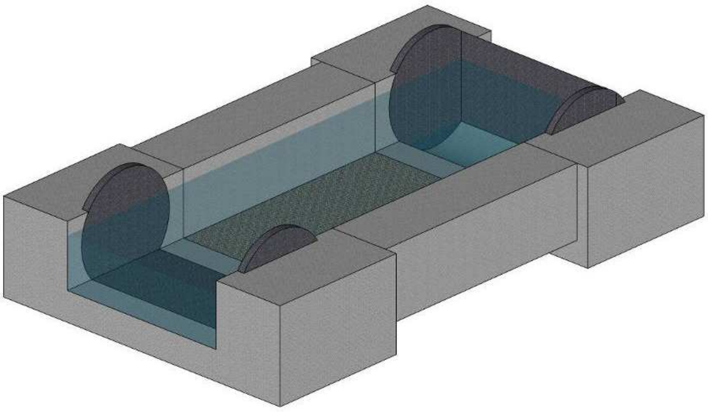


Figure 2-4 Impression of a segment gate

2.1.2.5 Sector gate

The sector-gate type is primarily known from the storm surge barrier in the Nieuwe Waterweg, although it also used on a smaller scale in locks. Possible movement mechanisms are: hydraulic cylinder, tooth path.

Figure 2-5 Sector gate

2.1.2.6 Swing gate

The swing-gate type is used in the storm surge barrier in the lagoon near Venice (Italy). As a variant to this, a shifting lock gate (without under-water hinge points) is presented. Possible movement mechanisms are hydraulic cylinder, cable winch.

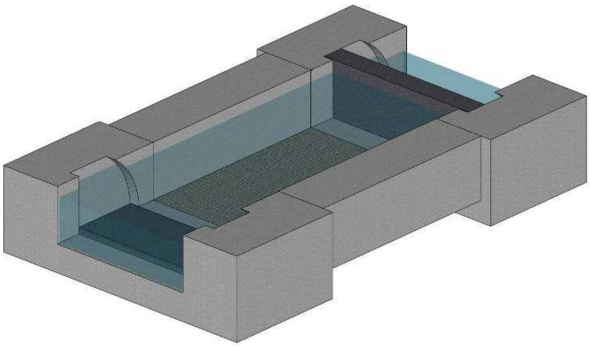


Figure 2-6 Impression of a swing gate

2.1.2.7 Lift gate

A frequently used type of lock gate in case of wide lock chambers is the lift gate. The biggest disadvantage of this type of gate is its limited air draught. On the other hand, it is a well-tested system and suitable for use with these dimensions. Possible movement mechanisms are cable winch.

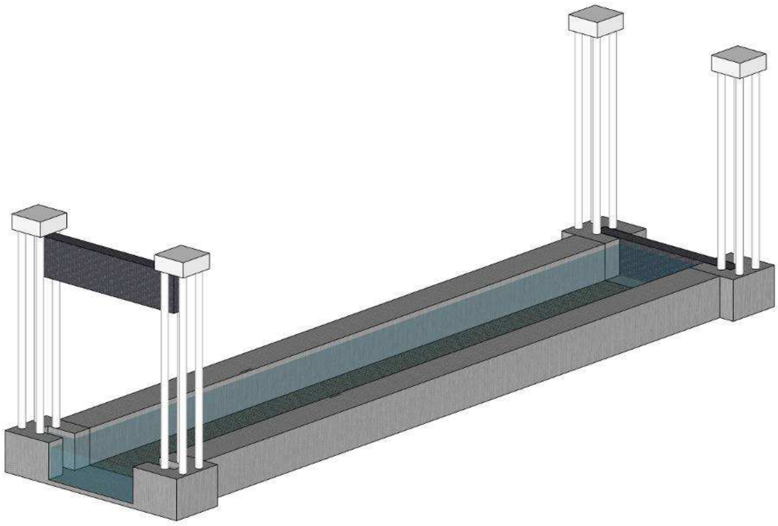


Figure 2-7 Impression of a lift gate

2.1.3 Need for innovation

The following paragraphs show the assessment in line with the initial assessment of gate type alternatives for the actual case of Niuewe Zeesluis in IJmuiden. Within the following arguments it is understood that none of the existing gates are advantageous for the new design case and some gates (Mitre gate and sector gate) can just meet the basic requirements of the case.

2.1.3.1 Assessment (3)

Throughout this section, the functionality of the existing types of gates is assessed. For further information on the requirements and criteria of assessment refer to chapter 3.

Mitre gate

The use of mitre gates seems a feasible solution for the lock gate. The retaining of a negative fall by means of pretensioning in the cylinders or an interlocking mechanism will not be technically feasible because of the large lock-chamber width.
The miter gates can be provided with a guiding system on the lock-chamber floor to reduce the forces on the hinge points as a result of the own weight and the traffic load. However, this part is sensitive to maintenance and, moreover, is in a poorly accessible place under water. To reduce the load on the hinge points as a result of the own weight, the use of air chambers in the lock gates may be opted for.

Straight rolling gate

From the study into the suitability of this type of lock gate, it was concluded that there is insufficient available space in all lock-chamber dimension variants. The transgression of the southern boundary is between 18 and 21 m. Optimization of the normative lock-head dimensions will not provide a solution here considering the substantial transgression.

Drop gate

The drop gate needs a gate casing underneath the lock chamber. This gate casing is sensitive to dirt and sludge, substantially reducing the reliability and, therefore, availability. The facilities that will need to be installed on the gate (e.g. water jets to clean the casing) represent extra components that increase sensitivity to maintenance and reduce reliability. Moreover, this gate casing can descend to a depth of approx. -48.0 meters N.A.P. This will negatively affect the investment costs of the substructure.

Segment gate

The use of segment gates does not seem a feasible solution for the lock gate. The segment gate is technically feasible and fits in well physically. However, it scores lowest where meeting the criteria is concerned. In particular, the poor exchangeability and poor maintainability will result in the required availability not being reached. Also, a traffic road stretch cannot be combined with the segment gate.

Sector gate

The total space occupation next to the lock chamber is rather large. however, it is smaller compared to the straight rolling gate type. In case of the zero variant, this gate type would, however, fit widthwise. The space occupation lengthwise is large for this type of gate, which is a disadvantage for the sailing into the existing Noordersluis. This solution is included in the further considerations of lock gates in the project.

Swing gate

The door casing in the lock floor will be sensitive to dirt and sludge. Both solutions are under water when opened and therefore not visible to ships. If the lock gate is not fully opened, the captain cannot see it, increasing the risk of a collision. Furthermore, the hinge points are sensitive to maintenance and are located in a poorly accessible location under water. For both solutions, extra facilities would be needed to be able to retain water on both sides.

Lift gate

The limited headroom is a compulsory requirement, which is why the lift gate is not considered a serious variant.

2.2 Introducing the concept of curved gate

2.2.1 Competing alternatives (3)

In realization of the project IJNZ, several innovative ideas were studied to meet the requirements of the project. This section provides a brief overview of these alternatives.

2.2.1.1 Telescoping gate

This type of gate operates similar to a rolling gate but is partly telescoped, allowing shortening of the length of the gate casing. This is favorable for the space occupation in the width of the lock chamber.

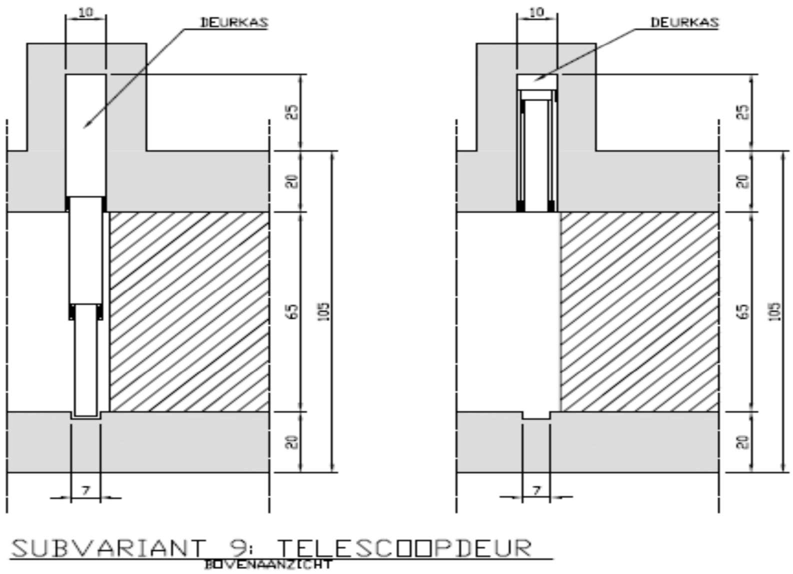


Figure 2-8 Telescoping gate

Assessment

The link in the middle of the gate forms the weakest part. This link is in a location where the bending moment is maximum. The inner part of the telescopic gate needs an extra moving device in order to project and retract. These extra moving parts decrease the reliability. The conclusion is that these disadvantages are too great for a gate type to be successful.

2.2.1.2 Vault gate

The vault gate consists of a circular surface in the lock floor attached to a single or double water barrier on top of it. When opened, the gates rest in a gate casing. During movement of the gate, the circular surface rotates horizontally around a vertical axis.

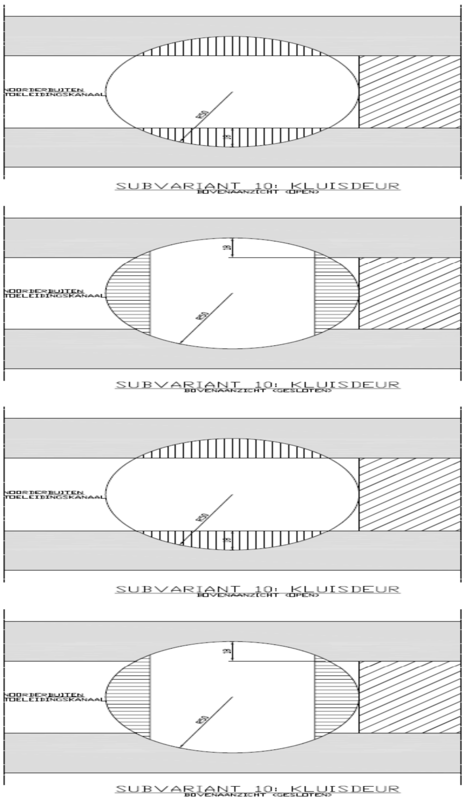


Figure 2-9 Vault gate solution

Assessment

The advantages of this solution include excellent visibility for the ship’s captain and the applicability of leveling openings in the lock gates. The rotating circular disk is located in the lock floor and therefore is sensitive to wear. Dirt and sludge collecting in the casing may cause problems. As a result, maintainability is unfavorable, especially because maintenance has to take place in the path of navigation. In addition, the exchange of parts of the lock gate is difficult. This is unfavorable for the availability. It is expected that the water sealing may become an obstacle because of the combination of the falling direction and the layout of the gate at the contact lines when the gate is closed.

2.2.1.3 Inflatable water barrier

At Ramspol, an inflatable water barrier is used as a storm surge barrier. A synthetic cloth lies open on the lock floor. A water barrier is formed by filling it with water and air. This solution is favorable regarding the occupation of space.

Assessment

The inflatable water barrier is not feasible for use in a lock as too much time is needed for opening and closing. The water barrier is difficult to create and is very sensitive to maintenance. Any collision into the cloth may not be immediately noticeable, but can cause great damage. For practical reasons the inflatable water barrier is not feasible for this purpose.

2.2.1.4 Curved rolling / sliding gate

The curved rolling gate looks like the straight rolling gate. However, the curved form reduces the space occupation next to the lock chamber. The size of the radius in relation to the total space occupation can be optimized. The force exerted results in bending of the gate. Therefore, there is no lateral thrust from the arching of the rolling gate.

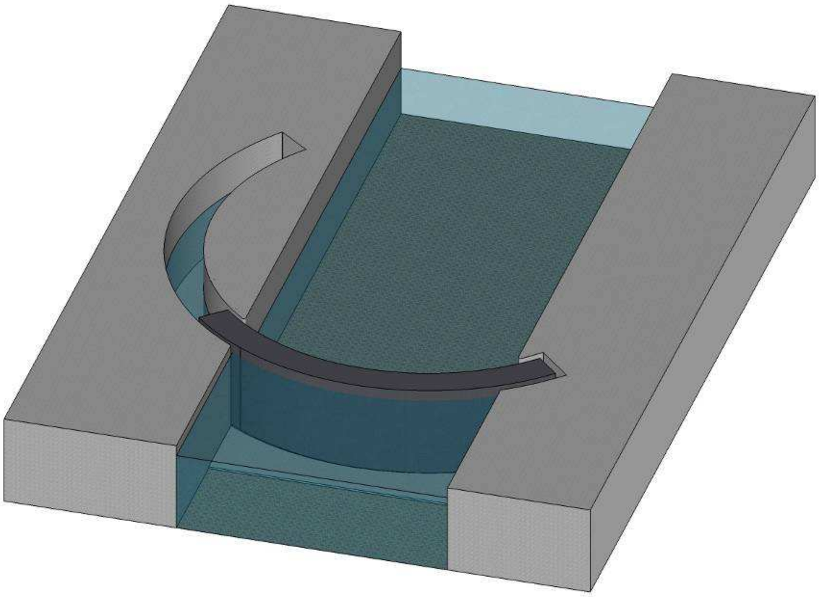


Figure 2-10 Curved rolling gate

The possibility of the sailing in of the curved rolling gate is a point of interest for the assessment of the feasibility of this solution.

Assessment

The use of curved rolling gates qualifies as a feasible solution for the lock gate. Because of the asymmetrical opening of the gate, the fresh-water/salt-water barrier is a disadvantage of this solution.

2.2.2 Advantages

Curved gate has two unique advantages on comparison to other innovative alternatives:

- It is structurally similar to straight rolling gates and sliding gates therefore it also has a good usage of cross-section and efficient design.
- It requires small width both for the recess and lock chamber.

2.2.3 *Challenges*

Since the curved rolling gate has been never designed for locks, proper concepts have not been developed for this type of gate. Regarding the previous studies and efforts on curved rolling gate, most problematic aspects of design seem to be 1) Bearing systems and horizontal supports, 2) Vertical support of the gate, 3) Mechanical devices and Movement mechanisms, 4) Guidance devices, 5) Sealing, 6) Floating stability and maintenance. In the following paragraphs it is tried to explain these aspects and their influence on the design and on each other.

Horizontal Bearing systems

Because of the special shape of the curved gate, normal bearings cannot be applied in this situation and special measures should be taken to provide horizontal support for the gate when it is closed. In this manner there have been already three variants proposed. While each one has its own advantages and disadvantages, it is tried to improve these variants or come up with a new variant for bearing system to satisfy the basic requirements of a working horizontal bearing. Based on the previous studies it is concluded that use of bearings with certain angle (conveniently parallel to the sides of the gate) is more reasonable than other proposed alternatives.

Variations in horizontal bearing system will affect the design for vertical bearing as the bearing systems work together to withstand the loads on the gate and convey them to the bottom and walls of the lock chamber. Generally, choice of horizontal bearings has a considerable effect on the stability of the gate and secondarily, on the sealing. Depending on the choice of the moving mechanism, horizontal bearings may also have some effect on the moving devices but they don’t limit the choices for the moving mechanism.

Bottom support system

Bottom support system of the gate is essentially important for providing vertical reaction during the moving process of the gate and stability of the gate while moving and when it is closed. It is also important to notice the bottom bearing system when designing for the maintenance, as they are hard to maintain. Choosing between a rolling support or sliding support and the variations within these alternatives is one of the challenges that has to be dealt with under this category.

Moving mechanisms

Finding the best moving mechanism for the gate is one of the biggest challenges in the design. Moving mechanism has a direct effect on the vertical supports and guidance devices and should be designed simultaneously with those elements. Because of the curved shape of the gate, regular moving devices do not work as sufficiently as they do in straight rolling gates. When moving, the gate exerts a force on the curved path at the bottom of the lock chamber. This force has a tangent component which drives the gate forward towards its place and a perpendicular component which is undesirable and introduces friction forces on the system which can result in the gate getting stuck or failure of the moving mechanism and devices.

Guidance devices

In relation with the problem that was mentioned in the previous section, guidance devices have to be designed specifically for this type of gate. Design of guidance devices would be dependent on the choice of moving mechanism. In addition, special provisions should be considered for the final stages of closing the gate in order to guide the gate into its final designated place. This is considered as a special case, because the loads would be somehow different (at least higher than normal) at those stages.

Sealing

During the design of main elements like vertical and horizontal bearings and the moving mechanism, special attention will be paid to the sealing of the gate. The choice of sealing provisions correlates closely with the choice of guidance devices and moving mechanisms.

Floating stability

The gate is required to have a high availability and therefore maintenance of the gate is of great importance. In general, a fast and practical procedure for maintenance should be foreseen in the design. Although different approaches may be possible for maintenance, changing the damaged gate with a new one may require the transport of the gate in the water and such a transport requires the gate to be stable during the floating process.

2.2.4 Background

The idea of curved (rolling) gate, has been presented in the report n^{o} 106 2009 of PIANC (4) as possible future concepts (4). Primary attempts have been made before in order to make a conceptual design for the curved gate. However, this concept has never reached to such stage of design since it has always been ruled out because it was evaluated as an unproven technology. In recent years and at the same time that the decision was being made for the new lock in IJNZ, the concept of curved gate was suddenly recognized as an appealing solution for the very high requirements of this project. In that manner, a number of research studies were carried out simultaneously on this subject including the current study. As far as the knowledge of the author goes, a primary study was done in number of engineering firms in The Netherlands such as ARCADIS, DHV and Iv-Infra. The most recognizable works are “Gate Design for Large, High Head Locks, The development of an innovative lock gate” by J.W. Doeksen (5) and “Design of Curved rolling gate Nieuwe Zeesluis Ijmuiden” by B.M.I. van Kortenhof, both as a result of the master graduation work with collaboration of TU Delft and DHV. Current study has been carried out on the basis of the initial evaluations for curved gates in Iv-Infra. The idea was initially developed for the feasibility study of IJNZ. This study was done within the same period of the two abovementioned titles. It takes a different path from these works, but it takes into account the outcomes of these works for the process of decision making, evaluations and conclusion.

3 Scope

3.1 Innovative Design of lock gates

Developing an innovative idea into a preliminary design has to be done in a well-defined framework. Current section describes certain characteristics and criteria of this framework which is presented in section 3.3.

3.1.1 Requirements

The requirements for performing an innovative design is best described by the report Innovations in navigation lock design (4):

- Reducing the costs by using new solutions that are better and cheaper.
- Improving reliability. This is not always possible with the existing technology, so new technologies can be needed to reduce risks of failure.
- New requirements appear in owners' specifications (e.g. reduced locking time, high redundancy, low breakdown, water saving policy, environment impact, and sabotage).
- Non-standard dimensions or performance criteria (e.g. high lift height, large lock size, high leveling speed).

3.1.2 Aspects

Comprehensive design of a lock complex takes numerous aspects into account. For preliminary design of this innovative type of gate, the following aspects are considered to be the most important ones.

<u>*Availability:*</u> By definition, availability is a fraction of life-time in which the structure is up and able to function properly.

$$Availability = \frac{Up\ time}{Up\ time + Down\ time}$$

$$Inherent\ Availability = A_i = \frac{MTBF}{MTBF + MTTR}$$

$$Operative\ Availability = A_o = \frac{MTBM}{MTBM + MDT}$$

$MTBF = Mean\ Time\ Between\ Failure$
$MTTR = Mean\ Time\ To\ Repair$

$MTBM = Mean\ Time\ Between\ Maintenance$
$MDT = Mean\ Down\ Time$
$= Time\ for\ Corrective\ Maintenace\ (CM) + Delays + Preventive\ Maintenance\ (PM)$

Paradoxically, adding more components to an overall system design can undermine efforts to achieve high availability. That is because complex systems inherently have more potential failure points and are more difficult to implement correctly.

Availability of the structure is related to the reliability and maintainability of the structure

Reliability: By definition, reliability is probability of no failure within a determined time period.

$$Reliability = P(No\ Failure) = 1 - P(Failure)$$

Redundancy: in engineering, an effective method of increasing the reliability of technical apparatus by incorporating an additional number of components and connections over the minimum necessary to perform specified functions under given operating conditions.
Figure 3-1 shows the different levels of undesired events which lead to the failure of the structure. The relevant maintenance measures are presented in the same figure. next topic will provide a brief insight on the maintenance issue.

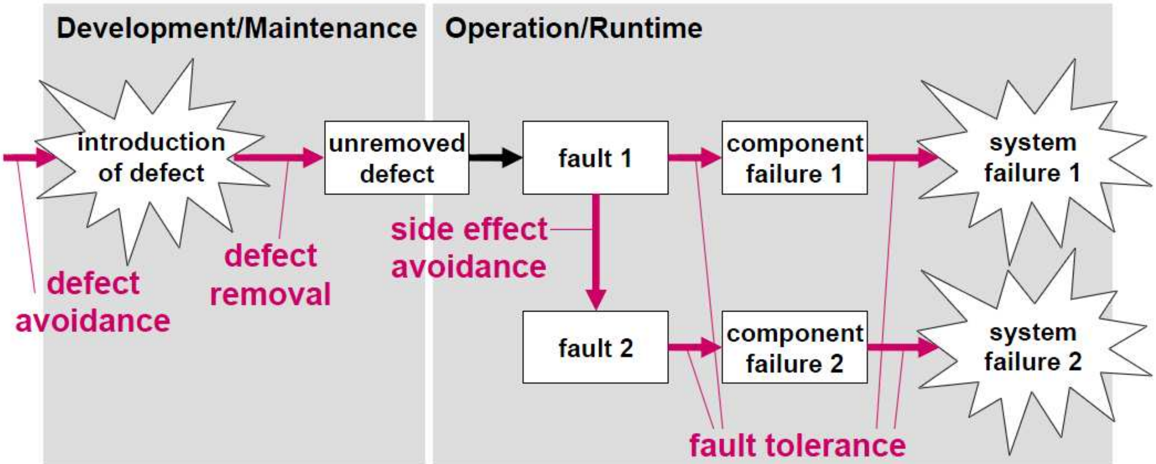


Figure 3-1: Failure development / Maintenance measures (6)

Maintainability: By definition, maintainability is the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources (IEC 60050-191).

$$Maintainability = P(Restoring\ within\ a\ certain\ time)$$

Safety: By definition, safety is the opposite of risk. This means that if the probability of critical failure and the corresponding loss (usually human loss and economical losses) is low, the structure is considered safe. In conclusion, reducing the probability of critical failure and reducing the afterward damages results in high safety (6).

Life cycle costs: Total costs of the construction, operation and maintenance are called the life cycle costs. These costs are considered while developing the preliminary design. Life cycle costs increase when each one of the previous aspects increases. Therefore, the challenge is to find the balance between the costs and functionality of the gate.

3.1.3 *Design areas*

As stated in the previous section, the functionality of the gate is considered as the focus of the design. In this manner, structural and mechanical elements of the gate are developed in the first stage of design along with sealing system of the gate. Furthermore, Hydraulics of the channel, North Sea and the lock are considered as the main external action on the gate. In the preliminary stage of design, more focus is given to the structural aspects of the gate. In this stage, a linear 3D analysis is done for the main structural elements of the gate.

3.2 Functional requirements

Due to the nature of the project, IJNZ was chosen to provide realistic boundary conditions for the design of the curved gate. The unique requirement of this project is the limited width of the future lock. This limitation put an emphasis on the required area and width of different alternatives. This section provides all the functional requirements of the new lock in IJmuiden.

3.2.1 *Case study: IJmond Sea entrance (Zeetoegang IJmond, Nieuwe Zeesluis)*

The Nieuwe Zeesluis will be built within the strip in-between the existing Noordersluis and Middensluis. The photograph of Figure 3-2 shows the area in which the Nieuwe Zeesluis can be built. Figure 3-3 provides an accurate illustration of the exact boundaries. The design length of the lock is 500 meters and the design depth is 25 meters. This boundary implies that the lock can have a maximum total width of 130 meters. (3)

Figure 3-2: Planned location of the New Sea Lock in IJmuiden lock complex

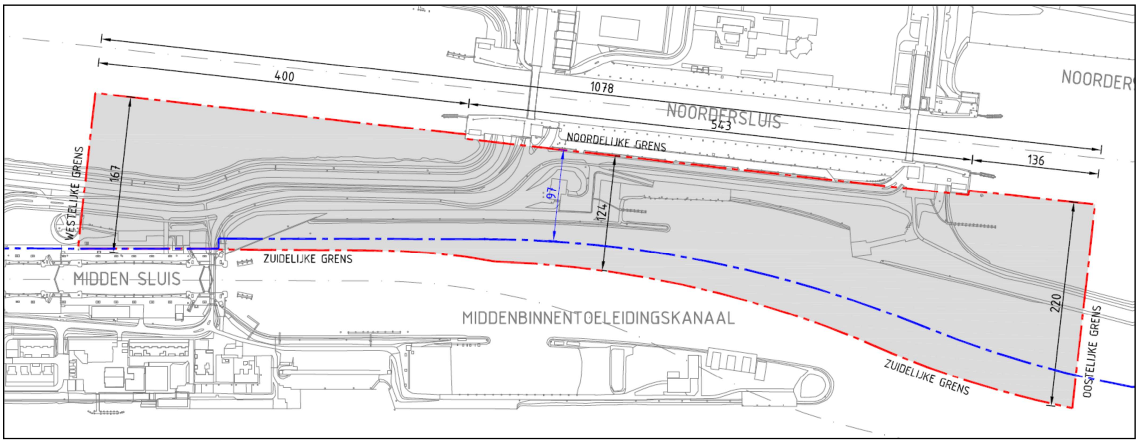


Figure 3-3: Summary of the boundaries for the possible location of the lock

3.2.1.1 Strating points

Design lifetime

Design lifetime of the gate's different parts is determined and given in Table 3-1.

Component	Minimum lifetime (Years)
Irreplaceable civil parts	100
Simple replaceable parts	50
Steel structures	50
Mechanical equipment	25
Electrical equipment	15
Operating system	10

Table 3-1: Design lifetime

Availability

The required availability for this lock in relation to the leveling function of the lock is 98%.

Lay-out

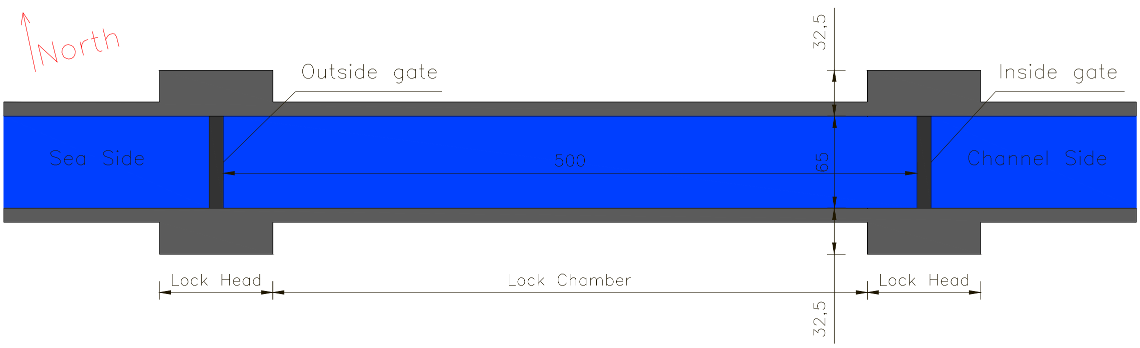


Figure 3-4: General lay-out of the lock (dimensions in meters)

Navigation levels

Navigation levels are shown in Figure 3-5 according to the hydraulic boundary conditions (7).

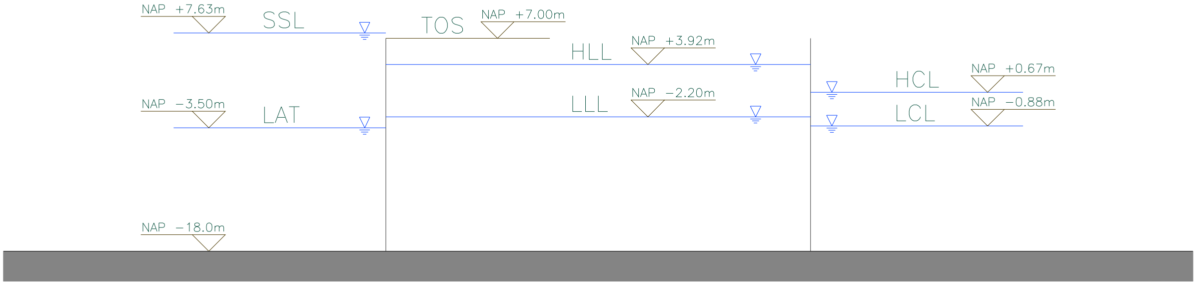


Figure 3-5: Navigational levels (Left side illustrates the Sea side and right side illustrates the channel side)

Leveling

Leveling openings can be used in the case of the miter gate, the curved rolling gate and the sector gate, as all gate types have a consistent thickness. However, it is decided that for the case of curved gate, the leveling shall be done via side and bottom culverts in the lock chamber in order to avoid complexity of the design for curved gate.

Water retaining

Water retaining function of the gate has to fulfill all the hydraulic conditions with the occurrence frequency of 10^{-4}.

Movement

Movement of the gate should take an average time of 15 minutes. Notice that this can change with regard to the hydraulic situation at the time of operation.

Traffic connection

The function of traffic connection is anticipated from the gate. This is considered in the design process but the connection itself is not designed.

3.3 Approach and work plan (framework)

Based on the assessments and evaluations in chapter 2, it can be seen that the traditional lock gates are not so appealing for this case and the new concept is more advantageous and suitable for this case. The idea of the curved gate has been developed with the main engineering approach as depicted in Figure 3-6. At the beginning of the work, the idea is realized and studied in order to recognize the challenges and advantages. The outcomes of this stage are technical problems that have to be solved in the following stage, the concept development stage. Figure 3-7 shows the approach for the concept development stage. A number of design objectives are defined according to the main design criteria. Secondly, it is tried to provide a number of relevant solutions for the design challenges that were highlighted in the previous stage. Basic design calculations accompanied by 2D structural analysis are provided for these solutions and by the help of the design objectives, the solutions are evaluated. By the end of this evaluation, a series of decisions are made in order to find the best combination of the solutions and the results of these decisions lead to a conceptual design which becomes a basis for the preliminary design. Figure 3-8 shows the overall approach in preliminary design stage of the gate. This stage improves the input for design by performing 3-Dimensional structural and stability analysis. The results of this stage will be used in detailed design of the main elements of the gate. Eventually, all the details combine to form an integrated design which will be evaluated at the very last part of this study. (Figure 3-9)

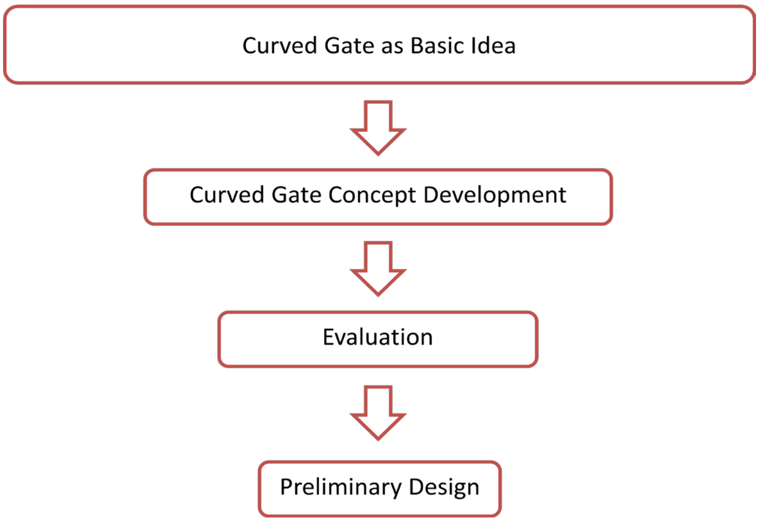


Figure 3-6: Main engineering approach to the study

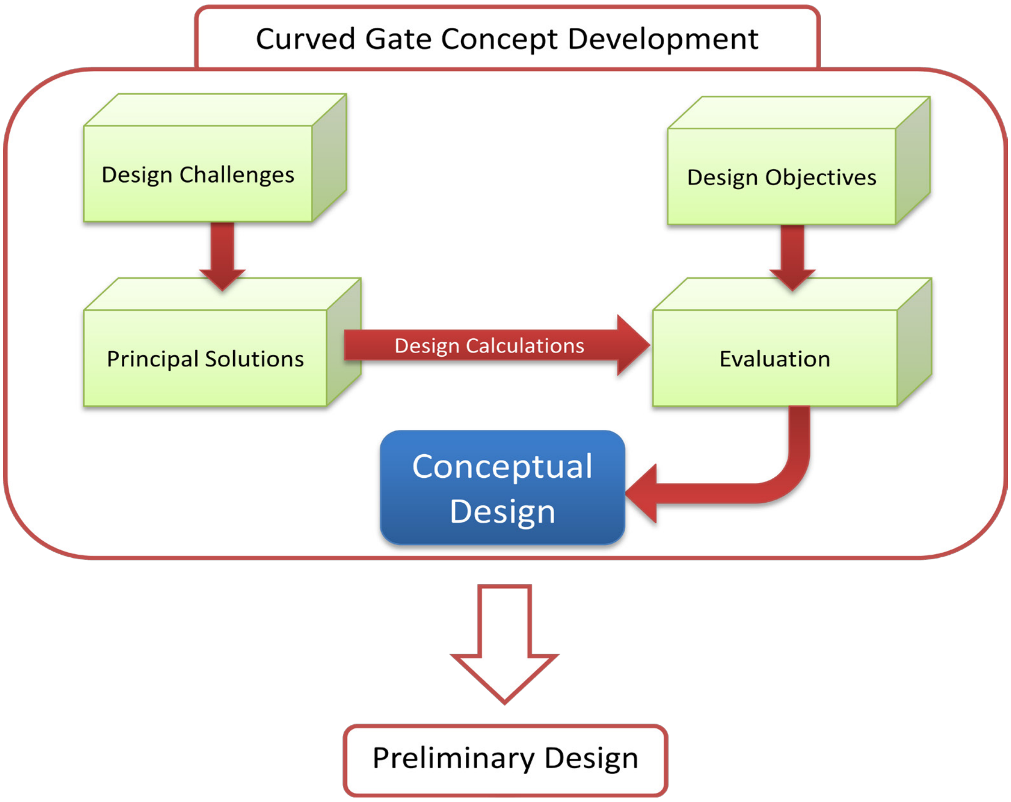


Figure 3-7: Approach for concept development

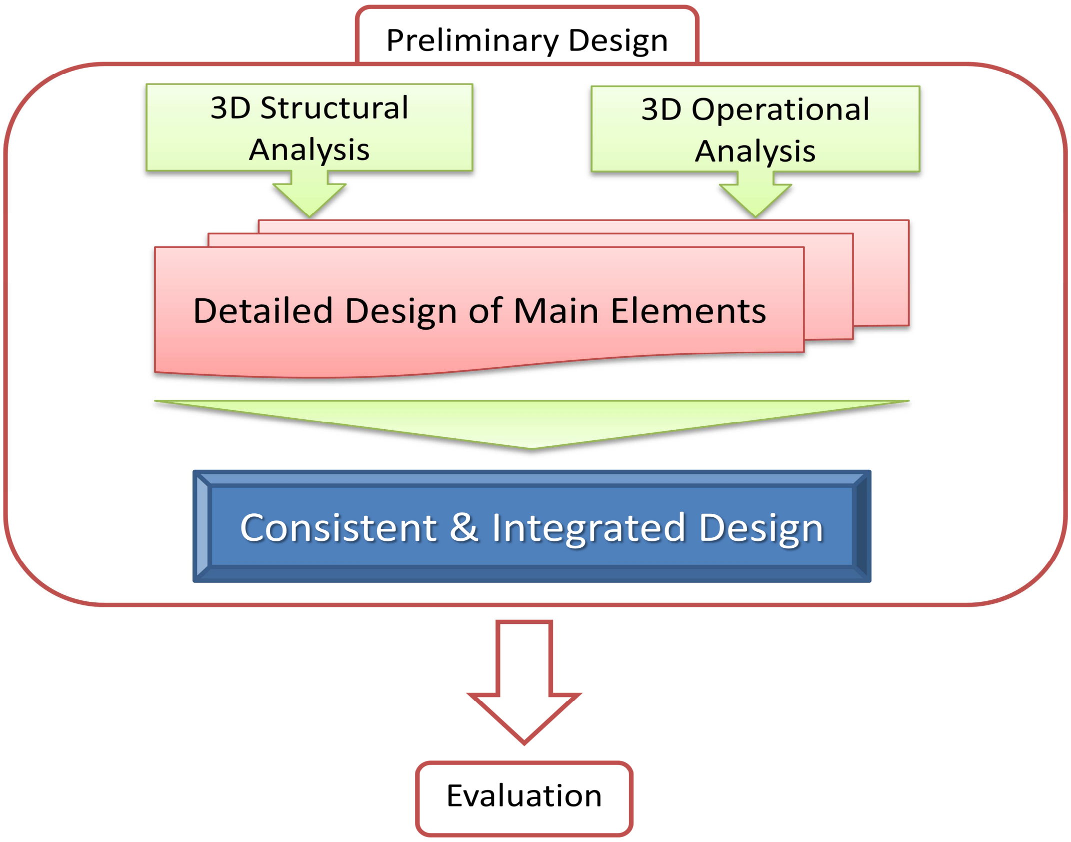


Figure 3-8: Approach for preliminary design

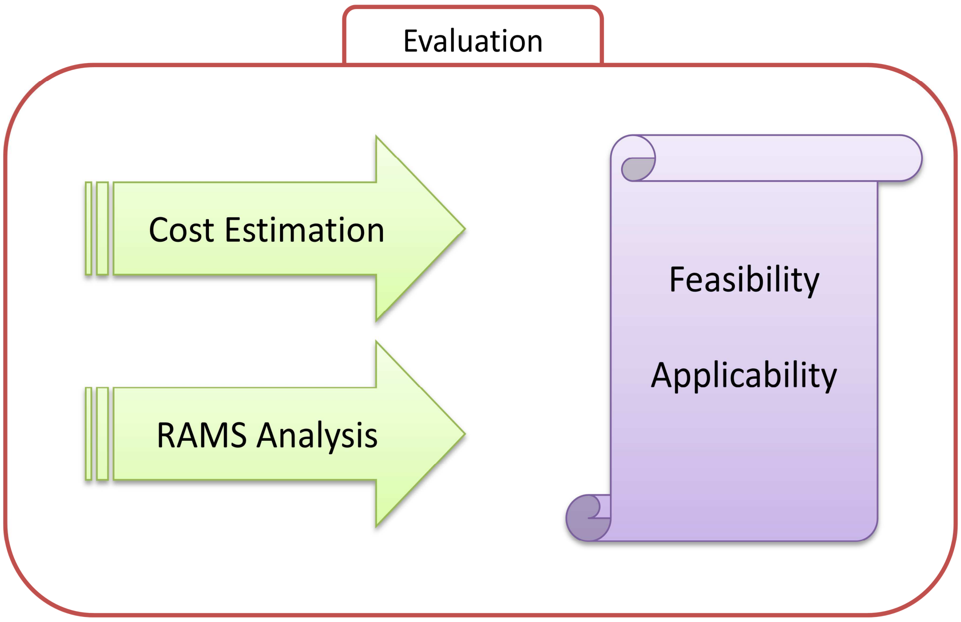


Figure 3-9: Approach for evaluation

4 Concept development

4.1 Design Objectives

Innovative design of curved gate, like any integrated design follows certain objectives which are known as “*design objectives*”. The approach for determining design objectives is based on two simple principles: Maximizing the Availability and Minimizing the Costs.

Availability of structure can be increased by increasing reliability (decreasing risks) and decreasing time and repetition of maintenance procedures. Total cost of the structure can be decreased by optimizing the construction, operation and maintenance costs. These measures can be translated into the following practical objectives:

- Minimum use of additional movable devices
- Decreasing maintenance necessity
- Simplicity (reasonable cost, design, construction and operation)
- Innovation

1. Minimum use of additional movable devices

Use of movable devices introduces certain risks in the gate operation. Mechanical devices which are necessary for providing the basic elements of stability such as pin supports (explained in section 4.4.3) are good examples of this type of movable devices. Lower probability of failure can be achieved in designing permanently fixed elements in comparison to movable devices. This can be justified by comparing fault trees for two elements which serve the same purpose but one depends on moving parts and the other one does not. Figure 4-1 shows a typical fault tree where the probability of occurring top event increases when a basic event adds to the tree.

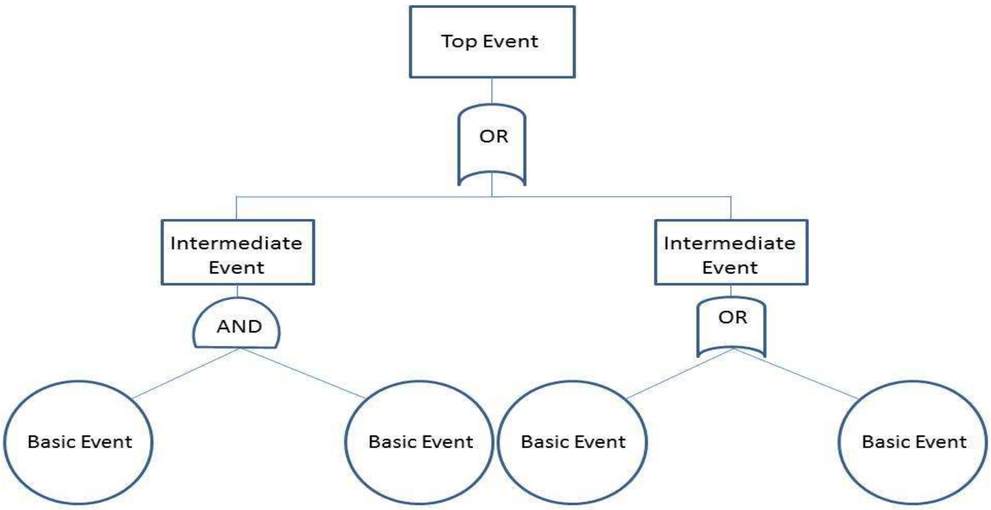


Figure 4-1: Typical fault tree

2. Decreasing maintenance necessity

Since the maintenance procedures for this scale of gate is extra costly and time-consuming and requires special measures, it is desired to avoid such procedures by designing the structure and all its elements to have the least demand for maintenance, inspection and periodic repair.

For instance, *wear* becomes a very important issue in design of a lock gate since the gate is being operated numerous times every day in its lifetime. Therefore, taking care of the wear problem can decrease the need for maintenance considerably.

3. Simplicity

Keeping the cost and complexity of the design, construction and maintenance at a reasonable level can be defined as simplicity. Design of a large scale structure, is inevitably complicated. Since the number of elements is excessively high, the construction process can become very difficult. A smart design should account for those complexities and reduce them especially in operation and maintenance procedures. In other words, simplicity of the design is one of the most important objectives next to innovation and cost-effectiveness.

4. Innovation

Because of the nature of current study, innovation is one of the main objectives that is intended to be achieved by the end. Since the graduation work builds upon a scientific ground, this criterion plays an important role in decision making process. The borders of innovation will be defined by the technological limitations and not the common practice nor the theoretical boundaries.

4.2 2D Structural Analysis and Curved Beam Analogy

The basis of conceptual design is described in section 3.3. The principle idea is to separate the structure into horizontal and vertical directions. A curved beam represents a simplified model of curved gate structure in horizontal directions (See (8) for description of curved beam analysis). The advantages of using 2D model are that because it is simple, assuring the general stability and equilibrium is easy and finally, making comparison is conveniently possible. A simple rigid curved wall in state of plane strain, represents the gate structure in vertical direction. This wall is considered to have zero strain along the lock width (9). However, notice that when the three-dimensional structure is simplified and modeled by two-dimensional elements, certain aspects of the actual gate behavior are inevitably ignored. Below a number of these aspects are described and some of the characteristics are adjusted to compensate for the undesired consequences.

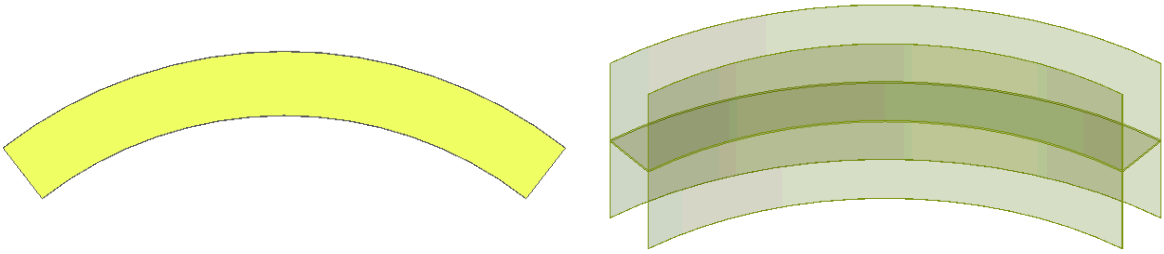


Figure 4-2: Impression of 2D Curved beam and perspective on cross-section of the beam

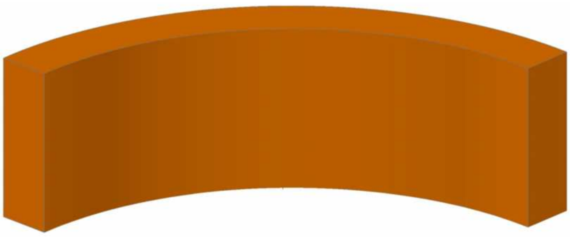


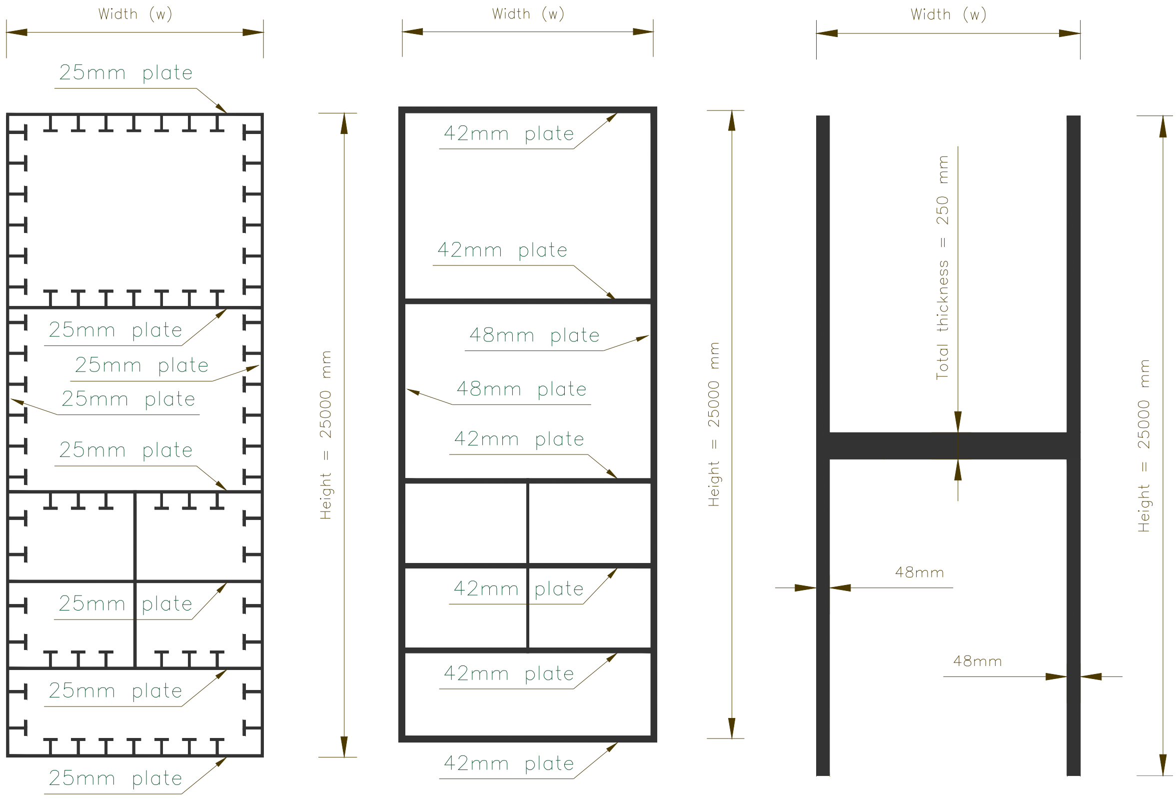
Figure 4-3: Impression of Rigid curved wall in state of plain strain

- Loads and boundary conditions have to be redefined for two dimensions. Section 4.3 gives a complete description of the loads in conceptual design. Boundary conditions in conceptual design are described in section 4.4.3.

- The cross section of the beam should represent the structural behavior of the actual gate. In this manner, the cross-section of the curved beam has the same moment of inertia in the direction of horizontal loads as the gate structure. Section 5.3.7 describes the comprehensive approach for such simplification. Figure 4-4 shows the simplification in two steps. The assumed value for plate thickness is 25 mm for all the plates based on similar reference projects (10). According to the calculations in section 5.3.7, the equivalent plate thickness is approximately 48 mm. The global moment of inertia for the gate cross-section is calculated as below:

$$I = \frac{1}{12} * 250 * w^3 + 2 * 25000 * 48 * \left(\frac{w}{2}\right)^2 + 2 * \frac{1}{12} * 25000 * 48^3$$
$$= 20.8\, w^3 + 600000\, w^2 + 460800000\ [mm^4]$$

It can be seen that the moment of inertia consists of three terms. The first one is related to the horizontal plates of the gate and the second and third one are related to the skin plates. The contribution of these terms varies as follows:
If the width of the gate changes from 2.00 meters to 12.00 meters, the contribution of the first term to the whole moment of inertia changes from 6.5% to 29.4%. This contribution for the second term changes from 93.5% to 70.6% and for the third term from 0.018% to 0.0004%. Therefore, the third term will be ignored due to its small contribution and since the second term has the most contribution, the width of the cross-section (in general, the width of the gate) becomes the most important variable in design. The skin plate thickness and horizontal plate thickness are respectively the next important parameters in global design.



Typical cross-section of the gate *Simplified cross-section of the gate* *Cross-section of the curved beam*

Figure 4-4: Simplification process of gate cross-section

- Since the load distribution is not uniform in total height of the gate, the reactions and internal forces would not be the same all over the height. In order to account for the maximum force, a correction factor should be considered. In order to calculate the correction factor, an assumption is made that the reaction force distribution follows the same distribution as the horizontal loads (Figure 4-5). Therefore, the Correction factor is calculated by dividing the maximum horizontal distributed load by the average distributed load. According to Figure A 1 in Appendix A, the maximum horizontally distributed load has a magnitude of 107.2 kN/m^2. The average distributed load is calculated by dividing the total load by the height of the gate (2276 / 25 = 91.04 kN/m^2). Therefore the Correction factor can be calculated:

$$Correction\ factor = \frac{Maximum\ horizontal\ pressure}{Average\ pressure} = \frac{107.2}{91.04} = 1.18$$

$$\Rightarrow\ An\ \mathbf{increase\ of\ 20}\%\ will\ be\ considered\ for\ results\ from\ 2-D\ analysis$$

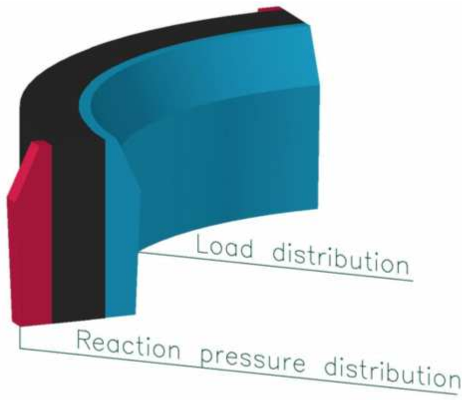


Figure 4-5: Predicted pressure distribution on supports

- Horizontal loads can affect the vertical behavior of the gate and vice versa. In section 4.4.3 it is tried to minimize this interaction.

- Torsional behavior of the gate (which is a combination of vertical and horizontal characteristics of the gate) cannot be considered within the limits of this simplification and will be ignored in this stage of design.

In section 4.5, the calculations for two-dimensional analysis of the gate are given based on the proposed solutions in section 4.4.

4.3 Design Loads

4.3.1 Dominant load conditions

Next step in conceptual design, after defining the design objectives and right before shaping the principal solutions, is realizing which loads affect the design by most. Since the design is being made for the feasibility study, it is wise to investigate only on the governing situations. A governing situation in an innovative design has the highest requirements for certain aspects of design and introduces highest risks on the structure. Therefore, the main elements (as mentioned in section 2.2.3) shall be designed in accordance to these governing situations in order to prove the reliability of the design. The governing situations for design of this innovative gate are described.

Gate in closed situation

Reliability of the gate in water retaining, is studied while the gate is closed. The closed situation is merely addressed to the time when the gate is closed for reasons other than navigational purposes. In fact in these situations, navigation is not even possible anymore; either due to extreme low water or extreme high water. In these two situations, total horizontal pressure on the gate is maximum at one side of the gate and the internal forces and deformations are consequently maximum. Therefore, two load conditions are considered for studying the gate in closed situation. Maximum positive head (extreme hydraulic situation from sea-side) and the maximum negative head (extreme hydraulic situation from canal-side). These load conditions are the governing cases for structural design of the gate. For instance, general structural system of the gate, required width, element dimensions and gate stiffness are determined by these load conditions.

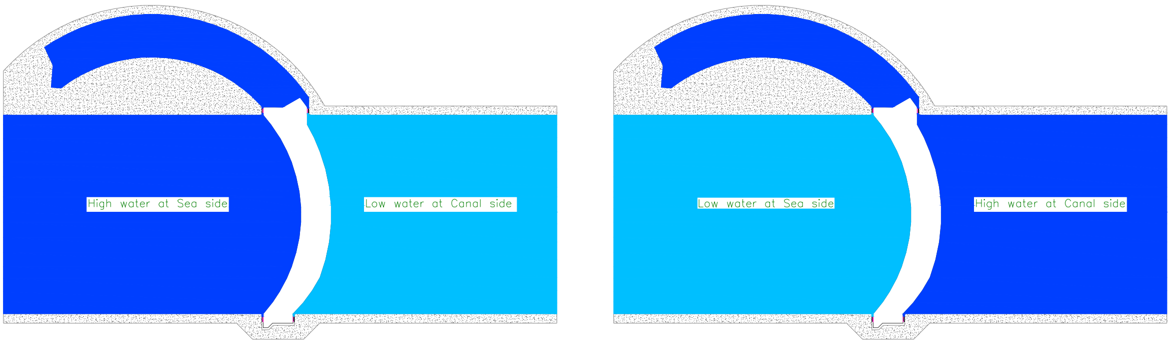


Figure 4-6: Gate in closed situation (Left: Positive head, Right: Negative head)

Gate during operation

Functionality for navigation is studied during the operation of the gate. Operation is referred to the opening and closing process of the gate mainly for navigation (see also section 2.1.1). Stability of the gate has to be assured during these processes in the design. In this manner, Load conditions during the opening/closing operation of the gate are considered. Figure 4-7 and Figure 4-8 show steps in the operation of the gate. The conceptual design for the feasibility study has to satisfy the stability requirements through the entire process of opening and closing of the gate and for all the possible water levels between the minimum and maximum allowable water level for navigation. That being said, the most critical phase of the operation is initiation of opening (First drawing in Figure 4-8) due to three reasons:

- Maximum surface of the gate is exposed to the hydraulic loads in comparison to any other phase during operation.

- Maximum water level difference can happen in this phase due to leveling tolerances.
- Maximum driving force has to be applied in this phase.

Therefore, the load condition in this phase of the gate is considered for the design of the gate. This design will only focus on the stability of the gate during any other phase and loads are also considered qualitatively.

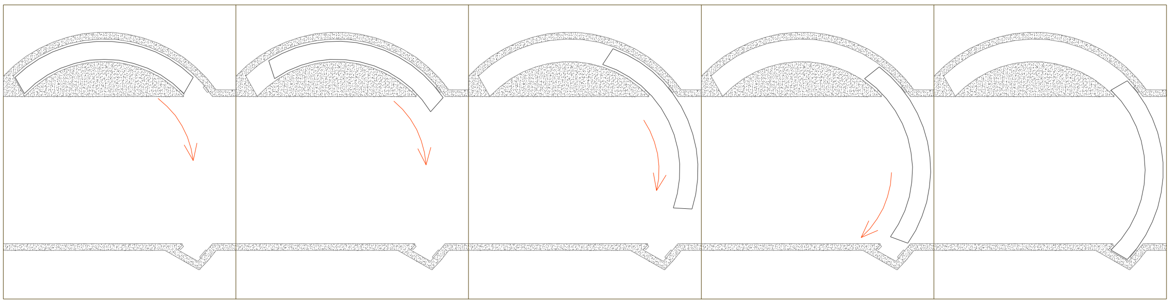


Figure 4-7: Closing process

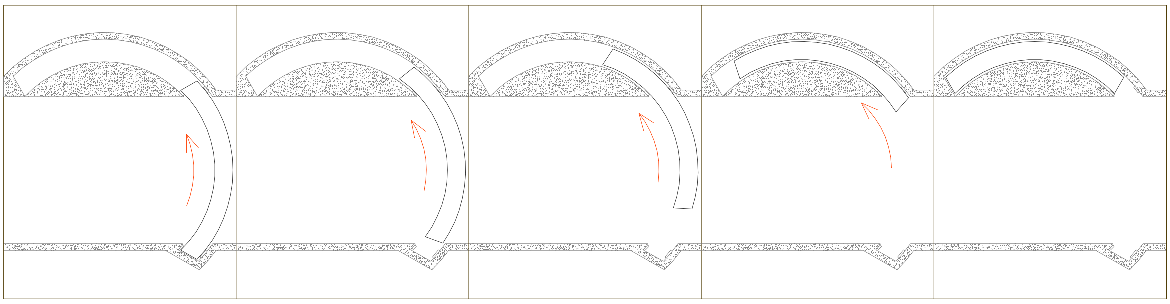


Figure 4-8: Opening process

This load condition is the governing case for design of the certain elements of the gate. For instance, driving mechanism and guidance system are determined based on this load condition.

Gate during maintenance

Availability of the gate is directly dependent on the certain behaviors and characteristics of the gate during maintenance. High availability demand, as seen in functional requirements (section 3.2.1) implies that maintenance procedure of the gate should be short (in this case study, 24 hours). Therefore the exchange procedure of the gate needs to be done within one day and that is only possible if the gate is floatable all by itself. Therefore, the load condition during the exchange of the gate is considered as the governing condition for floating stability of the gate. This load condition is governing for design of certain elements and details. For instance, buoyancy chambers, general shape of the gate (moment of inertia) and the recess are influenced by this load condition.

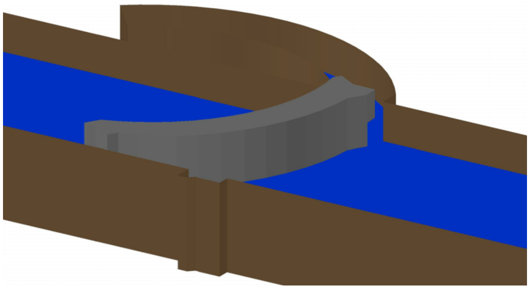


Figure 4-9: Gate during exchange process

4.3.2 Dominant loads

A complete list of all possible loads in design of the curved gate, is given in Appendix A. Dominant loads are selected based on their contribution on the design in accordance to governing situations that are discussed in section 4.3.1 and as a result, loads that are considered in the conceptual design are:

- Self-weight
- Buoyancy
- Salinity
- Hydrostatic water pressure
- Wave loads
- Driving forces
- Friction

As described in section 0 the structure is simplified into a curved beam for the conceptual design level. Therefore loads have to be defined and adjusted to be applied on the beam. In the following paragraphs, dominant loads are described and quantified:

4.3.2.1 Hydraulic loads

Hydrostatic water pressure

Largest load case is the hydrostatic water pressure on the gate. Three conditions are considered for hydrostatic water pressure. Positive head, Negative head and operation. The first two are considered for the gate in closed situation and are discussed in section 4.3.1. The third case is the maximum design head during opening of the gate and is determined in functional requirements of the project (11). Salinity of water is considered while calculating these loads.

Salinity

Difference in density of water between two sides of the lock complex is important when calculating the hydraulic loads on the lock gate. Since the largest horizontal loads on the structure are the hydraulic loads, taking the salinity of water into account, has a considerable contribution to the design loads on the structure. Water density has been measured as below:

Salt water density (North Sea) = 10.22 kN/m^3
Sweet water density (North sea channel) = 10.00 kN/m^3

Wave loads

Next to hydrostatic water pressure, wave loads make a considerable proportion of hydraulic loads on the gate structure. characteristics of the design waves can be seen in Appendix A. However, important issue on calculating the loads is the method which is used for estimating hydrodynamic water pressure on the gate. In extreme wave condition, method of Goda (12) and (13) is used. For wave loads during the opening/closing of the gate, method of Sainfluo is used. A brief study on the proper method for calculation of loads is given in Appendix B.

Hydraulic loads are applied as uniformly distributed line loads on the curved beam. Figure 4-10 shows the load magnitude for the three load cases. These values are calculated based on the diagrams in Figure A 1, Figure A 2 and Figure A 3 in Appendix A.

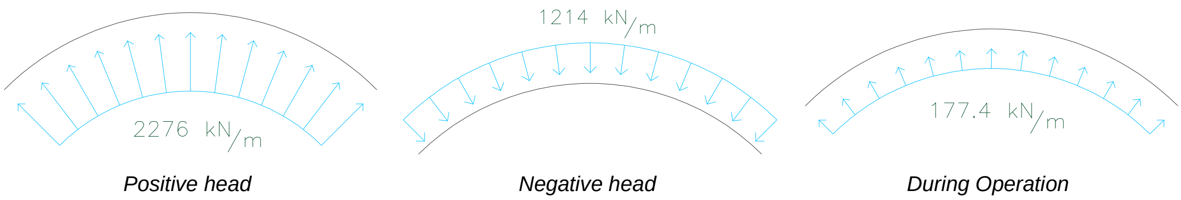


Figure 4-10: 2D Distributed design hydraulic loads on curved beam (conceptual design)

4.3.2.2 Self-weight

Large scale of the structure automatically implies that the gate is an extremely heavy structure. Predicting self-weight at the beginning of the design process is rather difficult. The initial guess had been taken by simplifying the problem into a curved beam and calculating the required cross-section based on a rough estimation of the loads and resistance. Consequently, total weight of the structure, was estimated to be around 4000 Tons, taking into account for the stiffeners and elements which may have not been considered in simplified cross-section. In the next chapter, total weight of the structure is calculated with more precision.

4.3.2.3 Buoyancy

The magnitude of the buoyancy force is directly dependent on the design. Total weight of the structure, vertical bearing capacity and floatability are the contributing parameters which affect the buoyancy forces on the structure. Buoyancy force can be provided by buoyancy chambers as it is required for the stability of gate. Therefore, it needs to be estimated during the design process. Detailed properties of the buoyancy chambers can be found in Appendix D and section 5.6.2.

4.3.2.4 Driving force

The magnitude, point of application and direction of driving force is dependent on the design choices for driving mechanism and guidance system. In addition, these characteristics of the driving force also change during different phases of operation. Therefore, the driving force has to be determined specifically for different situations and based on the other design choices (or boundary conditions within each alternative) and the stage of operation which the gate is in.

4.3.2.5 Friction

One of the governing loads during the operation of the gate is friction. Friction loads are also dependent on the reaction forces and forces in the contact areas of the structure and the guidance system. Obviously, the friction force depends on the friction coefficient of the materials which are in contact. Static friction coefficient of materials that are used in the design, is presented in Table 4-1.

Material 1	Material 2	Static Friction coefficient
UHMWPE	Stainless Steel	0.16 (14)
Steel	Steel	0.40 (15)
Steel	Rubber	0.80 (15)

Table 4-1: Friction coefficient of materials

4.4 Principles and solutions

Throughout this section, the basic solutions and principles for concept development are introduced. Section 4.4.1 discusses the general shape and layout of the structure and based on the qualitative preferences, gives the geometrical starting points. The following sections, categorize the solutions regarding the main elements and aspects of the new lock gate. Each category, clarifies the solutions and the required measures in order to provide the concept into practice. The main purpose of this section is to widen the range of the conceptual solutions; however these concepts are filtered by certain primary criteria such as feasibility in a sense of theory and practice respectively. As discussed in chapter 3, current study is determined to deliver a preliminary design within its scope. Therefore, developing some of the concepts lies outside the scope of this study since they require a thorough investigation as they deal with uncertainties and unexplored regions of technology. Nonetheless, these concepts are introduced briefly for the future developments and the results and recommendations of this study are given to provide initial data.

4.4.1 General Layout

Section 3.2 provides certain boundaries for the design. Here, the variations for general layout of the gate are studied first and the main geometrical parameters and limitations are determined afterwards. Based on the given arguments in this section, starting points for general shape of the gate are chosen.

Water retaining side(s)

Functional requirements in section 3.2 demand a double sided water retaining. This can be delivered in two possible ways. First would be using two separate gates with a one-sided retaining function (Figure 4-12). Second option would be using a single gate with a double-sided water retaining function (Figure 4-11).

In order to determine which one of these options are preferable, the water retaining capability of the curved gate has to be evaluated at either sides (convex side and hollow side).

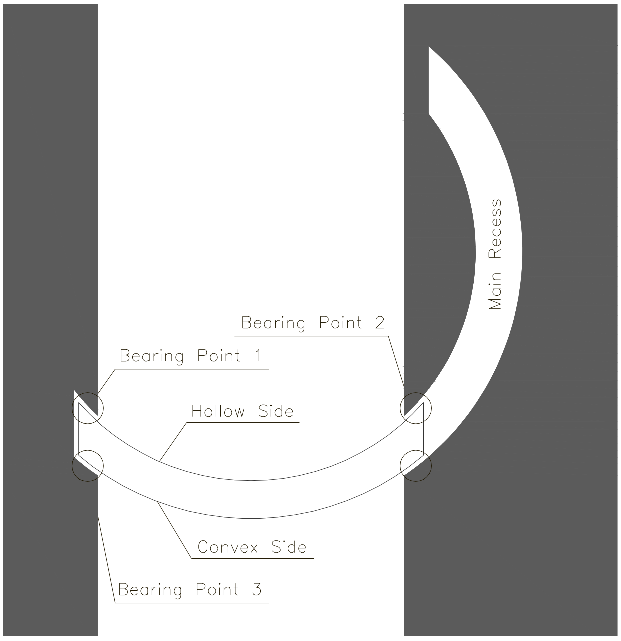


Figure 4-11: Names and Terms for the purpose of retaining side determination

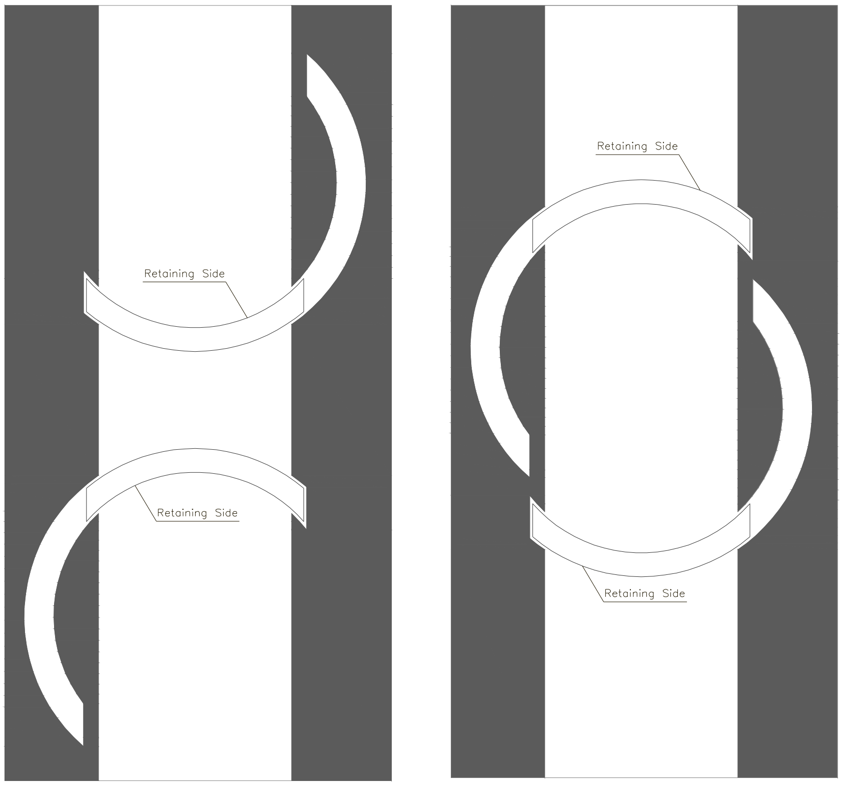


Figure 4-12: Alternatives with one-sided water retaining

- Figure 4-13 shows the difference between the general behavior of the gate for the cases which the loads are on convex side and hollow side. Notice that the actual behavior also depends on the structural system and the structural boundary conditions which are discussed thoroughly in section 4.4.3. Since the structural behavior does not give any limitations for the water retaining function at neither sides of the gate, this subject is not governing for determination of retaining side of the gate.

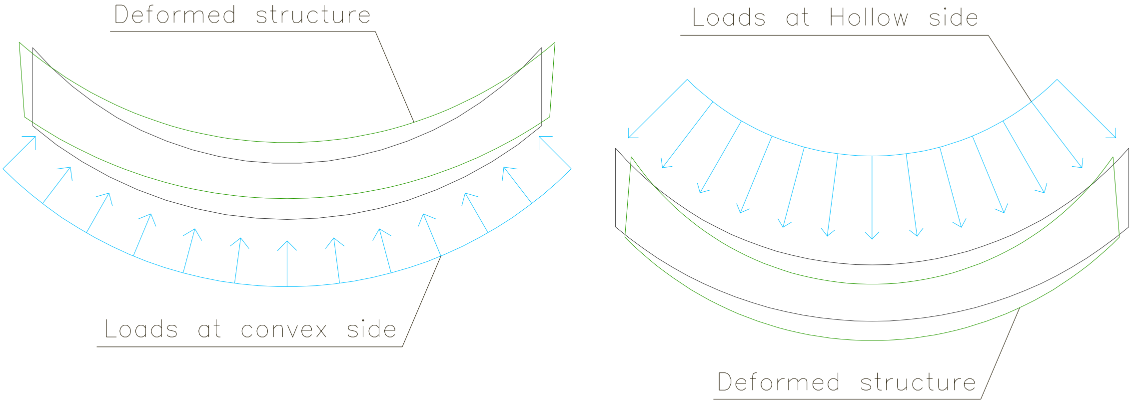


Figure 4-13: Gate behavior for different retaining situations

- In Figure 4-11, the bearing points are shown. High water at the convex side implies that the gate will rest on bearing points 1 and 2. As it can be seen, the concrete area behind the bearing points are relatively small. On the other hand, when high water is at the hollow side, the gate rests on bearing points 3 and 4 which provide a vast concrete area as support. Therefore, it is preferable for the stress level in concrete to keep the high water at the hollow side.

- Double-sided retaining introduces extra costs for the gate in comparison to the one-sided retaining. This extra costs include extra sealing provisions, extra bearings, and extra skin plates at both sides of the gate. On the other hand, making use of two separate one-sided retaining gates implies the extra cost of a gate structure, operating equipment, extra space in the lock head and extra maintenance costs. In conclusion, use of a single double sided retaining gate at each end of the lock chamber is preferred.

Reserve gates and Maintenance procedure
In spite of structural and operational provisions, predicted maintenance procedure may require an extra set of reserve gates located one at each end of the lock. Here, two possible maintenance procedures are described which can affect the design.

1. Maintenance on location: This procedure implies that the gate will be repaired in its recess. During the repair and maintenance procedure, the recess is closed and dried out and the reserve gate has to be employed. Therefore, this procedure requires two sets of gates with separate recess accompanied by separate equipment and devices (Figure 4-14).

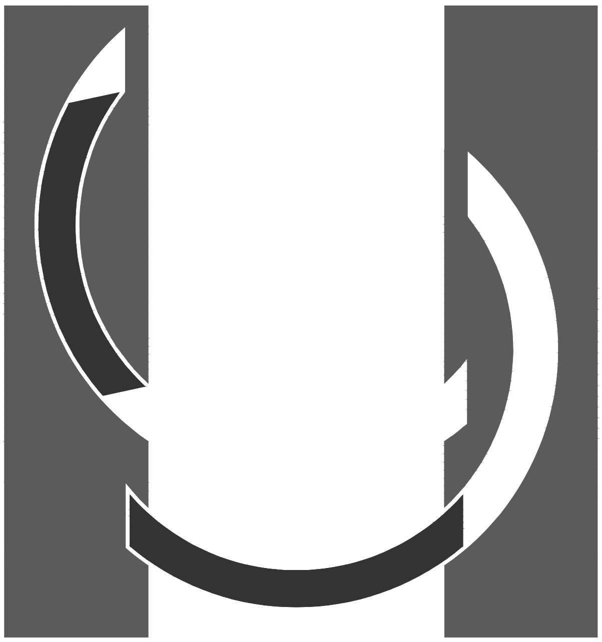


Figure 4-14: Maintenance on location

2. Maintenance by gate exchange: This procedure implies the defected gate will be exchanged by the reserve gate and it would be repaired at another location. This procedure does not require extra recess neither extra equipment. However, the gate needs to be checked for floating stability during the exchange procedure.

The costs of extra recess and operating device is considered to be much higher than floating provisions for the gate. Therefore, the second maintenance procedure (maintenance by gate exchange) is chosen as the starting point for conceptual design. Figure 4-15 shows the conclusion of the arguments in this section.

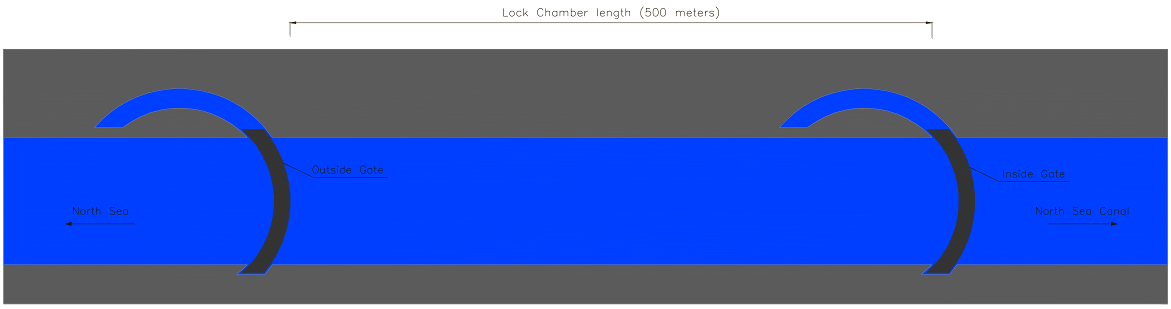


Figure 4-15: General Layout of the gates in the lock complex (Starting point)

Geometrical boundaries

Lock Width

Total width of the lock is 130 meters. The width of the lock chamber is 65 meters and that leaves 65 meters for the rest. The minimum required width for the side with main recess is estimated as below:

$$Minimum\ estimated\ width_{main\ recess\ side} = [25m]_{Main\ recess} + [3m]_{Concrete\ wall} + [8m]_{Traffic\ connection} + [6m]_{Operating\ equipment} \approx 42m$$

This minimum width for the opposite side (the side with the bearing recess) is estimated similarly as below:

$$Minimum\ estimated\ width_{Bearing\ recess\ side} = [5m]_{Small\ recess} + [3m]_{concrete\ wall} + [8m]_{Traffic\ connection} \approx 16m$$

Therefore, for the starting point, it is decided to divide the lock width into three parts (Figure 4-16):

- Bearing recess side (South side) 20 meters
- Lock chamber 65 meters
- Main recess side (North side) 45 meters

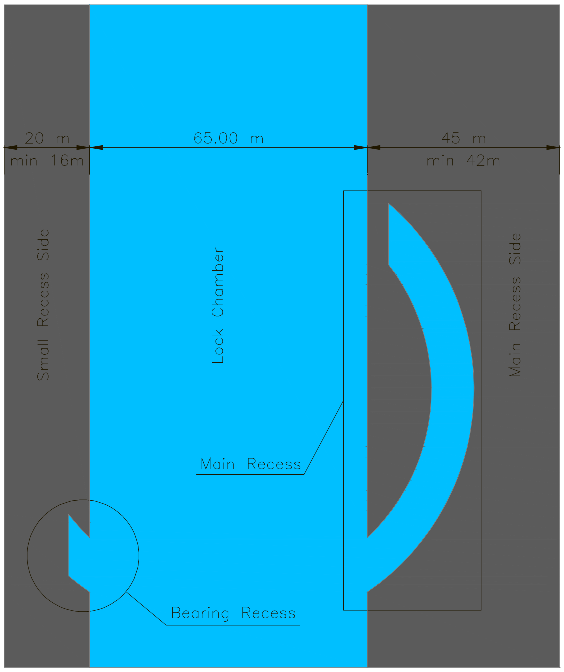


Figure 4-16: Lock width division

Gate Radius

In order to set a starting point for the radius of the gate, the limitations for this parameter have to be realized first.

- The minimum theoretical dimension for inner radius of the gate can be calculated by considering the following criteria: Total length of the recess needs to be at least equal to the lock chamber width so that the gate would fit in the recess. In this manner, the minimum inner radius belongs to the circle which its center lies on the centerline of the lock chamber and cuts through the chamber wall by the length of chamber width (Figure 4-17, Left).

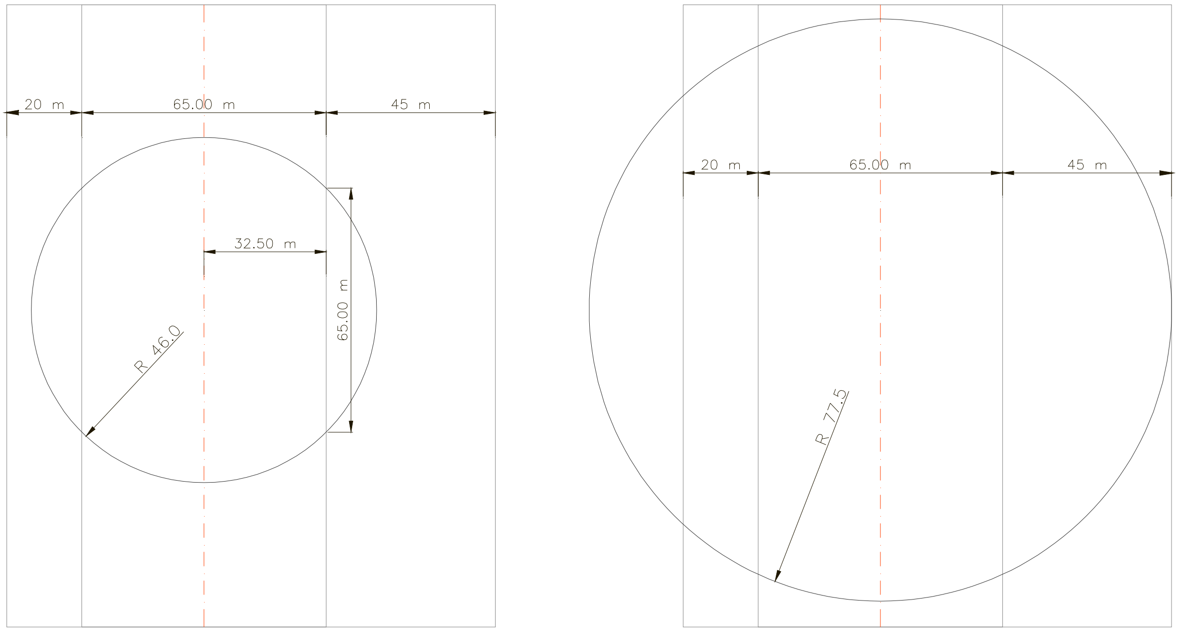


Figure 4-17: Limitation of Gate Radius (Left: Inner Radius , Right: Outer Radius)

- The theoretical maximum dimension for outer radius can be calculated by considering the following criteria: The outer radius of the recess has to stay within the lock boundaries. In this manner, the maximum outer radius belongs to the circle which its center lies on the centerline of the lock chamber and is tangent to the redefined boundary (Figure 4-17, Right).

- Figure 4-17 shows that the gate radius has to be between 46.0 and 77.5 meters. However, these values are rather theoretical and the practical range of the radius is smaller than the above. For clarification, an additional wall thickness of 3 meters will also be considered and subtracted from each boundary. So the range becomes R_{inner} > 49.0 m and R_{outer} < 74.5 m. Since the smaller radius for gate implies smaller total dimension, the minimum practical inner radius is chosen to be inner radius of the curved gate. Therefore, the outer radius will be determined by the required structural width of the gate (Figure 4-18).

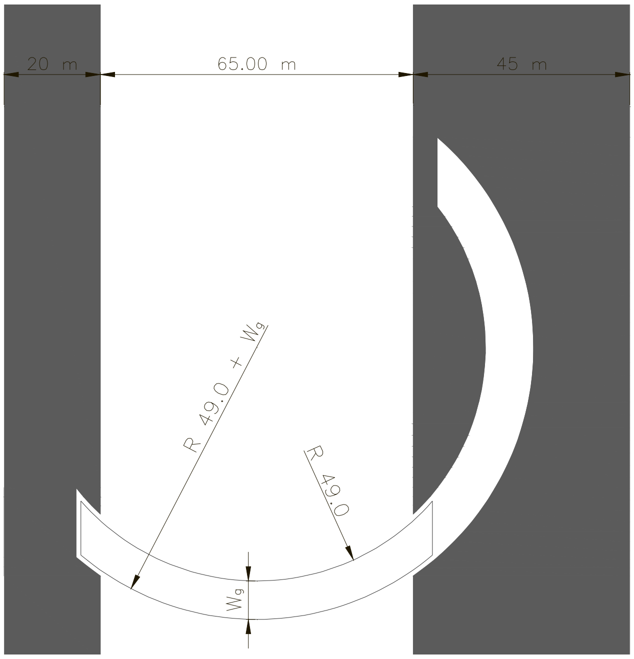


Figure 4-18: Geometrical starting point for the gate

4.4.2 Materials

Gate

Common choice of material for gate structures is steel (1). The following points can justify this choice in the current design:

- Due to the double-sided retaining function, main structural elements have to overcome both compressive and tensile stresses effectively.
- Due to the large scale of the gate, assembling, construction and possible repair of the gate is time-consuming. Therefore the preference is given to the material which the construction and maintenance is cheaper and faster.

Bearings and Guiding

The requirements for the bearings and guiding system is high strength, low friction and low wear. The following section describes the UHMWPE material which satisfies these requirements. Therefore the choice of material for bearing and guiding system is UHMWPE.

UHMWPE

Ultra-high-molecular-weight polyethylene (UHMWPE), is a subset of the thermoplastic polyethylene. UHMWPE is a very tough material, with a high impact strength (1.6 kJ/m) (16). The following advantages can be named for this type of material:

- Highly resistant to corrosive chemical
- Extremely low moisture absorption (~0%)
- Very low coefficient of friction
- Self-lubricating
- Highly resistant to abrasion, in some forms being 15 times more resistant to abrasion than carbon steel
- Odorless, tasteless, and nontoxic

4.4.3 *Structural System*

One of the governing and most effective choices of design for the innovative curved gate is the structural system. This section, studies the horizontal structural system and vertical structural system separately. For horizontal systems, the variations are quite different from each other and the choice considerably affects the design especially in terms of cost and details. As for the vertical systems, the variations are not broad and decision making is rather easier and clearer.

Horizontal Structural System

1. *Arched structural system (With pinned supports)*

The principle of arched structural system implies on a compression-only or tension-only behavior in the beam. Bending moments in such systems are relatively small and not governing in design. On the other hand, the axial forces are large and governing for cross-section determination.
The main advantages of this concept are:

- Efficient use of materials because of small cross-section
- Small deflections

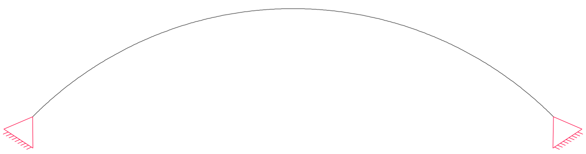
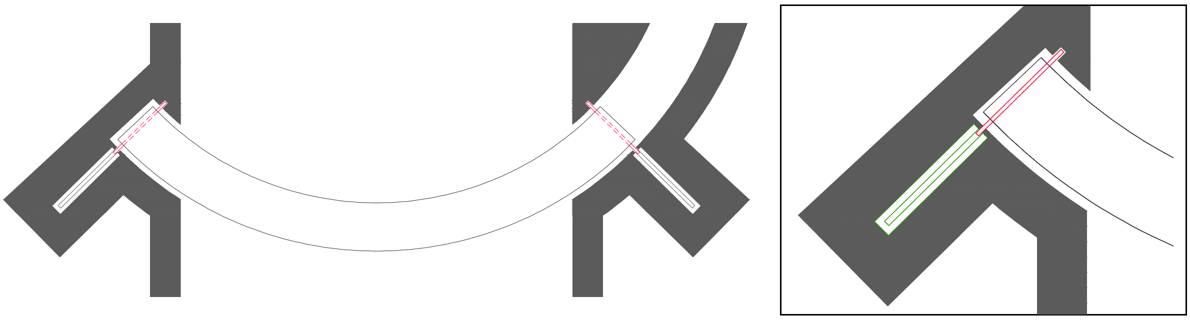


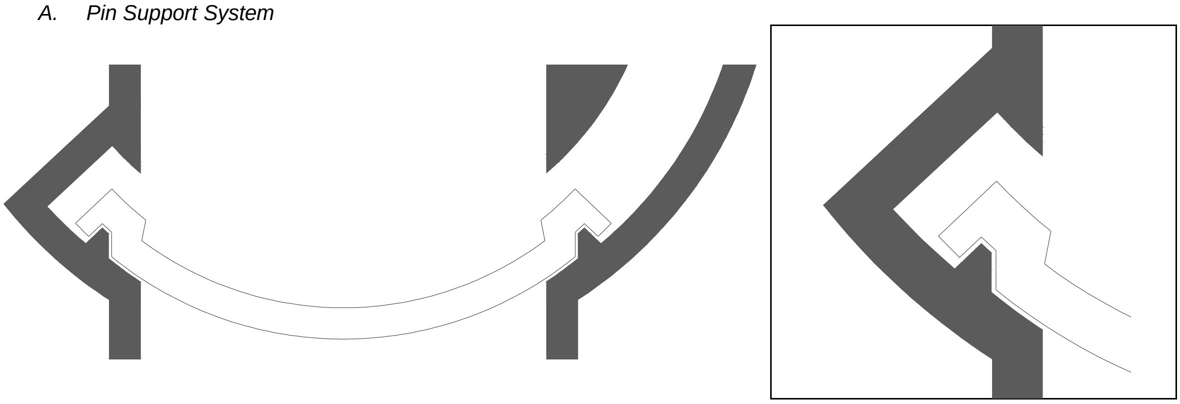
Figure 4-19: Structural model - Arched structural system

Figure 4-19 shows the structural model of this concept. As it can be seen, the end supports for the beam are pinned. The main challenge of this concept is providing a working solution for pinned support in practice. Figure 4-20 suggests three possible alternatives for this problem (5). These alternative solutions work either on the basis of bringing the gate to the support or bringing the support to the gate.

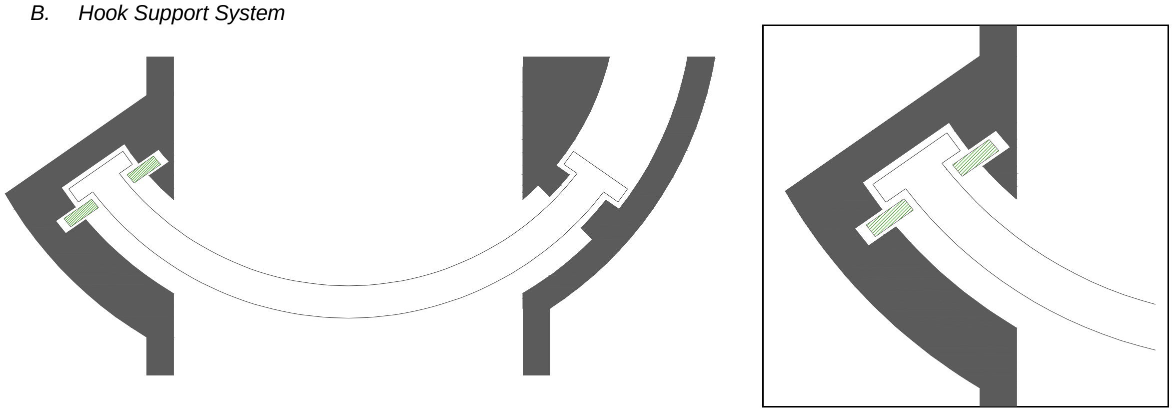
- In Solution A (Pin support), at each end of the gate a number of openings are considered and a pin will pass through each of these openings. Pins are operated by a special device which is situated and secured in lock head.
- Solution B (Hook support) implies on moving the gate towards the support. This solution suggests that the gate moves towards the closing position and then it would be forced towards the hook structure in the lock head which can then act as an arched system.
- In Solution C (Wedge support), the gate is constructed with T-shaped ends. Gate is supported on concrete notches at one end and by steel wedge elements at the other end.



A. Pin Support System



B. Hook Support System



C. Wedge Support System

Figure 4-20: Alternative solutions for providing pinned support (5)

2. Beam structural system with parallel supports (Roller supports parallel to lock centerline)

Principle 2 (and also principle 3) implies on the flexural beam behavior. This principle suggests that the beam will be supported by two roller supports at each end which can prevent any movement in the longitudinal direction of lock chamber. Notice that movements in the perpendicular direction are bound by friction between the gate and the supports. In addition, the brake system of moving device will prevent the gate from transverse movements. Therefore, the beam is modeled like the beam in Figure 4-21. Bending moments are relatively large in this principle and are governing for the design of cross-section.

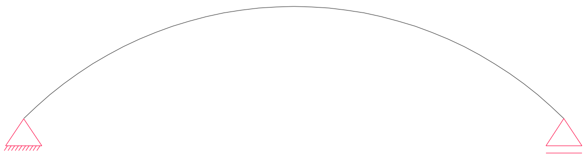
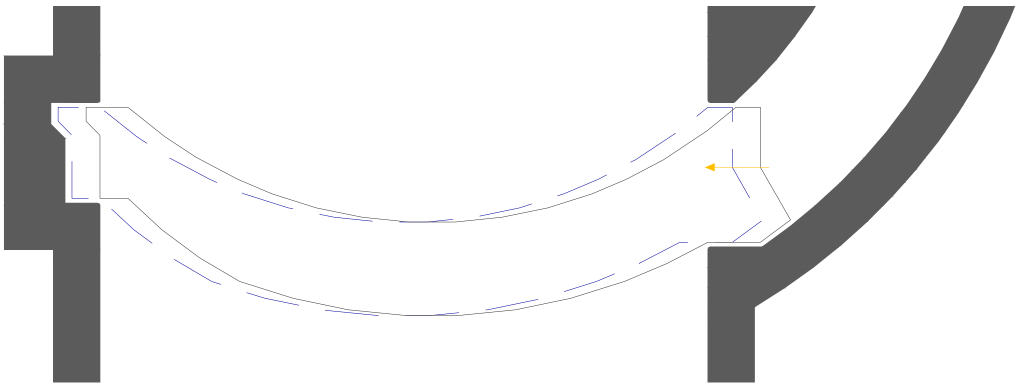
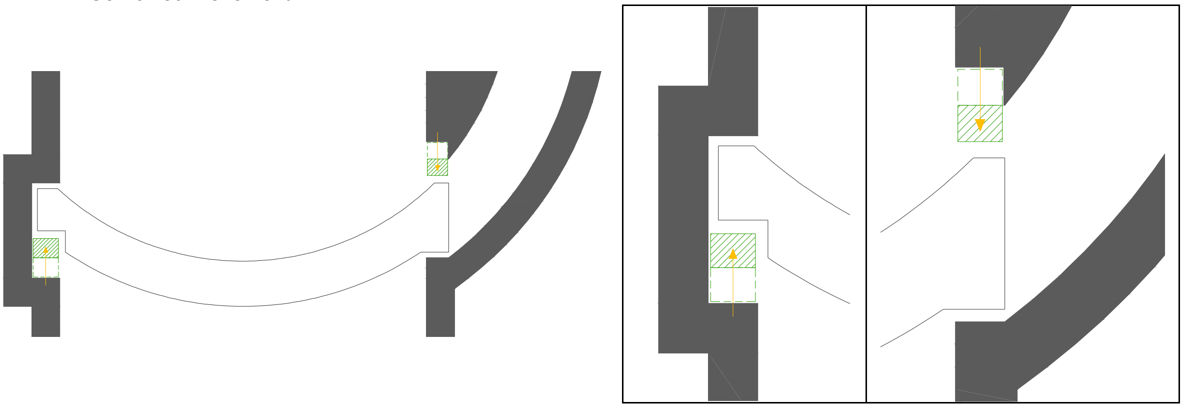


Figure 4-21: Structural model - Beam structural system with parallel supports

The main challenge in this principle is providing the parallel supports. This problem occurs due to the geometrical shape of the lock head, gate and its rotational movement. Therefore, in order to solve the problem, these characteristics have to be adjusted. Figure 4-22 suggests two alternative solutions for providing the parallel supports.



A. Combined movement



B. Movable supports

Figure 4-22: Alternative solutions for providing parallel supports

- Solution A (Combined movement) introduces the idea of having a combination of rotational and straight movement in sequence. It implies that during the closing operation, the gate will rotate from the recess towards the chamber and when it reaches the point where no further rotation is possible (solid line in Figure 4-22-A), it will move horizontally towards the other bearing recess and it stops (dashed drawing in Figure 4-22-A).
- Solution B (Movable supports) works on the basis of bringing the supports to the gate and the movement of the gate remains solely rotational. As it can be seen in Figure 4-22, the shape of the lock head and the shape of the gate are both adjusted to form the desired structural system. However, since the movement of the gate is not to be disturbed in this alternative, two of the bearings have to be movable. These bearings are retracted to the lock head during the closing/opening process and will be pushed back towards the gate bearing points (presumably by a hydraulic jack) once the gate has been closed.

3. *Beam structural system with sloped supports (Roller supports perpendicular to gate centerline)*

Flexural beam behavior is the main structural behavior in principle 3. This principle suggests that the beam will be supported by two roller supports at each end which can prevent any movement perpendicular to the gate axis. Movements along the gate axis are bound by friction between the gate and the supports. In addition, the brake system of moving device will prevent the gate from transverse movements. Therefore, the beam is modeled like the beam in Figure 4-23. Bending moments are largest in this principle and are governing for the design of cross-section.

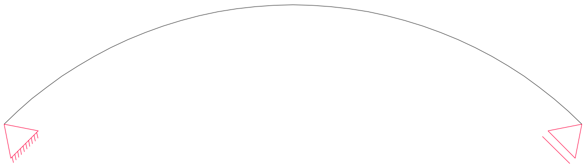


Figure 4-23: Structural model - Beam structural system with sloped supports

The main challenge in this principle is providing sufficient strength for the supports in lock head. As it can be seen in Figure 4-24, a small length of concrete in the bearing has to provide enough strength for resisting the internal force caused by reaction force. In this manner, two main solutions can be given in case of low resistance in concrete:

- Reinforcement, prestressing or use of higher strength concrete
- Use of steel structure as a bearing in lock head

Figure 4-24: Providing beam structural system with sloped support

Bottom horizontal support

All the principles that were introduced in this section, are based on the assumption that the gate is supported horizontally only on two ends. In some cases (10), the deformation of the gate becomes more than acceptable. Therefore, the alternative of having extra supports somewhere in between the overall horizontal supports could be studied (Figure 4-25). Notice that this alternative can be applied on all the three principles.

In order to distribute the horizontal load between the bearing points, and in order to prevent contact between the bottom bearing and the guiding track, a few centimeters distance may be kept between the bottom horizontal bearings and bearing points in chamber bottom.

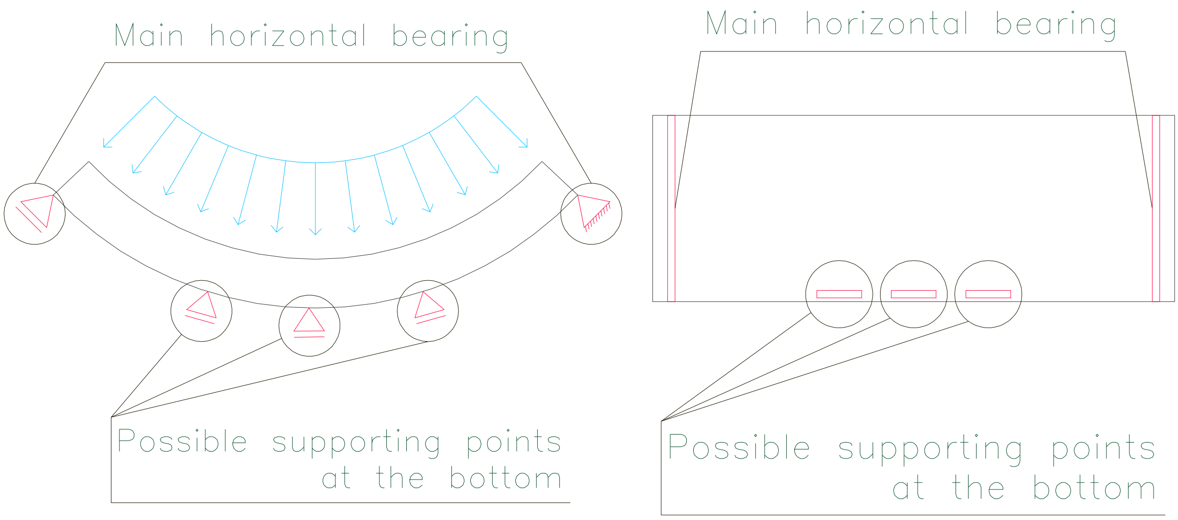


Figure 4-25: Horizontal support at bottom

Vertical Structural System

Basically, number and location of supporting points determines the structural behavior in vertical plane. In this section, it is tried to provide a starting point for vertical supports. Therefore, the variations for number and location of the supporting points are discussed and evaluated qualitatively:

- The gate structure can be supported on a continuous line over the whole length. This variation is theoretically a good and reliable option in a sense that due to the distribution of reaction force over the length of the gate, stresses are small and the degree of indeterminacy is infinitely high which guarantees the stability of the gate against overturning. However in practice, this is in fact a negative point because it is almost impossible (or at least extremely expensive) to achieve such small tolerances and build a gate which is in effective contact with its foundation at all its length. This problem still remains when the number of contact points reaches to 4 contact points. In general, when the structure is indeterminate, a number of supports (equal to the degree of indeterminacy) are redundant and all the supports have to be designed as if these redundant supports were not functioning. This increases the costs for no good reason.
- In case of 3 supporting points, the curved gate structure is still indeterminate and the vertical supports are still redundant. However, this redundancy cannot be understood when the gate is being studied only in vertical direction. For understanding this, the horizontal supports (or guidance) should also be considered in the global support system. Figure 4-26 shows the gate with a guidance and three supports. One out of these three supports is redundant and therefore, the supports have to be designed accordingly. Therefore, since it is inefficiently expensive to opt for more than 2 supporting points, two support points at the bottom would be the final choice. Needless to say, that gate will not be stable against rotating around Y-Axis (along the chamber) if only one support is used.

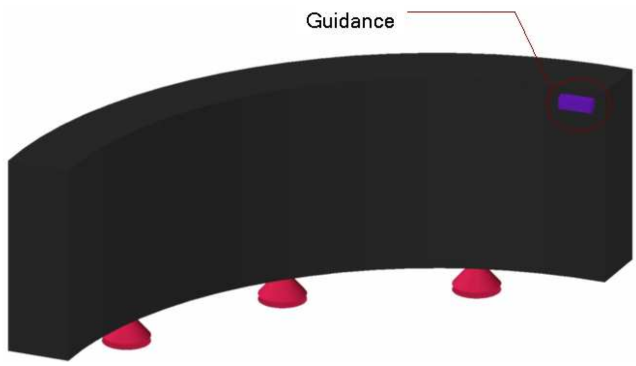


Figure 4-26: Gate with three vertical supporting points

- As mentioned in section 2.2.2, one of the advantages of the curved gate concept is its symmetry. This principle will be kept in the choice for the supporting location. Therefore, the supporting points will be situated on the gate centerline symmetrically. In order to determine their position along the centerline, the position of the center of gravity (CoG) will have to be first determined. If the supports are situated in line with CoG, there would be no overturning moment around that line. This has the advantage of making the horizontal and vertical structural load bearing systems separate. Figure 4-27 shows the choice of supporting points and the vertical structural model of the gate.

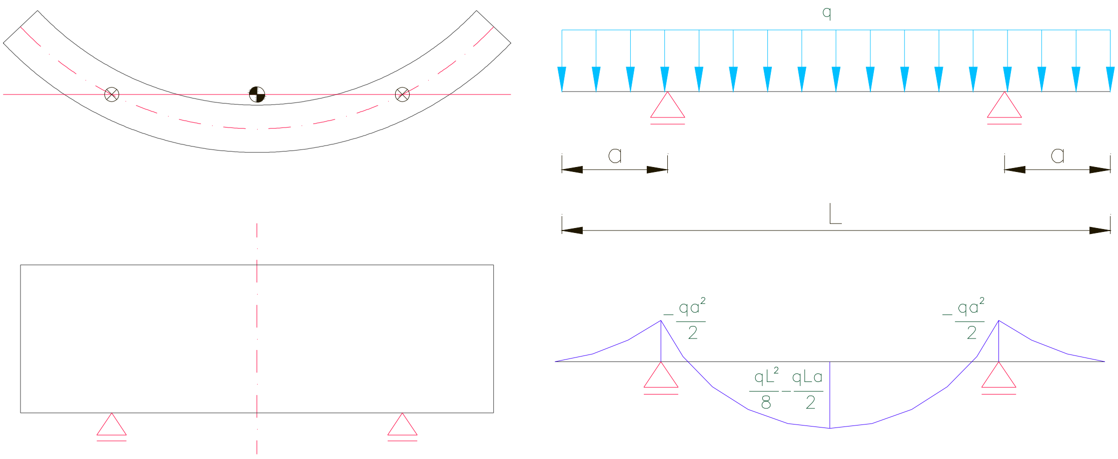


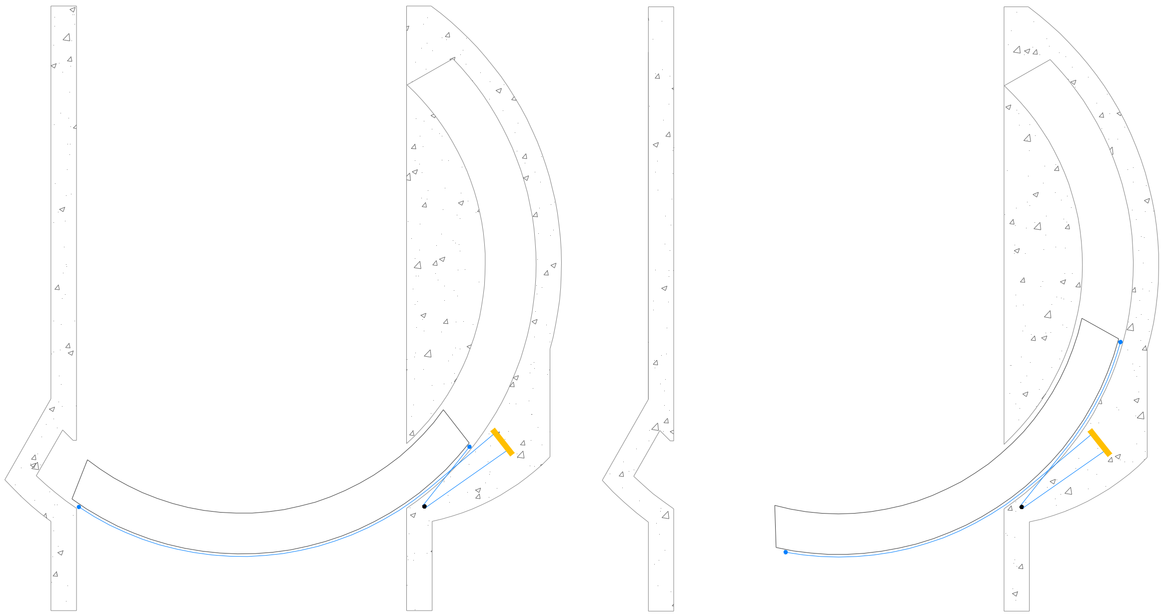
Figure 4-27: Choice of starting point for vertical supporting points and illustration of structural model and resulting bending moments

4.4.4 *Operating System and Driving Mechanism*

The dimensions of the gate structure, special rotational movement, eccentric driving force and excessive friction imply that the operating system should be a large, special and expensive compartment of the lock gate. The operating system has to provide sufficient force and power to overcome the forces during the opening/closing process and operate the gate in the desired time. In addition, it should provide a stable condition through the whole operation and it should also be able to provide horizontal reaction force during closed situation. This section discusses a number of relevant alternatives for the driving mechanism and the proper guidance system.

1. *Cables*

In this alternative, cables are used to move the gate with the help of the operating system situated near the opening of the main recess. The operating system consists of engines, a gear box, a brake, drums and cables which hang outside the gate structure and close to the skin. The cable operating system is often used in straight rolling gates [reference panama] but it has never been applied in such geometry and scale of the curved gate in current design. Figure 4-28 shows the operating steps with the cable drive system.



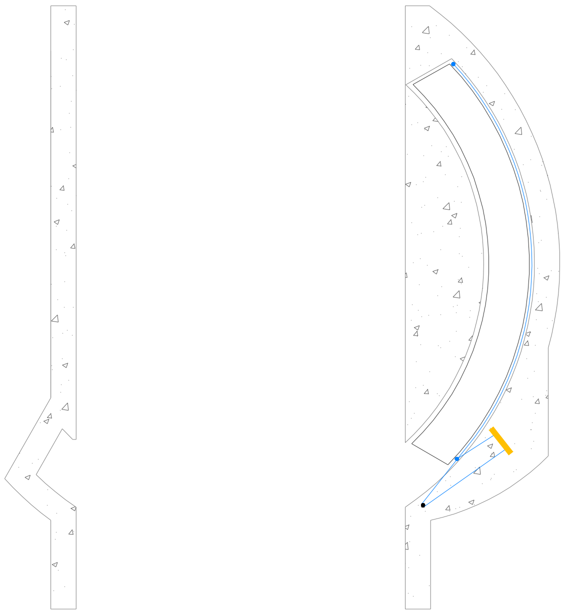


Figure 4-28: Cable Operating System

The following advantages can be named for use of cable system drive as moving mechanism:

- Sufficient experience with cable drive operational system.
- Easy to inspect and maintain.
- No conflict with gate fluctuations

And the disadvantages are:

- Extra heavy weight of the cables.
- Need of synchronization in case of multi cable drive
- Relatively high need of maintenance
- Possible movement lags due to cable deflections

2. *Racks and Pinions*

This alternative has become one of the common solutions for the movement of curved gates in general such as masslland barier. In this concept, a row of steel teeth (racks) is attached to the gate in the level where the pinions are located. When the pinions start to rotate, the racks on the gate will engage in the movement of the pinions and with the help of guiding system, the gate will follow the intended curved path and reaches to its final position. In an alternate operating device, friction wheel drive concept is used which is similar to the concept of racks and pinions but instead of engaging the teeth, the movement is transformed by friction in contact points. For both operating devices, very small tolerances are predicted and in case of friction wheel drive, the wheels have to be pushed by a certain device towards the gate in order to keep the required pressure on the contact surface.

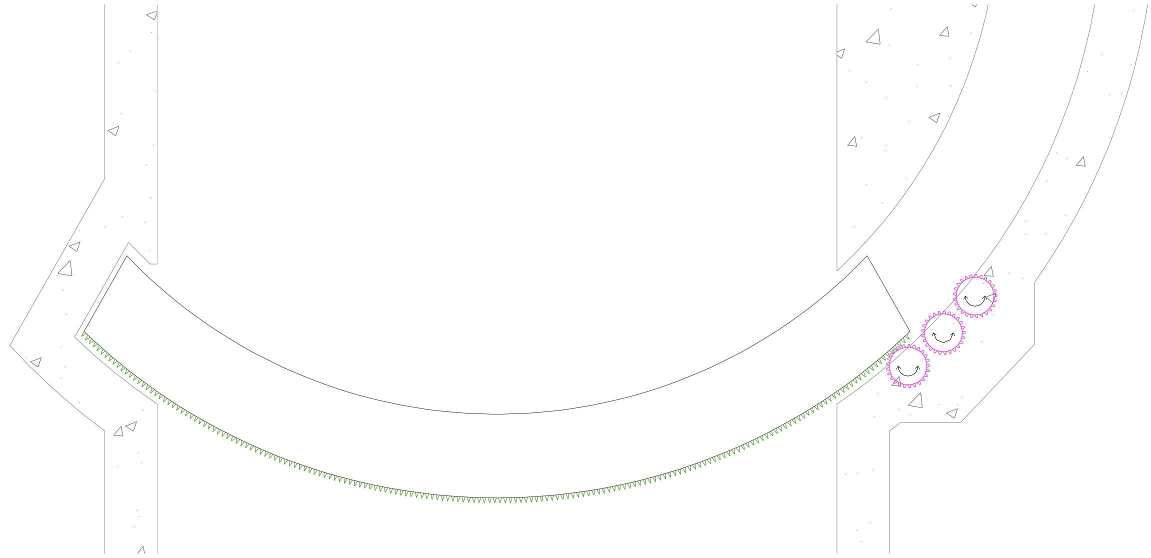


Figure 4-29: Racks and Pinions operating system

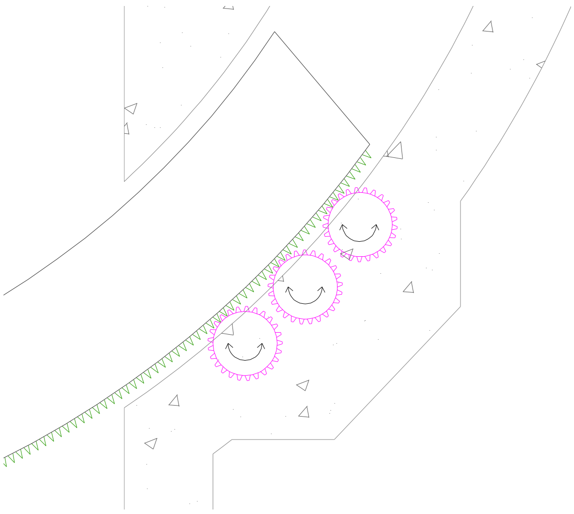


Figure 4-30: Racks and Pinions in movement

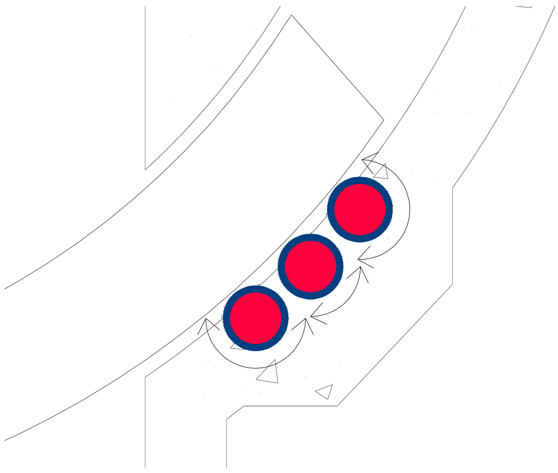


Figure 4-31: Friction wheel drive alternative

The following advantages can be named for use of racks and pinions (or friction wheel drive) as moving mechanism:

- Instant and effective movement control
- Relatively longer life time (in comparison to cables)

And the disadvantages are:

- Directly affected by gate fluctuations
- need of constant pressure on the contact surfaces
- Difficult maintenance

3. Locomotive

Use of locomotive as an operating system has been done for numerous draw bridges and in lock complexes the locomotives are used for transporting the vessels inside the lock chambers for example in lock complexes in Panama canal. However, it has never been used as the main operating device for the movement of the gate. The locomotive moves based on the same basis as racks and pinions. The Pinions are located inside the locomotive and as they are being operated by the engines and gearbox which are also located inside the locomotive, they turn and move along the predicted path by engaging with the rack along the path. Additional guidance are required for the locomotive in order to stay in course. The locomotive system is intentionally pushed towards the racks in order to guarantee the constant effective contact with the racks. Figure 4-32 shows the general layout for this concept.

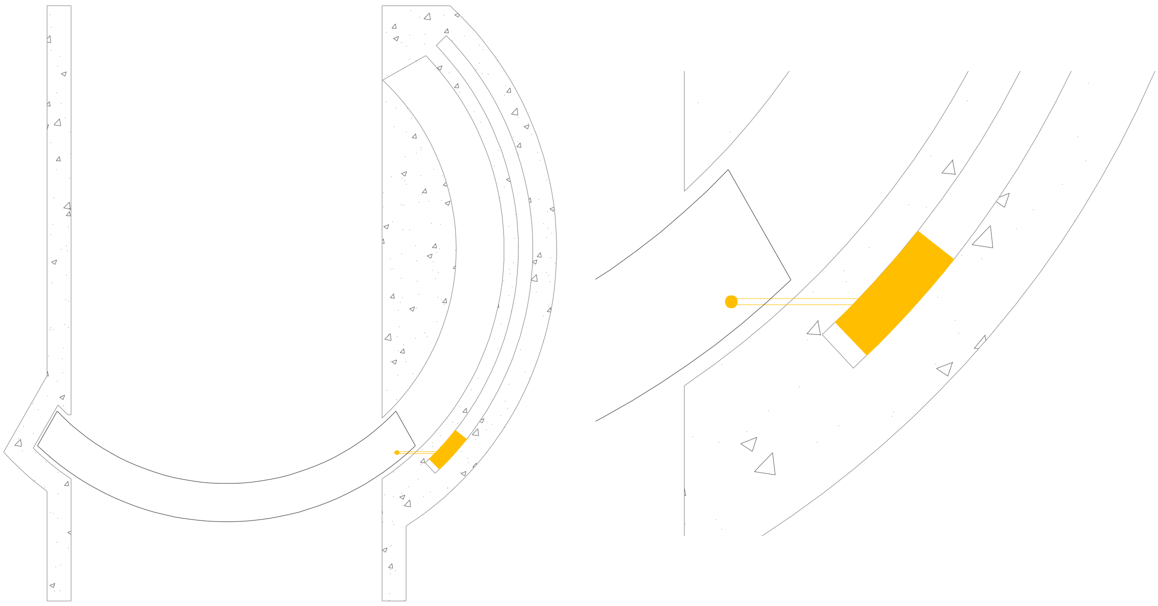


Figure 4-32: Locomotive Operating System

The following advantages can be named for use of locomotive as moving mechanism:

- Sealed and separate environment of the locomotive makes the necessity of the maintenance low and the procedure simple.
- Not directly affected by the gate fluctuations
- Possibility of use in case of combined movement system

And the disadvantages are:

- Requires a large and heavy connecting device between the gate and locomotive
- Lack of experience in current special layout and scale

Guidance system

In addition to the main operating system, the guidance system is responsible for movement of the gate in a controlled situation. In the case of curved gate, the guidance system has to work together with the operating system in order to make the rotation of the gate possible. In that manner the minimum guiding points on the gate are three points to take care of the stability of the gate during the movement. At the position of the vertical supporting points at the bottom of the gate, there will be guiding points as well. The third point needs to be at the top of the gate in order to maintain the stability of the gate along the whole height and since it needs to be in contact with the guidance track on the lock head at all the times, it would be located at the recess side of the gate. Figure 4-33shows the position of the guiding points on the gate.

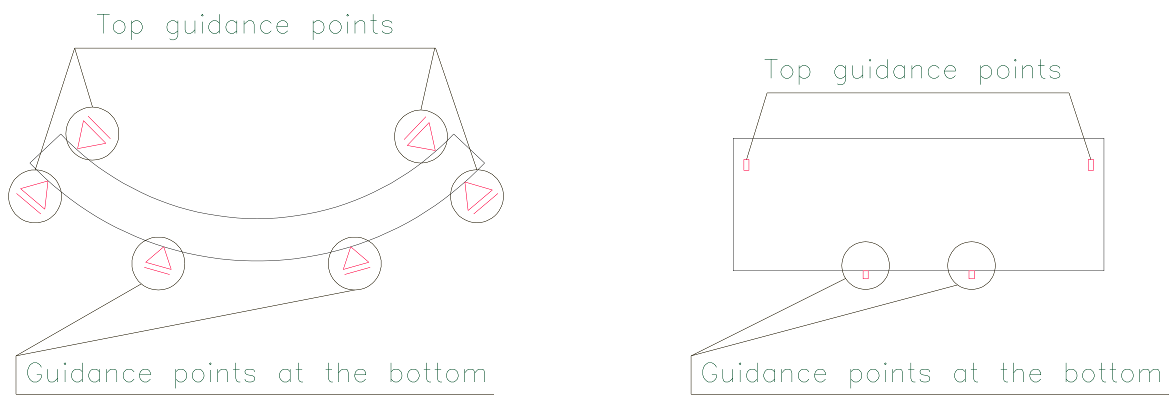


Figure 4-33: Position of guidance devices

The guidance devices help the movement of the gate in the sense of guiding the gate in the predefined path. However, the guidance devices introduce undesired friction forces which the driving force needs to overcome. Therefore it is important to choose the guidance devices wisely in order to decrease the friction. Below a number of solutions are provided:

Steel panels

The common device for guidance is steel panels. Use of steel panels is cheap and easy to construct and maintain. The friction coefficient for this solution is 0.17 according to section 4.3.2.5.

Hydrofender

Use of horizontal hydrofender is an innovative alternative for the guidance device. The principle in horizontal hydrofender guidance device is to reduce the friction by the help of creating a water film between the device and the guiding track. In spite of its low friction coefficient (0.01), this solution has no experimental ground to rely on and it is expensive and difficult to construct. The reliability of such system is low due to lack of enough knowledge and undeveloped technology. (17)

Rolling wheels

Use of roller carriages in vertical support and guidance system is a common engineering solution. Horizontal guidance device needs to resist larger forces during the movement of the gate in comparison to the vertical supports. The friction coefficient for this alternative is very low (0.01). On the other hand, the dimensions of these wheels are supposedly large and the wear in the guidance system is high. The cost for construction and maintenance is relatively higher in this alternative and in addition, this alternative has also never been used as guidance mounted on the gate structure itself but occasionally on the lock head.

4.4.5 *Bottom Support System*

Bottom support system is a multifunctional device. This device has to provide vertical reaction for the structure and also make the movement of the gate possible by providing a low friction mechanism during movement. In other words, the bottom support system is also part of the guidance system. Therefore, by choosing bottom support system, also the guidance system is determined. The following choices are studied in this section:

- Roller carriage
- Hydro-foot
- Sliding
- Floating

Roller carriage

The very traditional way of a low friction guiding is use of wheels or better said roller carriages as the support system. In this solution, a set of wheels are placed inside a carriage which can roll above the predicted rails. This carriage is connected to the gate via an elastomeric support. The fluctuations of the gate during the opening/ closing operation would not be transmitted to the carriage hence it would be able to roll on the rail without the danger of falling off track. Roller carriage has never been used in such scale for small radius.

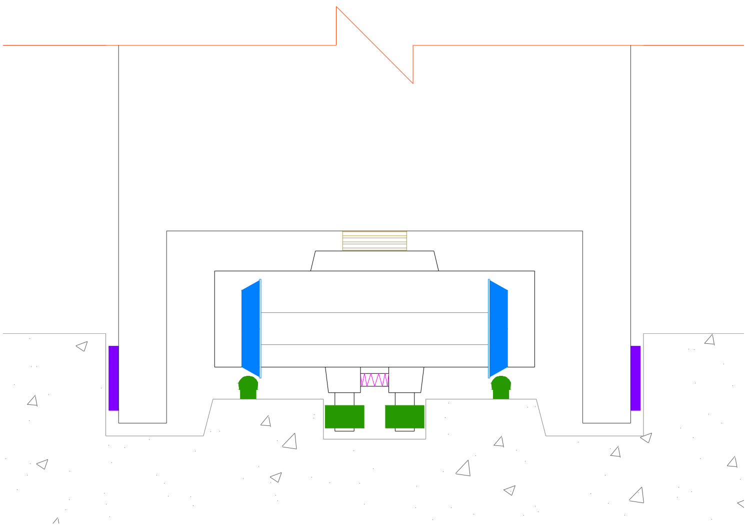


Figure 4-34: Roller carriage support system (cross-section)

The following can be named as advantages of the roller carriage:

- Sufficient experience in practice and design
- Possibility of handling the curvature of the rail due to wheel's special shape and slope
- known maintenance procedure

And the disadvantages are:

- High wear and necessity of maintenance
- Difficult underwater maintenance or exchange
- Unable to undertake a combined movement track
- Very difficult to construct the curved rail with acceptable tolerances.

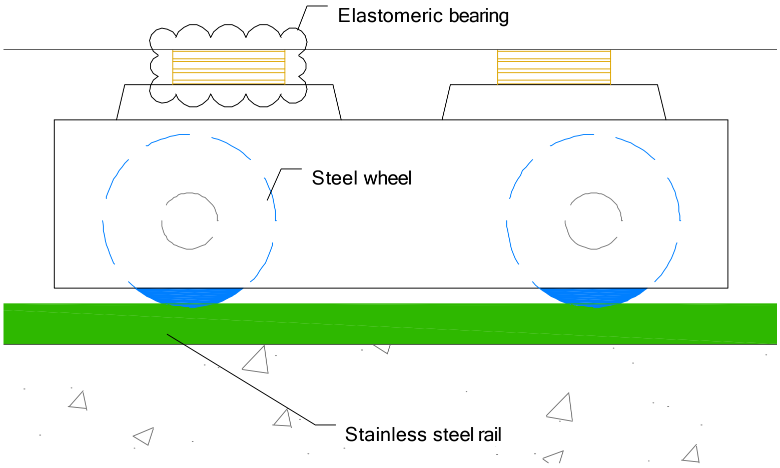


Figure 4-35: Roller carriage support system (side view)

Hydro-foot

Recent technology provides a solution of hydro-foot support and guiding system which is based on the "Hydro-guiding" principle. The principle relies on the concept of sliding over a thin water film. The hydro-foot is supplied with a water pump which provides enough pressure at the contact surface of the bottom support and the corresponding hydro-track. The hydro-track is usually made with UHMWPE. The main reasons for preferring this material over steel are mentioned in this section. The friction coefficient can get decreased down to one-hundredth of the original friction coefficient in the absence of water film. Experiments show that a one-thirtieth decrease is an upper limit for the sliding friction with water film. (14) The theory and field of application for hyfro-foot can be found in "Testrsultaten Hydrogeleiding" D. Ros and "Gate design for large, high head locks", J.W. Doeksen.

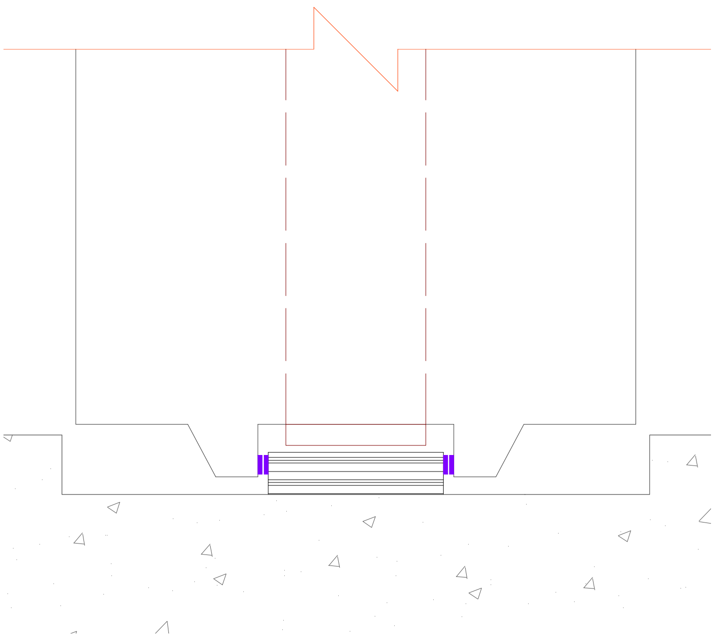


Figure 4-36: Hydro-foot as bottom support system

The Advantages of using hydro-foot as the bottom support system are:

- Low wear and tear
- Low maintenance necessity and easy maintenance and replacement procedure
- Redundancy of the sliding system
- Lower total cost in comparison to roller carriage

And the disadvantage are:

- Lack of sufficient experience in practice
- High pressure pumps required

The main reasons for making the sliding foot of stainless steel and plastic hydro-track are (18):

- Damage in the hydro-track of plastic does not cause any damage to the stainless steel sliding surface; A damaged hydro-track of stainless steel acts like a cheese slicer for the sliding surface of plastic elements.
- The second reason is that the unevenness of the hydro-track of plastic during the passages of the stainless steel sliding surface by wear and deflection becomes smaller: the hydraulic path evens out "automatically".
- The third reason is that with a sliding foot of stainless steel, the more noble surface is much smaller than in a hydro-track of stainless steel. This will increase the likelihood and extent of galvanic corrosion substantially.
- The fourth reason is that the life-time of a hydro-track of synthetic material can be large because it is a greater wear volume available there.

Sliding

As oppose to the previous alternatives, this concept investigates the possibility of using a simpler bottom support device which does not brig the advantage of the hydro-foot and roller carriage which is frictionless guiding. This alternative implies on lowering the costs and complications in the bottom support system in exchange of higher friction forces and consequently higher required driving force. Notice that the support system in this concept needs to have high wear resistance. Or otherwise it requires intensive maintenance care during the lifetime of the gate. The sliding device can simply be a round metal pad made from a high resistance material. The friction coefficient also needs to be as low as possible. This alternative however is introduced briefly in this section and it cannot be a reliable solution for this design. The main challenge is finding a proper material with the characteristics as described in this paragraph. Further investigation in using the state-of-the-art materials can lead to creation of more innovative and developed concepts.

Floating

Floating of the gate during daily operation is also another possible solution for design of the bottom support system. In this situation, the gate will float during the opening/closing operation and be brought back on its supports on the lock bed when the water retaining function is desired. This alternative simplifies the bottom support system the most by decreasing the requirements of the support system. However, the floating of the gate in such scale is considerably more complicated and more delicate operating mechanism. Floating mechanism needs a whole set of guiding device system along the gate structure and the lock chamber. Due to the complications of this concept and high level of risk, this concept is not developed any further. However, because of its advantages in reducing the driving force and simplifying the support system, it worth future investigation in the engineering studies.

4.4.6 *Sealing*

The variations in the sealing system of the curved gate do not cross the limits of current technology and common practice. However the intrinsic requirements of the design imply that the sealing system needs to be as efficient and less conflicting as possible. Less conflicting can be explained by the least interfering in the operation process for instance zero or very low friction. Below, the variation of the sealing systems and the variations for the type of the seal are discussed:

Sealing system

The sealing system can be applied on double lines of the gate or only on one line at the bottom of the gate. In general, the choice depends on the seal type that is being used at the bottom of the gate. As mentioned above, the least interference is expected from the sealing system. The single line seal is arguably cheaper than the double line seal from the construction point of view. On the other hand, the maintenance for the single line seal can be more expensive. Figure 4-37 shows the sealing members at the bottom of the gate for single line option and for the double line option. It can be seen that the single line sealing member, has to move and operate in a narrow chamber at the bottom of the lock bed. This becomes an issue for the sedimentation of the chamber during the lifetime of the gate. The narrow chamber at the bottom of the lock bed is difficult to clean and it will be filled very fast. Therefore, if this option is selected, a reliable mechanism for washing the mud out of the narrow chamber should be considered.

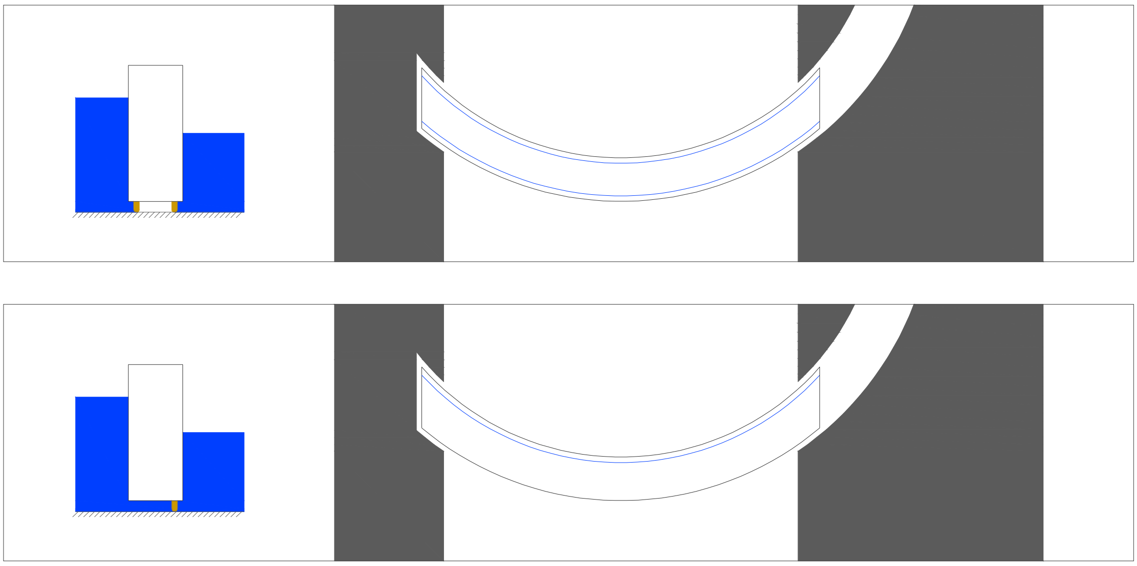


Figure 4-37: Sealing variations, Double sided seal (Top) and single side seal (Bottom)

Sealing type

In today’s engineering world, there are numerous types of sealing devices and sealing elements. For this type of gate, the proper vertical seal and a proper bottom seal has to be chosen. The criteria are mentioned earlier in this section. Therefore, the following alternatives are considered.

Notice that for the special case of solution A of principle 2 (Combined movement in beam structural system with parallel supports) a special type of sealing device is proposed which its functionality is based on the hydraulic pressure difference. It is assumed that choice of a reliable sealing system has a low dependency and influence on the choices for other elements of the gate.

4.5 Calculations / Analysis of solutions

After reviewing the choices in the concept development stage of the design, each alternative and option has to be analyzed and quantified in order to make a more accurate decision based on the realistic estimations. Current section provides calculations for the introduced concepts in the previous section in the following categories:

- Structural Analysis
- Floating Stability
- Bearing and Guiding
- Driving Force
- Extra details

4.5.1 Structural Analysis

Criteria

In this section, the results of the structural analysis are presented for the sake of comparison. In order to unify the results for making a consistent decision, two criteria are defined in this section.

- First, the maximum allowable stress is 200 Mpa.
- Second, the maximum allowable deflection is between 30 and 40 millimeters.

The basis for these criteria is mainly the previous similar projects such as Panama Canal. For determining the allowable stress, only global stresses are considered. This means that the fatigue stress, local stresses and second-order effects are not included within this 200 Mpa and that is why this value seems relatively low.

As for the deflection, it has to be such that it does not cause a main function of the gate to stop. For example, large deflection can cause a leak through the sealing system and the water tightness of the gate will be disturbed.

Table 4-2 show the chosen width of the gate in different structural systems. All the relevant forces are shown in this section based on these chosen widths.

Structural System	Width	R	2θ
	m	m	°
1. Arched	2	50	81
2. Beam with parallel supports	10	54	74
3. Beam with sloped supports	12	55	72

Table 4-2: Chosen width and characteristics of cross-section for 3 principles

Figure 4-38 shows the distributed force and the simplified version of the force. In addition, it shows the corresponding details of the calculations in this section.

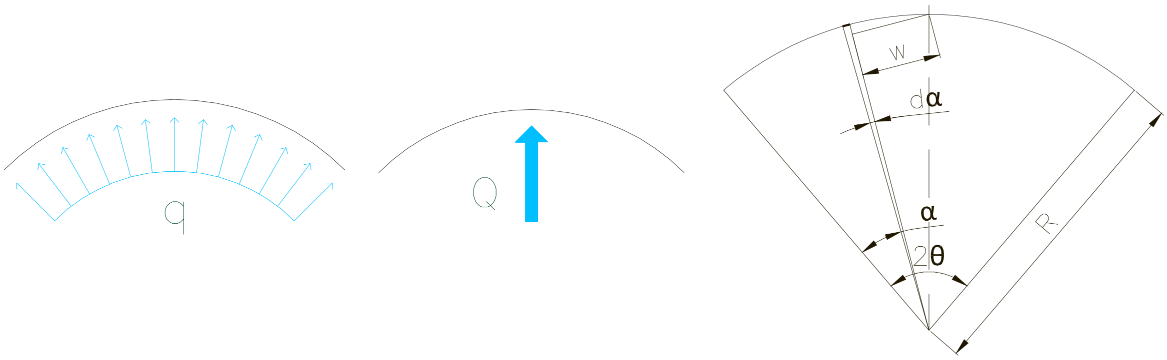


Figure 4-38: Calculation of total horizontal force

Total force on the gate is calculated as below and the results are presented in Table 4-3:

$$Q = \int_0^l q_v dr = \int_0^{2\theta} q.\cos(2\theta - \alpha)\, R d\alpha = qR[Sin(\theta) - Sin(-\theta)] = 2qRSin\theta$$

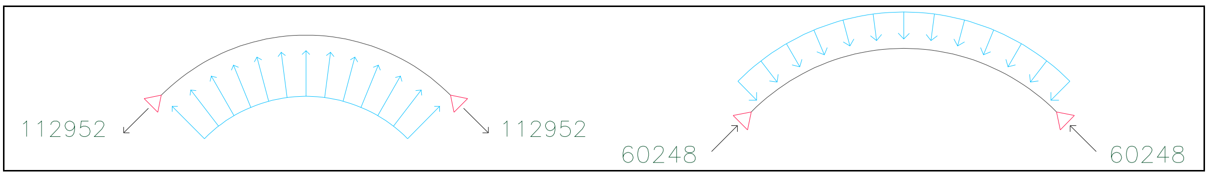
q = 2276 kN/m²		
R	2θ	Q
m	°	kN
50	81	147814
54	74	147931
55	72	147158

q = -1214 kN/m²		
R	2θ	Q
m	°	kN
50	81	-78843
54	74	-78905
55	72	-78493

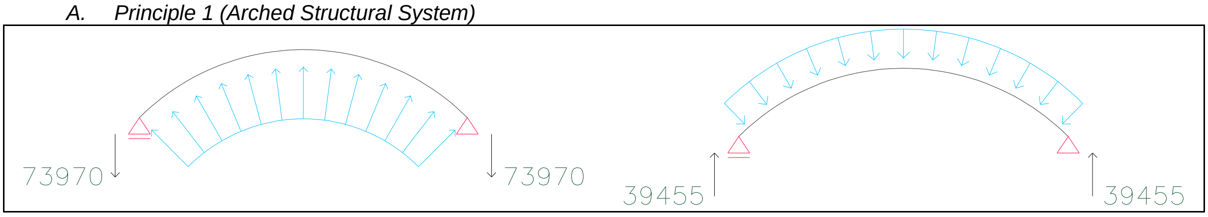
Table 4-3: Total horizontal force on gate

Once the total horizontal force is known, the reaction forces can be calculated by knowing the angle of the supports. Figure 4-39 shows these reaction forces in different alternatives.

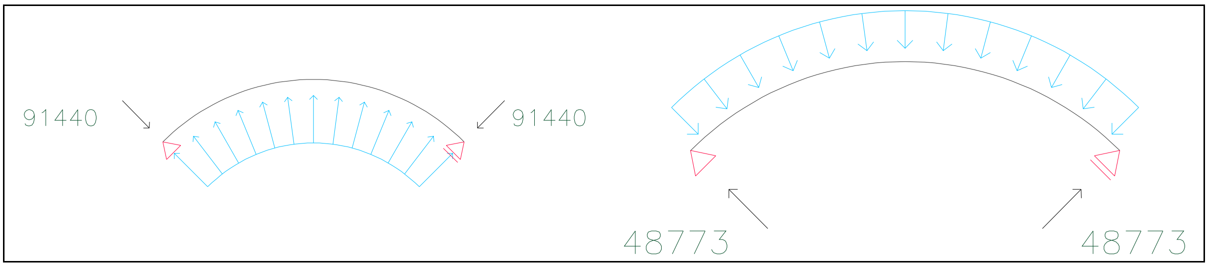
Reactions



A. *Principle 1 (Arched Structural System)*



B. *Principle 2 (Beam Structural System with parallel supports)*



C. *Principle 3 (Beam Structural System with sloped supports)*

Figure 4-39: Reaction forces [kN] (Left: Positive head - Right: Negative head)

Internal forces

Internal forces are basically calculated by the Scia-engineer software. However, the following equation, Table 4-4 and Table 4-5 calculates the maximum bending moment in the gate.

$M_{q,m} = Bending\ moment\ caused\ by\ the\ distributes\ load\ at\ the\ middle\ of\ the\ gate$

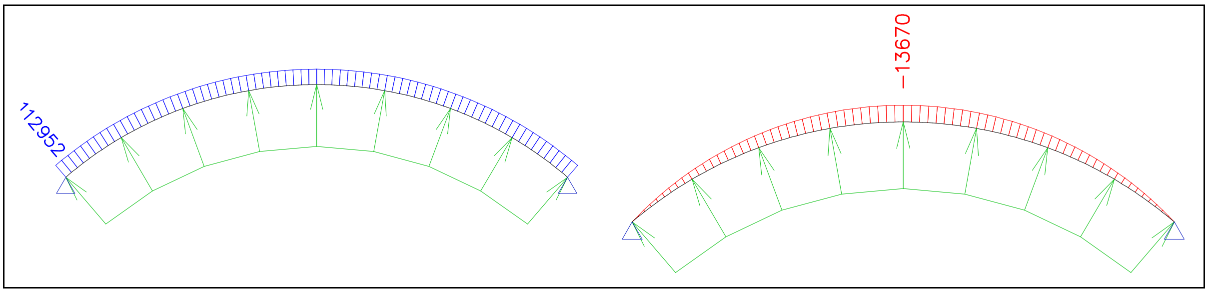
$$M_{q,m} = \int_{0}^{32.5} q.w.dr = \int_{0}^{\theta} q.R.\sin(\theta - \alpha)\,Rd\alpha = qR^2[Cos(0) - Cos(\theta)] = qR^2(1 - Cos\theta)$$

q = 2276 kN/m^2						
Structural System	R	2θ	$M_{q,m}$	Reaction	$M_{R,m}$	M_m
	m	°	kN-m	kN	kN-m	kN-m
1. Arched	50	81	1363290	112952	1353131	-10159
2. Beam with parallel supports	54	74	1336419	73970	2404025	-1067606
3. Beam with sloped supports	55	72	1314899	91440	2956090	-1641191

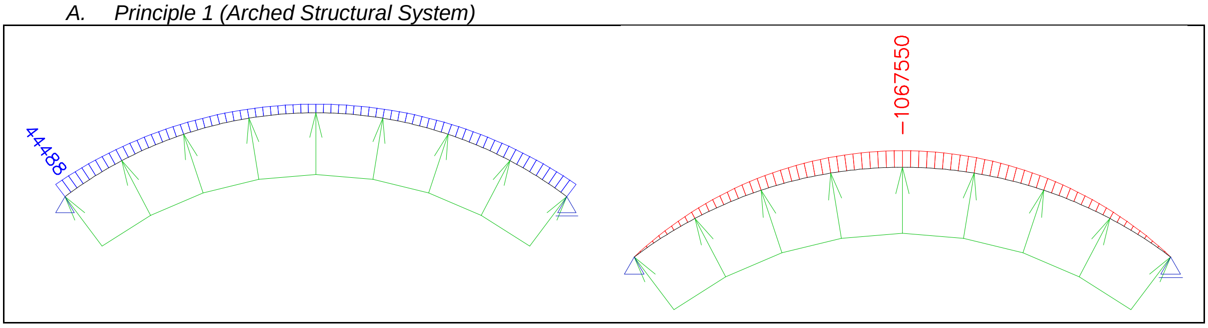
Table 4-4: Maximum Bending moment for Positive head

q = -1214 kN/m^2						
Structural System	R	2θ	$M_{q,m}$	Reaction	$M_{R,m}$	M_m
	m	°	kN-m	kN	kN-m	kN-m
1. Arched	50	81	-727168	60248	721753,1	5415
2. Beam with parallel supports	54	74	-712835	39455	1282288	569452
3. Beam with sloped supports	55	72	-701356	48773	1576743	875386

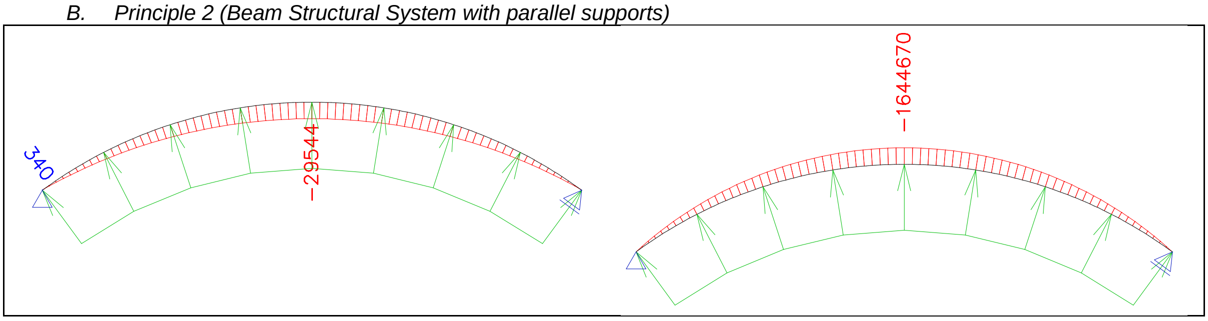
Table 4-5: Maximum Bending moment for Negative head



A. *Principle 1 (Arched Structural System)*

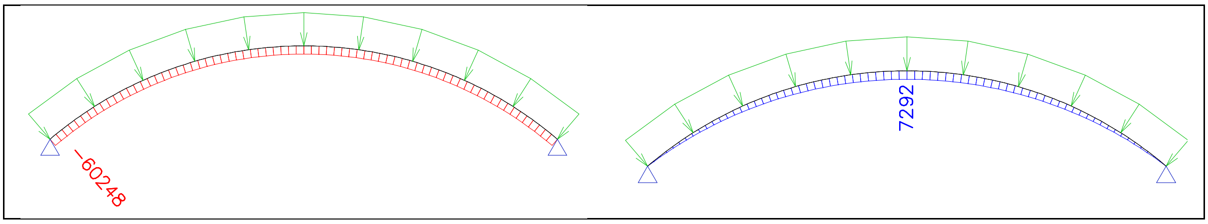


B. *Principle 2 (Beam Structural System with parallel supports)*

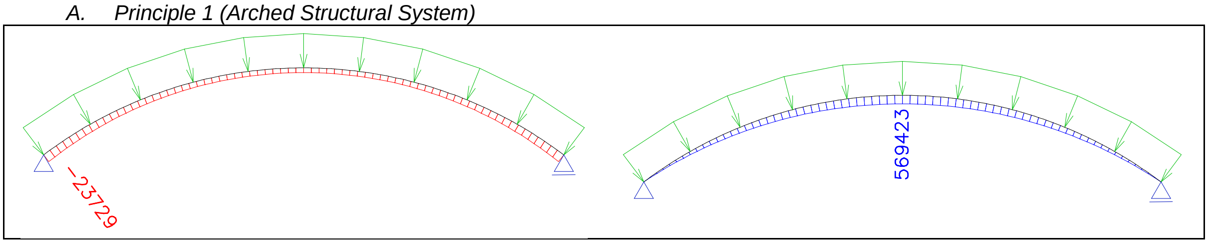


C. *Principle 3 (Beam Structural System with sloped supports)*

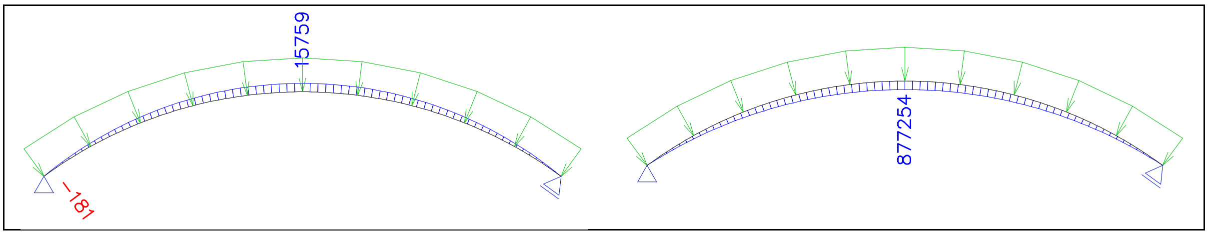
Figure 4-40: Internal forces in Positive head (Left: Axial force [kN] - Right: Bending moment [kN-m])



A. *Principle 1 (Arched Structural System)*



B. *Principle 2 (Beam Structural System with parallel supports)*



C. *Principle 3 (Beam Structural System with sloped supports)*

Figure 4-41: Internal forces in Negative head (Left: Axial force [kN] - Right: Bending moment [kN-m])

Member stresses

Internal stresses have been calculated based on two methods of Curved beam theory and Euler-Bernoulli beam theory. The results can be seen in Table 4-7 and Table 4-8.

Structural System	t	R_{Inner}	R_{Outer}	$R_{Centerline}$	d	t_w	h	y^+	y^-	A	c	I
	m	m	m	m	m	m	m	m	m	m^2	m	m^4
1. Arched	0,048	49	51	50	2	0,25	0,02	0,98	1,02	2,88	1,0	2,57
2. Beam with parallel supports	0,048	49	59	54	10	0,25	0,46	4,54	5,46	4,88	5,0	80,80
3. Beam with sloped supports	0,048	49	61	55	12	0,25	0,65	5,35	6,65	5,38	6,0	122,34

Table 4-6: Calculation of cross-sectional properties

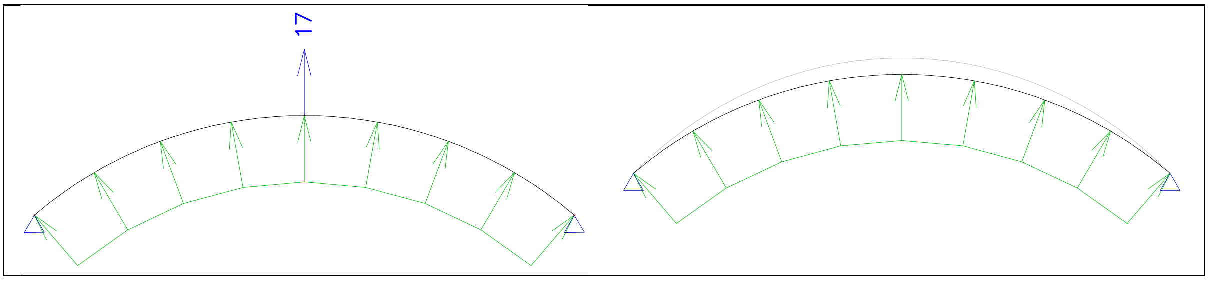
Structural System	M	N	My^+/Ahr	N/A	Stress	My^-/Ahr	N/A	Stress
	kN-m	kN	kN/m^2	kN/m^2	N/mm^2	kN/m^2	kN/m^2	N/mm^2
1. Arched	13670	112952	4752	39274	44	-4752	39274	35
2. Beam with parallel supports	1067550	44488	43788	9124	53	-43788	9124	-35
3. Beam with sloped supports	1644670	29544	50988	5496	56	-50988	5496	-45

Table 4-7: Maximum Stress calculation for positive head (Curved beam theory)

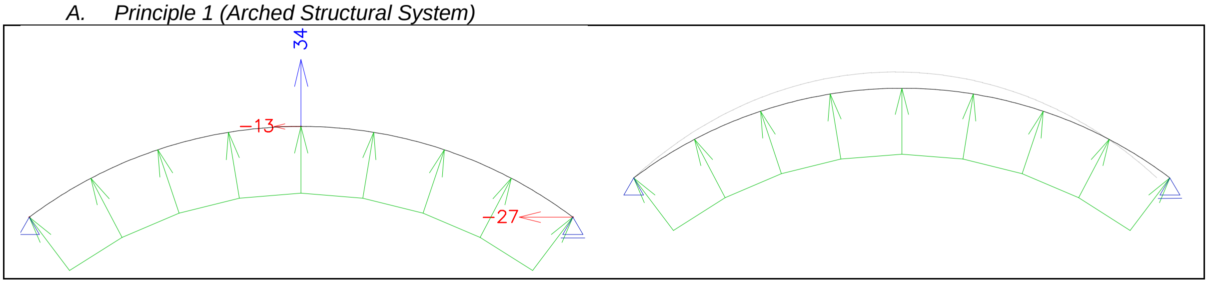
Structural System	M	N	Mc/I	N/A	Stress
	kN-m	kN	kN/m^2	kN/m^2	N/mm^2
1. Arched	13670	112952	5327	39274	45
2. Beam with parallel supports	1067550	44488	66061	9124	75
3. Beam with sloped supports	1644670	29544	80659	5496	86

Table 4-8: Maximum Stress calculation for positive head (Straight beam theory)

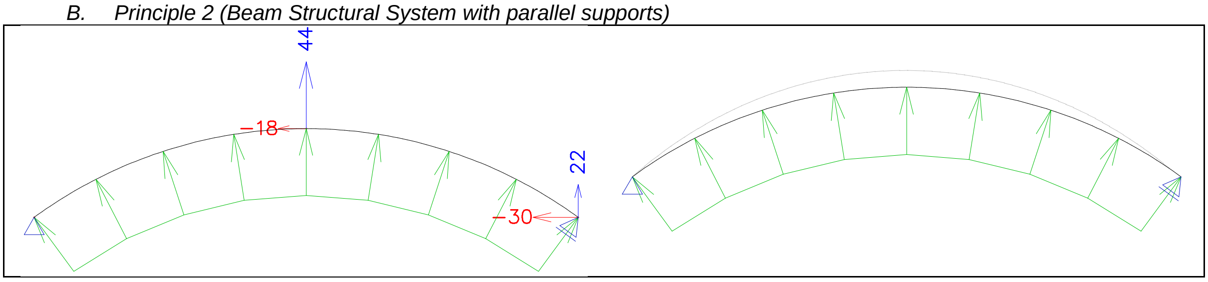
Deformation



A. Principle 1 (Arched Structural System)

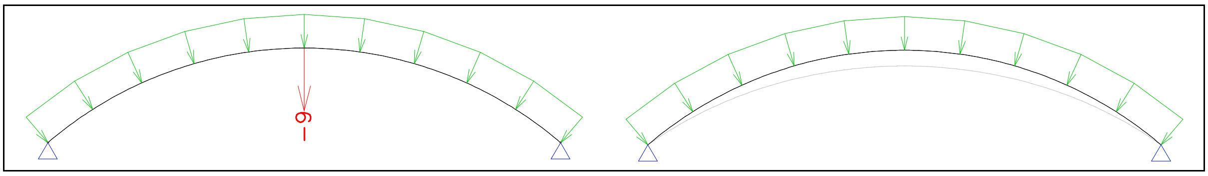


B. Principle 2 (Beam Structural System with parallel supports)

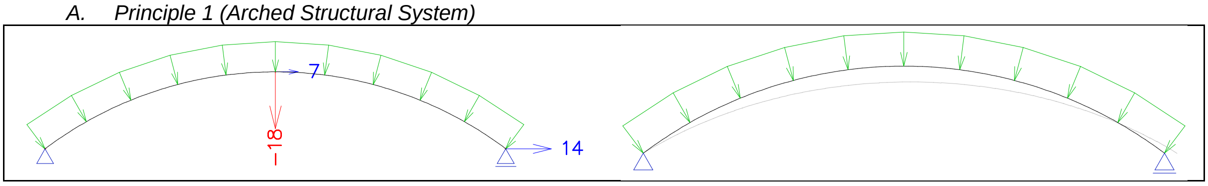


C. Principle 3 (Beam Structural System with sloped supports)

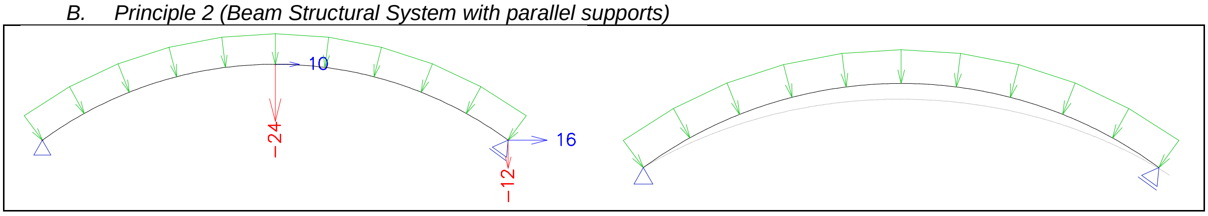
Figure 4-42: Deformation of gate in Positive head [mm]



A. Principle 1 (Arched Structural System)



B. Principle 2 (Beam Structural System with parallel supports)



C. Principle 3 (Beam Structural System with sloped supports)

Figure 4-43: Deformation of gate in Negative head [mm]

Horizontal bottom support

Figure 4-42 shows the maximum deformation for the structure. Maximum deformation in the middle of the gate lies in the acceptable range for principle 1 and principle 2 of the horizontal structural system. However, this value is slightly higher for principle 3. This implies that use of horizontal bottom support can be studied versus stiffening the structure for instance by opting for a wider cross-section.

Bearing in concrete

Alternative C is the most convenient to provide reaction force for, since it does not require any movable parts. However, the concrete area behind the bearing is very small but is still able to provide reaction forces for extreme negative head situation. A simple calculation is done:
Shear strength of concrete at the designated section:

$$v_{b-} = C_{Rd,c}.k.(100.\rho_1.f_{ck})^{1/3} = 0.12 * 1.63 * (100 * 0.02 * 35)^{1/3} = 1.21\ \mathrm{MPa}$$

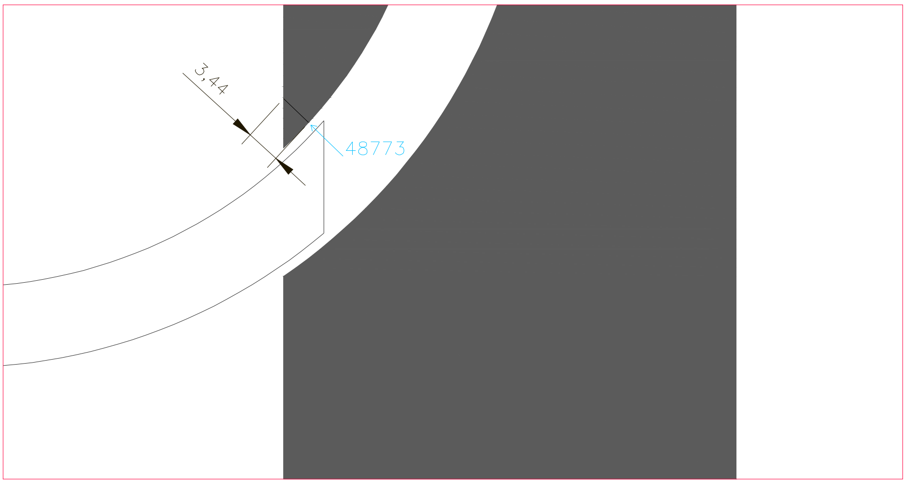


Figure 4-44: Reaction force and the resisting cross-section [Units: kN & m]

Design shear stress at the cross-section:

$$v_{d-} = \frac{48773 * 10^{-3} * 1.2}{3.44 * 25} = 0.68\ \mathrm{Mpa}$$

It can be seen that the shear resistance of the concrete is sufficient with a safety factor of 1.78. Moreover, the bending moments will result in additional stresses at the cross-section. For sufficient resistance and reliability of the lock head structure, proper reinforcement should be considered in the concrete.

4.5.2 *Floating stability*

Before the structure could be analyzed in the vertical direction, the weight of the structure and buoyancy forces on the structure should be determined. This section provides the first estimations on these values based on the floating stability criterion.

Weight

Weight of the structure can easily be estimated by considering the total steel volume of the curved beam. In this manner, the cross-sectional area of the beam will be calculated based on the chosen width in section 4.5.1. Then this value (W') will be multiplied by the length of the curved beam. In order to take into account the weight of the stiffeners, installations, guidance devices and other devices on the gate, the calculated weight will be increased by 50%. Although an increase of 50% is done based on experience, but it is verified in chapter 5 when the calculation of weight is done based on the preliminary design. The final estimated weight for each principle can be seen in Table 4-9.

$$A = 2 \times 25000 \times 48 + 250 \times (w - 2 \times 48)$$

Structural System	width	L	A	V	W'	W
	[mm]	[m]	[mm^2]	[m^3]	[Tons]	[Tons]
1. Arched	2000	70,76	2876000	203,5	1598	2396
2. Beam with parallel supports	10000	69,74	4876000	340,1	2669	4004
3. Beam with sloped supports	12000	69,54	5376000	373,8	2935	4402

Table 4-9: Estimated weight

Buoyancy and Hydrostatic stability

The hydrostatic stability of each alternative is calculated based on the estimated weight and estimated buoyancy chamber volume (see section 4.5.4) and the results can be seen in Table 4-10. Details of the calculation are the same as in Appendix F. It can be seen that the arched structural system, has the disadvantage of not being statically stable for the purpose of transferring the gate for construction or maintenance.

Structural System	W	V_B	I_{yy}	KB	BM	KG	GM
	[Tons]	[m^3]	[m^4]	[m]	[m]	[m]	[m]
1. Arched	2396	2210	3658	6,88	1,56	12	-3,56
2. Beam with parallel supports	4004	3760	28781	6,89	7,20	12	2,09
3. Beam with sloped supports	4402	4060	39445	6,88	9,13	12	4,01

Table 4-10: Calculations of hydrostatic stability

4.5.3 *Driving Force*

In order to evaluate the alternatives for operating systems, the driving force needs to be calculated. Each operating system can then be designed for the required driving force. This section discusses the driving mechanisms for each operating system and calculates the driving force for each structural system (horizontal structural systems in section 4.4.3).

Vertically Eccentric Driving Force

The equipments of operating system have to be sealed and prevented against constant water contact. Therefore, the most suited place for the machineries is the top of the lock head and above the water level. Placing the operating system at top of the lock head implies that the driving force will act on the gate with a certain eccentricity which results in a moment on the gate structure. This moment, increases the pressure on one supporting point (the nearer support during opening) and decreases the pressure on the other one (the further support during opening). Figure 4-45 depicts this effect during the opening process. The reaction forces on supporting points will be taken into account on calculations of section 4.5.4.

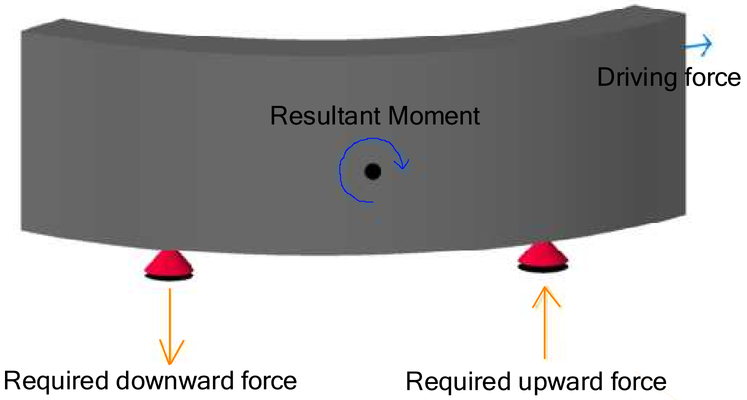


Figure 4-45: Effect of driving force eccentricity (During opening process)

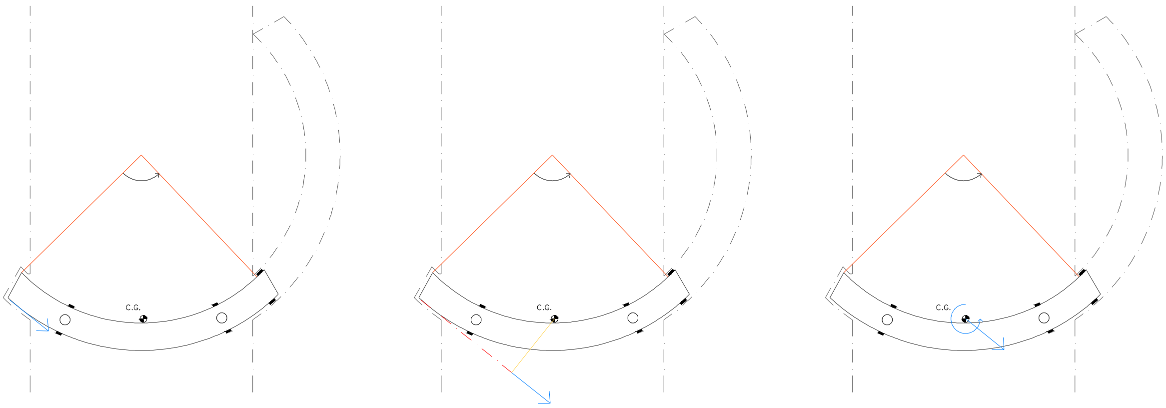
Horizontally Eccentric Driving Force

The driving force is eccentric in horizontal plane as well. Therefore it needs to be transformed to the center of gravity of the gate. This transformation will result in a turning moment and a force in the center of gravity. Due to differences in the acting point and acting direction of the driving force in different alternatives, three different driving mechanisms are studied in current section. Two situations are considered for each alternative:

- Forces at initiation of opening
- Forces halfway during the opening

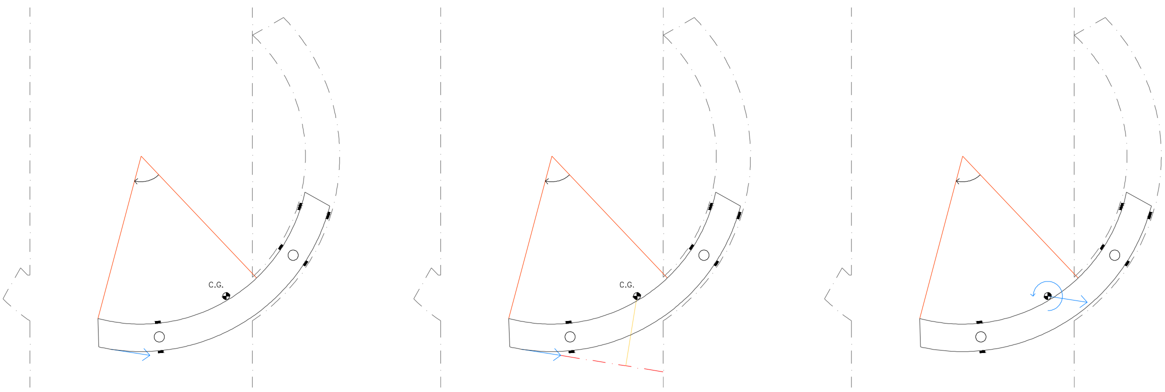
Cable

In cable driving system, the force is always applied at one point on the gate and it is always tangent to the curve at that point. Therefore, the eccentricity always remains the same but on the other hand, the direction of the force changes during the movement. Figure 4-46 and Figure 4-47 show the actual and transformed force and the resulting turning moment.



Actual point and direction of driving force	*Extension and eccentricity of driving force*	*Transformed force and resulting moment*

Figure 4-46: Driving force transformation at initiation of openeing for cable alternative

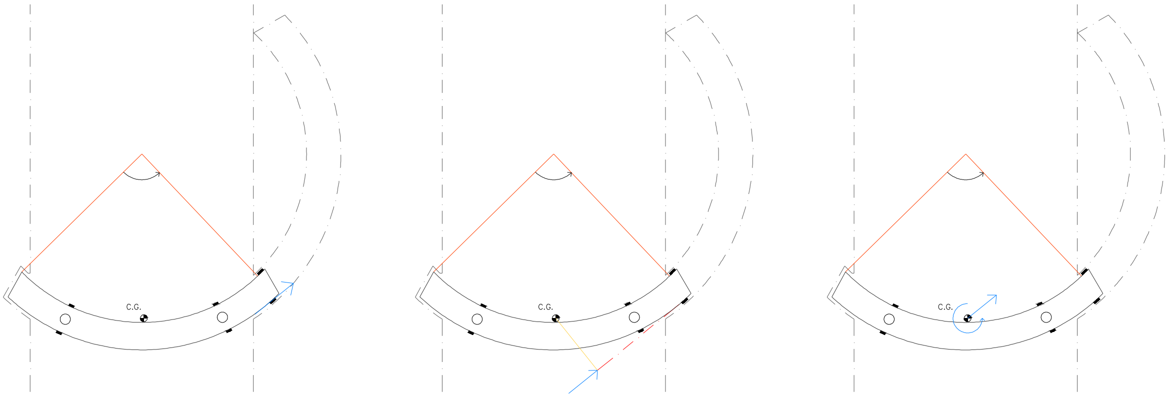


Actual point and direction of driving force	*Extension and eccentricity of driving force*	*Transformed force and resulting moment*

Figure 4-47: Driving force transformation halfway during the openeing for cable alternative

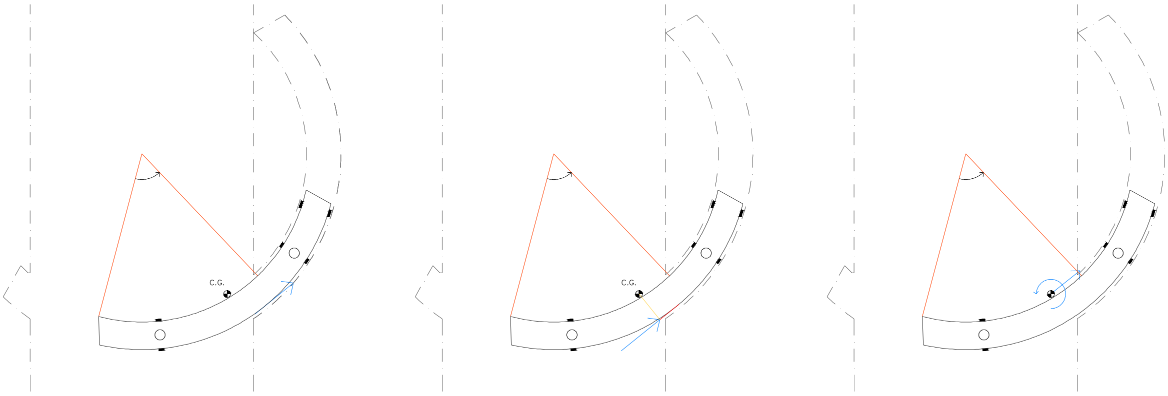
Racks and pinions

In driving system of racks and pinions, the force is always applied at one point on the lock head and since it is always tangent to the gate curve at that point, its direction remains the same during the whole movement process. The eccentricity however changes during the movement. Figure 4-48 and Figure 4-49 show the actual and transformed force and the resulting turning moment for this alternative.



Actual point and direction of driving force	*Extension and eccentricity of driving force*	*Transformed force and resulting moment*

Figure 4-48: Driving force transformation at initiation of openeing for Racks and pinions alternative

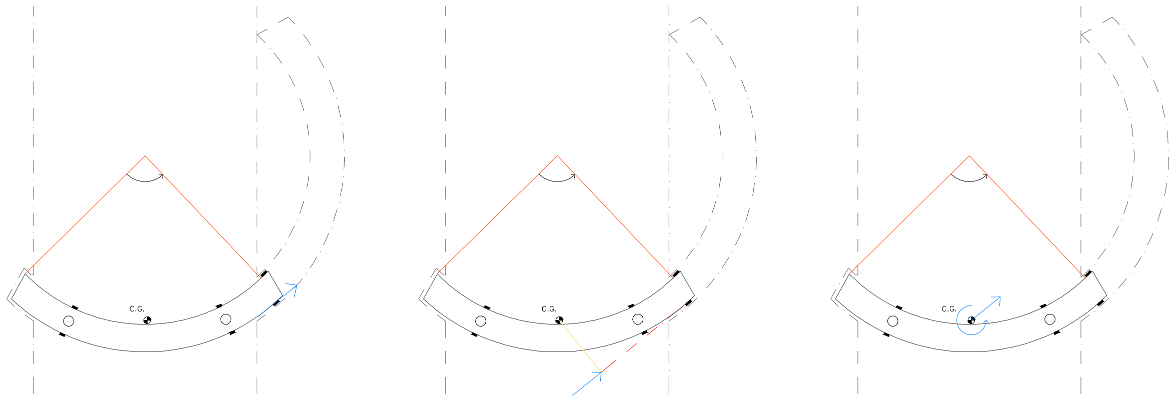


Actual point and direction of driving force	*Extension and eccentricity of driving force*	*Transformed force and resulting moment*

Figure 4-49: Driving force transformation halfway during the openeing for Racks and pinions alternative

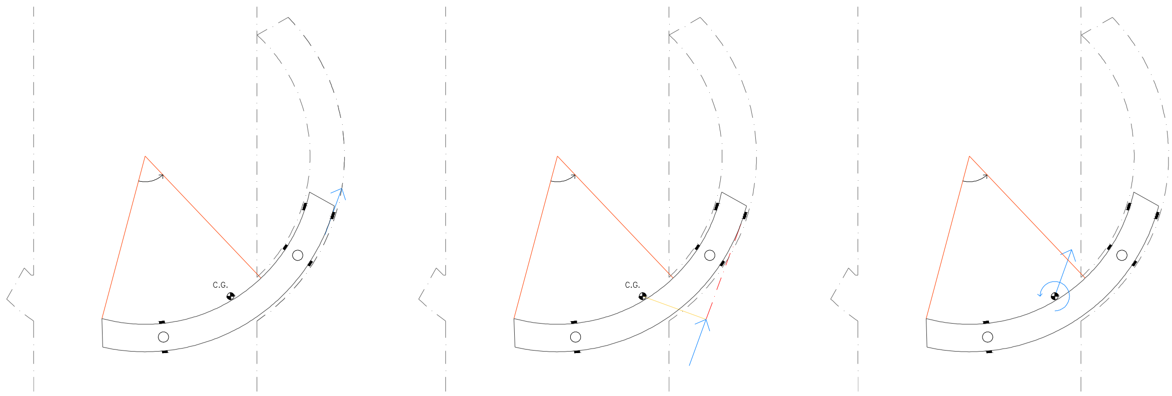
Locomotive

When the driving force is provided by the locomotive, the force is always applied at one point on the gate. The direction of the force follows the direction of the locomotive movement and therefore it changes during the movement. The direction of the force changes not only globally, but also relative to the gate and as a result the eccentricity changes slightly during the movement too. Figure 4-50 and Figure 4-51 show the actual and transformed force and the resulting turning moment.



Actual point and direction of driving force | *Extension and eccentricity of driving force* | *Transformed force and resulting moment*

Figure 4-50: Driving force transformation at initiation of openeing for Locomotive alternative



Actual point and direction of driving force | *Extension and eccentricity of driving force* | *Transformed force and resulting moment*

Figure 4-51: Driving force transformation halfway during the openeing for Locomotive alternative

Calculation of Driving Force

As concluded in section 4.3.1, the maximum hydraulic loads are being applied on the structure at initiation of the opening process. At this moment of time, the maximum driving force is required for the movement of the gate. The operating system needs to provide enough driving force in order to overcome the following forces:

- Friction forces caused by the weight of the structure
- Friction forces caused by the hydraulic loads
- Friction forces caused by the eccentricity of driving force

Notice that the inertia forces and water displacement forces are not considered in conceptual design due to their small magnitude in comparison to the abovementioned forces. (19)

Figure 4-52 shows the driving force and the resisting friction forces that the driving force has to overcome. For calculation of the driving force, the moment equilibrium around the turning point (center of the gate's arch) is written. The minimum required driving force is calculated as follows:

$$\Sigma M_O = 0 \Rightarrow (V_1 + V_2) * R_c + (S_1 + S_2 + S_3) * R_o - F_D * r = 0$$

$$\Rightarrow F_D = \frac{(V_1 + V_2) * R_c + (S_1 + S_2 + S_3) * R_o}{r}$$

$R_c = Radius\ of\ gate\ centerline$

$R_o = Outer\ Radius\ of\ gate$

In the equation above, S_1, S_2 and S_3 are the friction forces on the guidance points. Figure 4-53 shows the forces on three guidance points. V_1 and V_2 are the friction forces on the bottom supporting points. For calculation of the driving force, these forces have to be calculated as below:

$$S_1 + S_2 + S_3 = k_h \times [(H'_1 - H_1) + (H'_2 - H_2) + (H'_3 - H_3)]$$
$$= k_h \times [(H'_1 + H'_2 + H'_3) - (H_1 + H_2 + H_3)]$$

$$V_1 + V_2 = k_v \times [\left({}^{W-B}/_2 + R_{dr}\right) + \left({}^{W-B}/_2 - R_{dr}\right) = k_v \times (W - B)$$

Where

$k_h = friction\ coefficient\ for\ horizontal\ guidance\ (Steel - UHMWPE) = 0.17$

$H'_1\ \&\ H'_2\ \&\ H'_3 = Reaction\ forces\ caused\ by\ hydraulic\ loads$

$H_1\ \&\ H_2\ \&\ H_3 = Reaction\ forces\ caused\ by\ drining\ force$

$k_v = friction\ coefficient\ for\ bottom\ support\ system = 0.01$

$W = Weight\ of\ the\ structre$

$B = Buoyancy\ force$

$R_{dr} = Upward\ or\ downward\ reaction\ force\ on\ the\ supporting\ points\ due\ to$
$vertical\ eccentricity\ of\ driving\ force$

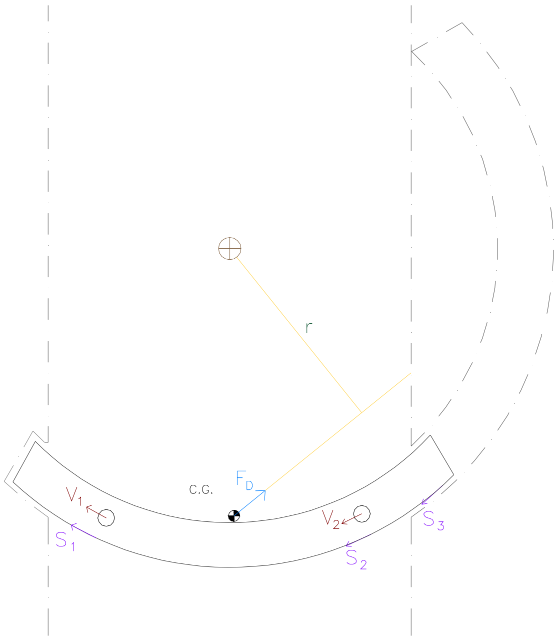


Figure 4-52: Driving force and resisting friction forces

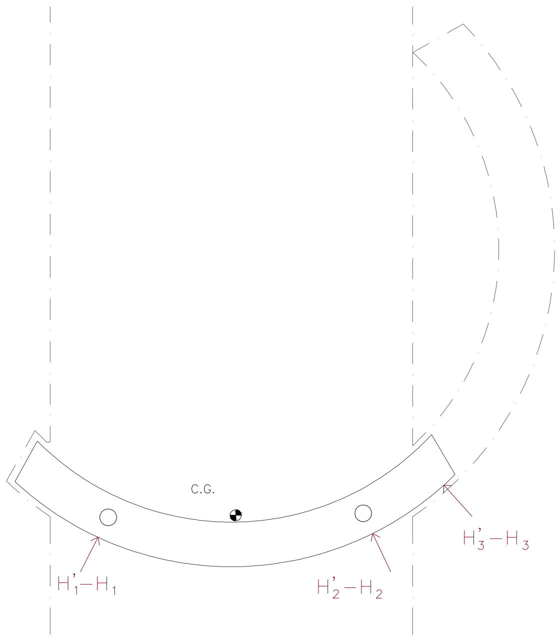


Figure 4-53: Forces on the guidance points

As it can be seen, the total reaction force from the hydraulic loads and the total reaction force from the driving force are required and the distribution of the force between the guiding points can be ignored in this simplified calculation. The following forces have to be determined:

Total hydraulic loads on the gate

Hydraulic loads during operation are shown in Figure 4-10. Total hydraulic loads (or total reaction forces) are estimated by considering the 177.4 kN/m uniform load on total width of the lock chamber (65m). Therefore:

$$H'_1 + H'_2 + H'_3 = 177.4 \times 65 = 11531\ kN$$

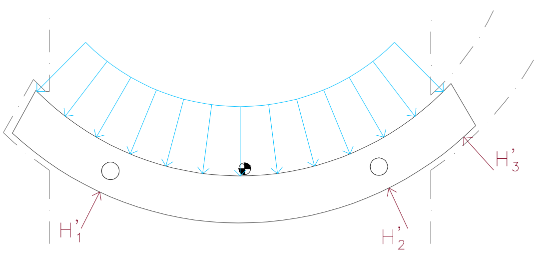


Figure 4-54: Hydraulic loads and reactions on the guidance points

Reaction forces on the guiding points caused by driving force

Gate is guided at three points; two at the bottom in the position of the supporting points and one at the top close to the end of the gate which always remains inside the recess (Figure 4-26). Since the total reaction forces caused by the driving force is required (and the actual distribution is not intended), the structure is simplified into a determinate gate structure with 2 guidance points. In this manner, it is assumed that the force will result in reaction forces only at the bottom guidance devices:

- Driving force (F) acts on the certain point of the gate as shown in Figure 4-46 to Figure 4-51.
- This force has an eccentricity (e) relative to the center of gravity. The driving force then can be considered as a force acting on the center of gravity and a moment (M = F.e).
- The fourth row in Figure 4-56 shows the fraction of the driving force and resulting moment acting on the guidance points. It is assumed that driving force will be divided equally between two guiding points and the resulting moment would also be distributed equally between those two.
- In the fifth row from Figure 4-56, effective driving force at the guidance points is calculated and divided into two components. The left figure shows the resultant components from the transformed force and the right figure shows the resultant components from the transformed moment.
- The last row of the same figure, shows the superposition of these components. “L” and “K” are in the direction of movement, “M” and “J” are perpendicular to the direction of movement.
- For calculation of the required driving force, the following expression will be used:

$$H_1 + H_2 + H_3 = M + J$$

- Notice that the same procedure applies for the cable alternative where the acting point of the driving force is different.

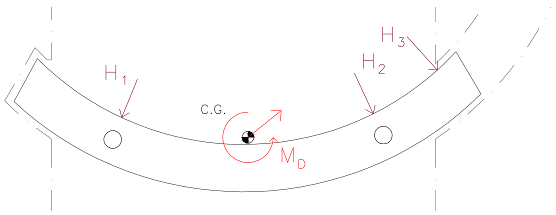
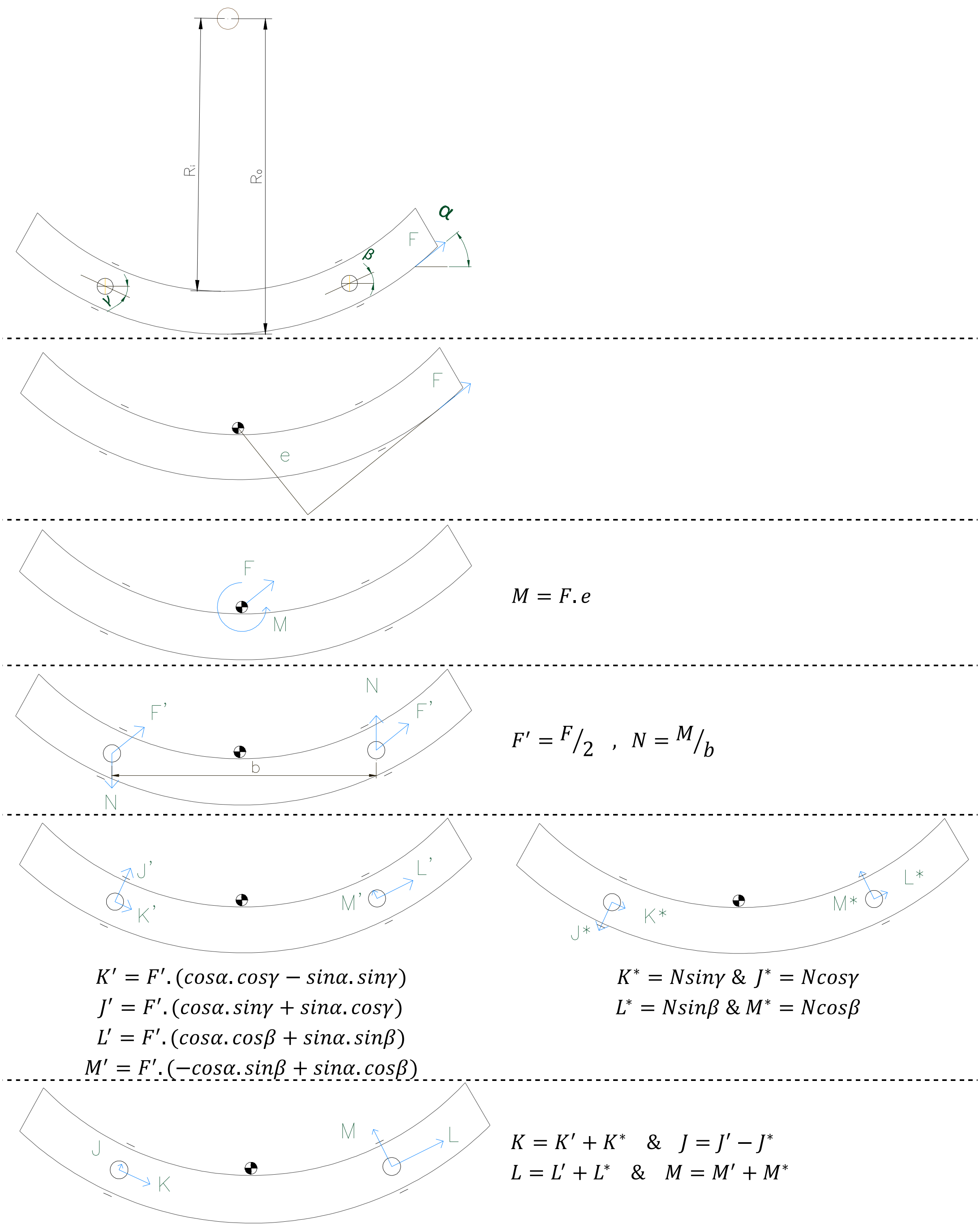


Figure 4-55: Driving force and reactions on the guidance points

Reaction forces on the supporting points caused by weight and buoyancy

The weight of the structure depends on the choice of the structural system and the dimensions of the gate. The buoyancy force will be designed according to the choice of structural system, driving force and stability requirements. Therefore, the exact value of these forces will only be known after determining the driving force. However as it can be seen, the friction coefficient for the bottom support system is only 0.01 (17) , (20) and additionally, the difference between the total weight and total buoyancy force is important for the driving force. Therefore, the following assumption is made. The arguments for determination of the weight and buoyancy are given in section 4.5.4 and the assumed value is verified. $W - B \approx 4000\ kN$



$$M = F.e$$

$$F' = {}^{F}/_{2} \quad , \quad N = {}^{M}/_{b}$$

$$K' = F'.(cos\alpha.cos\gamma - sin\alpha.sin\gamma)$$
$$J' = F'.(cos\alpha.sin\gamma + sin\alpha.cos\gamma)$$
$$L' = F'.(cos\alpha.cos\beta + sin\alpha.sin\beta)$$
$$M' = F'.(-cos\alpha.sin\beta + sin\alpha.cos\beta)$$

$$K^{*} = Nsin\gamma \;\&\; J^{*} = Ncos\gamma$$
$$L^{*} = Nsin\beta \;\&\; M^{*} = Ncos\beta$$

$$K = K' + K^{*} \quad \& \quad J = J' - J^{*}$$
$$L = L' + L^{*} \quad \& \quad M = M' + M^{*}$$

Figure 4-56: Transformation of driving force on the guiding points

- Calculation of M and J:

$$M = M' + M^* = F'.(-cos\alpha.sin\beta + sin\alpha.cos\beta) + Ncos\beta$$
$$J = J' - J^* = F'.(cos\alpha.sin\gamma + sin\alpha.cos\gamma) + Ncos\gamma$$

$$\alpha \approx 39° \;\; \& \;\; \beta \approx 25° \;\; \& \;\; \gamma \approx 25° \;\; \& \;\; b \approx 24.35m \;\; \& \;\; e \approx 19.5m$$

$$\Rightarrow \begin{cases} M = 0.5F_D.(-cos39°.sin25° + sin39°.cos25°) + 0.8F_D cos25° \\ J = 0.5F_D.(cos39°.sin25° + sin39°.cos25°) + 0.8F_D cos25° \end{cases}$$

$$\Rightarrow M + J = 0.6F_D$$

- Finally the driving force can be calculated:

$$\Rightarrow F_D = \frac{(V_1 + V_2) * R_c + (S_1 + S_2 + S_3) * R_o}{r}$$
$$\Rightarrow F_D = \frac{(k_v \times (W - B)) * R_c + (\, k_h \times [(H'_1 + H'_2 + H'_3) - (H_1 + H_2 + H_3)]) * R_o}{r}$$
$$\Rightarrow F_D = \frac{(0.01 \times (4000)) * R_c + (\, 0.17 \times [(11531) - (M + J)]) * R_o}{r}$$
$$\Rightarrow F_D * (r) = 40R_c + (1960 - \; 0.17 \times 0.6F_D) * R_o$$
$$\Rightarrow F_D * (r + 0.102R_o) = 40R_c + 1960R_o$$

Structural System	r	R_c	R_o	F_D
	m	m	m	kN
1. Arched	34.79	50	51	2550
2. Beam with parallel supports	37.67	54	59	2696
3. Beam with sloped supports	38.41	55	61	2728

Table 4-11: Required driving force for alternative principles

Table 4-11 shows the minimum required driving force for each alternative principle given in section 4.4.3. The driving force calculation method for the solution A in principle 2 (Combined movement in beam structural system with parallel supports) is different due to the different movement of the gate at the beginning of the opening. The calculations for this moving mechanism are given in section 5.5 and it can be seen that the required force is still in the same order of magnitude. Due to neglecting the inertia force and water displacement forces, and for compensating the approximations in this section, the design force for operating system will be set to 3000 kN. The following section will provide calculations for basic design of the operating systems.

Operating System Design

Cable

A very simple estimation for using the cables can be done as below:

Safety factor for cables which are used for movement is 4. Therefore, the nominal value for cable strength is 12000 kN. In case of using two cables simultaneously, each cable has to have a minimum strength of 6000 kN.

As a possible option, two set of steel cables “Neptune standard rope, type ALPHA” (21) with a nominal diameter of 87 mm can be used. This cable has a nominal breaking force of 6070 kN. The risks of using high strength cable are higher and considerations and provisions are more complicated.

In general, although using cables as operating system is possible, but as it can be seen, required cables are heavy (~32 kg per meter) and they also need massive equipment such as drums with engines installed in the area. In addition, if two cables are used, the equipment have to be carefully synchronized in order to make the smooth movement of the gate possible.

Racks and Pinions

A simple approach to design the operating device as racks and pinions is as follows:

If 8 engines are used, each engine has to provide a representative force of $F_{rep} = \left(\frac{3000}{8}\right) \approx 375\ kN.$

In that case:

$$M_{rep} = F_{rep}.\frac{d_p}{2} \approx 93.75\ kN.m$$

This representative moment requires approximately 93 kW power. This value has been calculated by assuming the following quantities: (Diameter of the pinions is assumed to be approximately 500 mm at its maximum, including the teeth.)

$$Rotation\ speed = \mathrm{n_r} = 8\ \ \mathrm{min}^{-1}$$

$$Adopted\ nominal\ motor\ speed = n_m = 1300\ min^{-1}$$

$$Adopted\ transmission\ ratio = i_{tr} = \frac{n_m}{n_r} = 162.5$$

$$Adopted\ efficiency = \eta_{dr} = 0.85$$

$$Adopted\ motor\ torque = M_m = \frac{M_{rep}}{i_{tr}.\eta_{dr}} = 679\ N.m$$

$$Required\ motor\ power = P_m = 2.\pi.M_m.n_m = 92.4\ kW$$

Using racks and pinions with 8 engines, doesn’t seem to be a simple solution nor it is easy to construct. However, it is more reliable than use of cables due to the problems that were mentioned in the previous section. In addition, these equipments have been used for moving bridges and offshore installations and have been proven reliable in practice and in large scales like the scale of current gate under study.

Locomotive

The locomotive option has similar calculations to the previous option for its engines. Therefore, in sense of costs and dimensions, it is similar to racks and pinions. The required number and characteristics of the engines is also similar to the previous calculations. Therefore, the same properties apply for the design of locomotive. Notice that the locomotive is different in operation mechanism than racks and pinions.

4.5.4 Bearing and Guiding

Vertical reactions

As explained in the previous section, the total buoyancy force has to be determined on the basis of the following criterion:

The minimum reaction force on a supporting point should never become lower than a certain limit. For the conceptual design step, and for the sake of comparison, this limit is set to 250 kN. The vertical reactions are calculated in this section accordingly. The following parameters are considered:

$W = Total\ structure\ weight$
$B_{min} = Minimum\ Buoyancy\ loads\ on\ structure\ during\ operation$
$B_{max} = Maximum\ Buoyancy\ loads\ on\ structure\ during\ operation$
$B_{Ch} = Upward\ Buoyancy\ force\ of\ Buoyancy\ chambers$
$R_{dr,u} = Upward\ reaction\ force\ caused\ by\ driving\ force$
$R_{dr,d} = Downward\ reaction\ force\ caused\ by\ driving\ force$

Two main load conditions are considered for calculation of vertical reactions:

1) Vertical reaction during operation in minimum water level
When the water level is at its minimum [NAP -2.20m] and the maximum driving force is acting on the gate (during opening), maximum reaction force occurs for the support which is closer to the operating system. This force is calculated as below:

$$Maximum\ Reaction\ force = \frac{W}{2} - \frac{B_{min}}{2} - \frac{B_{Ch}}{2} + R_{dr,u}$$

2) Vertical reaction during operation in minimum water level
When the water level is at its maximum [NAP +4.17m] and the maximum driving force is acting on the gate (during opening), minimum reaction force occurs for the support which is further from the operating system. This force is calculated as below:

$$Minimum\ Reaction\ force = \frac{W}{2} - \frac{B_{max}}{2} - \frac{B_{Ch}}{2} - R_{dr,d}$$

Table 4-12 shows the result of the buoyancy force determination and the maximum reaction calculation after proper iterations.

Structural System	W	B_{Ch}	B_{min}	B_{max}	R_{dr}	R_{max}	R_{min}
	kN	kN	kN	kN	kN	kN	kN
1. Arched	23963	**17500**	2219	2951	1500	3622	256
2. Beam with parallel supports	40041	**31600**	3707	4930	1500	3867	255
3. Beam with sloped supports	44020	**35100**	4076	5420	1500	3922	250

Table 4-12: Calculation of reaction forces and required Buoyancy force

Bottom support

Table 4-12 shows the maximum reaction force on the supporting points. As it can be seen, the reaction forces are relatively close to each other and in order to make a fare comparison, the bottom support system will be designed for a 4000 kN maximum reaction force.

Roller carriage

The design of a complete roller carriage is rather complicated and above the scope of this stage of design. However, in order to provide a better input for the evaluation of bottom support system, the rough dimension of the wheels will be calculated. Two parameters are considered for the conceptual design; Shear stress on the axel, bending stress on the axel. The size of the wheel is determined according to NEN 6786 (22).

<u>Shear stress control</u>

$$\tau = \frac{F}{A} \quad \& \quad F = \frac{4000}{4} = 1000kN \quad \& \quad A = \frac{\pi d^2}{4}$$

$$\Rightarrow \tau = \frac{1000 \times 4}{\pi d^2} = \frac{1273}{d^2} \leq 315 \frac{N}{mm^2} \Rightarrow d \geq 63\ mm \quad According\ to\ NEN\ 6786$$

<u>Bending stress control</u>

$$\sigma = \frac{0.5 \times 0.5 \times F \times 0.5L}{\frac{\pi}{32}.d^3} \quad \& \quad L \approx 6m \quad \& \quad F = 4000kN$$

$$\sigma = \frac{0.5 \times 0.5 \times 4000 \times 10^3 \times 0.5 \times 6}{\frac{\pi}{32}.d^3} = \frac{30557749}{d^3} \leq 315 \quad \Rightarrow d \geq 46mm \ \ According\ to\ NEN\ 6786$$

<u>Wheel size estimation:</u>

$$\sigma_{ver;rep} = \frac{F_{ver;rep}}{D.(b-2r)} \quad \& \quad \sigma_{ver;rep} \leq f_{ver;adm}$$

$$D = \frac{F_{ver;rep}}{\sigma_{ver;rep}.(b-2r)} \quad \& \quad \sigma_{ver;rep} \leq 5.7\frac{N}{mm^2} \quad \Rightarrow \quad D \geq \frac{1000}{5.7.(140-10)} \quad \Rightarrow \quad D \approx 1400mm$$

Hydro-foot

A complete design procedure for hydro-foot is given in Appendix E. The procedure of design is also the same for the case in this stage of design. The output for the conceptual design is as follows:

$Number\ of\ supports\ at\ each\ supporting\ point = 1$

$F_{max} = 4000kN,$ $\quad Outer\ diameter = 1.86\ m,$ $\quad Effective\ pressure\ area = 2.01\ m^2$

$P_s = 3Mpa,$ $\quad P_r(F_{max}) = 2.15\ Mpa,$ $\quad \beta = 0.7,$ $\quad Minimum\ film\ thickness = 0.12\ mm$

$h_{min} = 0.12\ mm,$ $\quad Q_{reg} = 19.6\frac{m^3}{hour},$ $\quad P_{pump} = 16.3\ kW$

4.6 Design decisions, Basis for preliminary design

4.6.1 Evaluation

In this section, the main alternatives are evaluated on the basis of design objectives that are described in section 4.1. Notice that the final decisions should be made based on availability and cost evaluation. Availability can be evaluated by considering the reliability and maintainability of the proposed principle. In addition to these criteria, the safety will be evaluated as well. Table 4-13 provides a qualitative grading system for the evaluation of the alternatives. Notice that the grades are solely for the sake of comparison and the choice of grades is subjective. In order to make the decision making process easier, a set of numbers are also assigned to these qualitative scores.

A	Advantageous	6
A^-	Advantageous with certain Negative points	5
N^+	Neutral with certain Positive points	4
N	Neutral	3
N^-	Neutral with certain Negative points	2
D^+	Disadvantageous with certain Positive points	1
D	Diasdvantageous	0

Table 4-13: Grading system for evaluation

4.6.1.1 Evaluation of structural systems

Structural system has the largest influence over the design. Section 4.5 holds the comparison between the structural systems in all the sub-categories. It is understood that the proposed structural systems in section 4.4.3, have noticeable differences in cross-sectional properties, weight and buoyancy. On the other hand, the choice of structural system does not change the quantitative requirements of other alternatives. For instance, all the structural principles require more or less the same driving force. In addition the resultant vertical reaction force on the bottom support system does not depend on the choice of structural system. However, notice that every structural system, has its own geometrical characteristics which can affect the other design choices due to limitations or advantages which cannot be described quantitatively.

1. *Arched structural system (With pinned supports)*

<u>Reliability:</u> This principle has the highest reaction forces (section 4.5.1). The bearing system has to provide this reaction force with a certain mechanism which involves number of movable devices (solution A & C). Reaction forces can also be provided by moving the special movement of the gate (solution B). The risks are arguably high when the mechanism has not been tried for this scale before. On the other hand the internal forces are relatively small in the structure and the required cross-section is rather small.

<u>Maintainability:</u> Due to special mechanism of the bearings and high wear in mechanical bearing devices, number and duration of maintenance procedures are estimated to be high for this principle. In addition, the gate is not able to float for the purpose of maintenance because of lack of hydrostatic stability and therefore the maintenance procedure is more difficult.

Availability: Based on the evaluation of reliability and maintenance, it is anticipated that in case of failure, down-time would be rather long and repair and fix procedures would be time-consuming. Since the method has not been used in this scale, unpredicted failures should be expected.

Safety: The side bearings of the gate need to overcome a large reaction force during the closed situation. On the other hand, the stresses in the structure are low. Notice that the small cross-section of the gate can result in buckling of the structure when the structure is in the compression-only mode.

Costs: Arched beam Principle suggests the most efficient design for the gate. However, this cannot be said about the bearing system itself. Bearing system in this principle is much more complicated than the other two cases and it needs mechanical and electrical equipment with high reliability. Since the costs for gate is a once in lifetime but the bearing system needs constant attention in sense of maintenance, total evaluation of costs is only advantageous in construction costs, but disadvantageous in maintenance costs.

Design objectives:

- Solution A and C make use of additional mechanical devices for providing the main supports of the structure. Solution B however, suggests a support system which is fixed but it still needs additional mechanical devices for moving the gate towards the supports.
- High possibility of wear in support system implies on high need for maintenance.
- Operation of the gate requires multiple processes and the synchronization of the associated devices makes this principle very complicated to design and construct.
- The idea of an arched mechanism for a lock gate is new and scientifically challenging

2. *Beam structural system with parallel supports (Roller supports parallel to lock centerline)*

Reliability: principle 2 has the lowest reaction forces. In solution B, the bearing system has to provide this reaction force with a certain mechanism which involves a movable device. The risks in this bearing system are relatively lower than principle 1 but admittedly still high. In solution A, due to the fact that bearings are fixed and they do not depend on any mechanical device, reliability of this system is higher than others. The deformation and internal forces are within a reasonable limit.

Maintainability: The gate structure, is floatable during maintenance which gives an advantage for the procedure. In solution A, no extra movable parts are being employed and as for solution B, movable parts are not favorable for maintenance.

Availability: Failure of the moving supports in solution B and failure of moving mechanism in executing the special movement of the gate in solution A, can cause non-availability of the gate.

Safety: Solution A provides a safe alternative due to low reactions, low internal forces and fixed bearings. Solution B, on the other hand is less safe due to the movable supports.

Costs: Solution A offers a rather cheap solution for the bearings and the gate itself. This can be said for the maintenance costs as well. in case of solution B, the costs are in between and the maintenance costs are high and the cost of construction of the movable bearings is higher than fixed bearing without movable parts.

Design objectives:

- Solution A has no movable parts as oppose to the solution B which relies on a movable support system for providing the required reaction. However, the movement of the solution A is rather complicated and needs a proper mechanism.
- Necessity of maintenance for solution B is higher than solution A. In general, the principle of beam with parallel supports does not require any particular maintenance in comparison to the other principles.
- Solution A seems like a simple solution for the operation and construction. However, the design of the guiding system is rather complicated because of the combined movement of the gate.
- Both solutions for this principle are innovative. Solution A is an interesting idea which tries to avoid having movable devices by changing the gate movement mechanism.

3. Beam structural system with sloped supports (Roller supports perpendicular to gate centerline)

Reliability: Reaction forces in principle 3 is larger than forces in principle 2 but as it has been calculated, the safety factor for the concrete and the whole bearing system is still acceptable. In addition, use of no movable parts in bearing system gives it an advantage in in sense of reliability to other cases. Internal forces are high in this alternative and the stress level in concrete is expected to be higher than all the other principles.

Maintainability: Maintenance of the gate structure and bearing systems remains in predictable and predefined procedures and since there are no mechanical parts in the bearing system, no extra measures are required for maintenance/inspection of the bearings.

Availability: Based on the evaluation of reliability and maintenance, this principle can deliver high availability.

Safety: The deformation of the gate is high in this alternative and it can result in certain failures in serviceability requirements. Aside the deformation, the principle is one of the most safe design alternatives.

Costs: Design of gate for this principle is the most expensive among the other cases. Bearing system on the other hand is relatively cheaper than the other options (except principle 2.A). Although the construction costs are high for this case, maintenance costs are lower due to the simple concept which involves the least possible mechanical and movable parts.

Design objectives:

- No additional movable device is required for construction of this alternative.
- Maintenance expectation is low for this alternative since the principle is simple.
- As mentioned, this principle is one of the simplest alternatives for the design of curved gate.
- The element of innovation in this structural principle is not comparable to the previous alternatives.

Table 4-14 and Table 4-15 show the qualitative evaluation of the horizontal structural systems based on the grading system given in Table 4-13.

Principle	Movable parts	Maintenance necessity	Simplicity	Innovation
1. A	D	D	D	A
1. B	N^-	D	D^+	A
1. C	D	D	D	N^+
2. A	A^-	N	A^-	A
2. B	D	D	D^+	N^+
3	A	N	A	N

Table 4-14: Evaluation of Horizontal structural systems based on design objectives

Principle	Reliability	Maintainability	Availability	Safety	Cost
1. A	D^+	D	N^-	D^+	A^-
1. B	N^-	D	N^-	N^-	A^-
1. C	D^+	D	N^-	D^+	A^-
2. A	N^+	N	N^+	A	N^+
2. B	D^+	D	N^-	N	N^-
3	A^-	N	A^-	A^-	D^+

Table 4-15: Evaluation of Horizontal structural systems based on general criteria

4.6.1.2 Evaluation of operating systems

1. *Cable drive system*

Reliability: Possible mechanisms of failure are cable break, joint break, drum failure, and other installation failures. In general, probability of defects and faults is relatively high and therefore, a high reliability of the system is difficult to achieve.

Maintainability: In general, maintenance of a cable drive system is difficult and expensive. Most often, cables need to be replaced and repairs are not possible.

Availability: As stated before, availability of the cable drive system could become an issue due to the large scale and curved shape of the movement.

Safety: Because of the large safety factors in the design of cables, this alternative is considered safe.

Costs: Total costs of this option are high. Maintenance costs are high because of difficult and repetitive procedures. Large diameter cables are needed which have to be especially made for the project and that makes it more expensive.

Design objectives:

- Maintenance necessity is relatively high because of limited life time of the cables.
- This option is rather simple except the fact that two cables have to be synchronized.
- The factor of innovation is limited to the curved shape of the cables. Otherwise, the concept of using cables is not new.

2. Racks and Pinions operating system

Reliability: The racks and pinion system has been used in design of sector gates recently. However, in current design, the contact pressure is a critical factor which can cause problems.

Maintainability: Pinions are located in the lock head. There should be an access to the room where the engines and pinions are placed. Any repair or replacement shall be done within this room. Racks on the gate can be repaired or replaced above the water surface.

Availability: Required time for maintenance is relatively low. On the other hand, the operational system can become non-available in high wave conditions and if accidentally the contact pressure is lost. In the case of friction drive with prestressed elastic wheels, the problem with high waves becomes less influential.

Safety: The engines which are used for the pinions have the ability to perform up to 3 times their power under special circumstances. The brake system can also perform well when the gate needs to remain closed or in a certain position. The design can be redundant, except the fact that the equipment is in contact with water, this alternative is safe.

Costs: The scale and power of the equipment is large and therefore, the costs are high. In addition the costs of replaceable racks on the gate ahs to be taken into account.

Design objectives:

- Wear and tear is relatively higher in this option due to gate fluctuations during the operation. Therefore, need of maintenance is higher in this case.
- This option is also simple except the synchronization of the multiple pinions and engines.
- Use of racks and pinions is an innovative idea in general. This concept has been used in movable bridges and sector gates.

Locomotive operating system

Reliability: Movement of the locomotive is done in a controlled environment. Therefore, the locomotive itself is a reliable device. In addition, the connection device can be designed with high reliability and safety factor.

Maintainability: Maintenance can be done in a completely separate area along the gate recess. This gives the advantage of quick fix and easy replacement procedures.

Availability: Except the total power failure or reaching the end of design life, the operational system can function well also in extreme hydraulic situations.

Safety: The sealed area of the locomotive reduces the danger for the equipment. The connecting device is a simple work of engineering which can be designed with a reasonable safety factor.

Costs: Construction of the locomotive is expensive because the wagon has to meet all the requirements for reliability and maintainability. However, the total costs reduce due to low maintenance costs.

Design objectives:

- Low wear and tear, leads to low necessity of maintenance.
- The concept is simple in design, operation and maintenance. The construction needs attention since this alternative has not been constructed for such a large scale with such low tolerances.
- The concept of locomotive has never been used for the movement purposes of the gate.

Table 4-16 and Table 4-17 show the qualitative evaluation of the operating systems based on the grading system given in Table 4-13.

Operating system	Movable parts	Maintenance necessity	Simplicity	Innovation
Cables	N.A.	N	N^-	D
Racks and Pinions	N.A.	N	N^-	N
Locomotive	N.A.	N^+	N^-	A^-

Table 4-16: Evaluation of operating systems based on design objectives

Operating system	Reliability	Maintainability	Availability	Safety	Cost
Cables	N^+	N	A^-	A	D
Racks and Pinions	N^+	N^-	N^+	A^-	N^-
Locomotive	A^-	A	A	A^-	N^-

Table 4-17: Evaluation of operating systems based on general criteria

4.6.1.3 Evaluation of Bottom bearing systems

1. *Roller carriage*

Reliability: Roller carriage has been used in several lock gates and is proved to be reliable.

Maintainability: Maintenance procedure of the roller carriage is difficult since it always requires divers and the gate has to be lifted.

Availability: Based on experience, the non-availability of the roller carriage is mainly because of periodic maintenance. Roller carriage has a low probability of failure and it barely stops functioning in normal situations.

Safety: roller carriage can safely provide the supporting function and the rolling function. However, the consequences of failure or break-down can lead to failure in other functions of the gate and cause serious problems.

Costs: Costs for construction of the roller carriages are high due to very small tolerances and many devices and pieces. The costs of maintenance are also high due to the reasons mentioned in the maintainability evaluation.

Design objectives:

- Roller carriage consists of many compartments which move relative to one another.
- Due to high wear, the necessity of maintenance is high.
- This option is simple in design and operation. Construction and maintenance are difficult but there is a lot of experience in this field.
- This device has been used for several rolling gates before and cannot be considered as innovative.

2. Hydro-foot

Reliability: The concept of hydro-foot has been shown as a reliable option based on many experiments. However due to limited practical samples, unpredicted failures are not realized yet.

Maintainability: Maintenance procedure for hydro-foot is relatively simple. Repair and replacement of the equipment or the hydro-foot, can be done without the need of divers.

Availability: Hydro-foot has a high rate of availability based on the experiments. The self-cleaning mechanism of the foot decreases the chance of mud accumulation on the track. This system has a high redundancy and can function well in extreme situations.

Safety: This option is one of the safest alternatives because even in case of failure, it can still be moved by the help of operational device. The consequences of critical failure are low.

Costs: total costs of hydro-foot are considerably low. Cost of maintenance is low. Main costs are due to the sensitive and accurate pipes at the very bottom of the foot and the high pressure water pumps.

Design objectives:

- No additional movable device is used in this option.
- Very low rate of wear and self washing mechanism of the hydro-foot, decreases the need for maintenance.
- Design, Construction, operation and maintenance is simple.
- The hydro-sliding concept is an innovative concept for lock gate which was introduced in recent years.

Table 4-18 and Table 4-19 show the qualitative evaluation of the horizontal structural systems based on the grading system given in Table 4-13.

Support system	Movable parts	Maintenance necessity	Simplicity	Innovation
Roller carriage	D^+	N^-	A^-	N
Hydro-foot	A	A^-	A^-	A

Table 4-18: Evaluation of support systems based on design objectives

Support system	Reliability	Maintainability	Availability	Safety	Cost
Roller carriage	A	N^-	N^+	A^-	N
Hydro-foot	A^-	A^-	A^-	A^-	A^-

Table 4-19: Evaluation of support systems based on general criteria

Summary

Table 4-20 to Table 4-22 show the quantitative evaluation of the alternatives and enable us to make a comparison before we can come to a conclusion. As stated before, the goal is to assemble the best combination of solution into one integrated concept. Based on the results, the beam with parallel support, locomotive drive system and hydro-foot have the highest score in this evaluation system.

Structural System	**Arched**			**Beam with parallel supports**		**Beam with Sloped supports**
	A	**B**	**C**	**D**	**E**	**F**
Design Objectives	6	9	4	**19**	5	18
RAMS	9	11	9	**21**	8	19
Availability vs. Costs	7	7	7	**8**	4	6

Table 4-20: Quantitative evaluation for structural systems

Operating System	**Cable**	**Racks and Pinions**	**Locomotive**
Design Objectives	5	8	**11**
RAMS	18	17	**24**
Availability vs. Costs	5	6	**8**

Table 4-21: Quantitative evaluation for operating systems

Support system	**Roller carriage**	**Hydro-foot**
Design Objectives	11	**22**
RAMS	20	**25**
Availability vs. Costs	7	**10**

Table 4-22: Quantitative evaluation for support systems

4.6.2 Concept description

This section presents the design decisions in the form of the final developed concept. The decisions are made based on the evaluation of the alternatives in the previous section. It is important to keep in mind that the decisions on the alternatives cannot be made in spite of other design decisions and the choices are dependent on each other. The goal in decision making process is to find the best combination of solutions. The following paragraph describes the chosen concept for the preliminary design:

- *Structural System (section 4.4.3):*
  Principle 2. Beam with parallel supports
  Solution B. Combined movement

- *Bottom bearing system (section 4.4.5):*
  Hydro-foot

- *Number and position of bottom supports (section 4.4.3):*
  2 supports at the line coinciding the center of gravity and perpendicular to the symmetry line

- *Horizontal support at the bottom (section 4.4.3):*
  None

- *Cross-section width (section 4.5.1):*
  10 meter

- *Type of horizontal guidance (section 4.4.4):*
  Steel block sliding on UHMWPE

- *Number of horizontal guidance (section 4.4.4):*
  5 guiding points (3 active points)

- *Position of horizontal guidance (section 4.4.4):*
  2 at the bottom (same as bottom support system)
  2 at the top in the area which always remains inside recess
  1 at the top only active on small recess

- *Operational system (section 0):*
  Locomotive with 8 engines

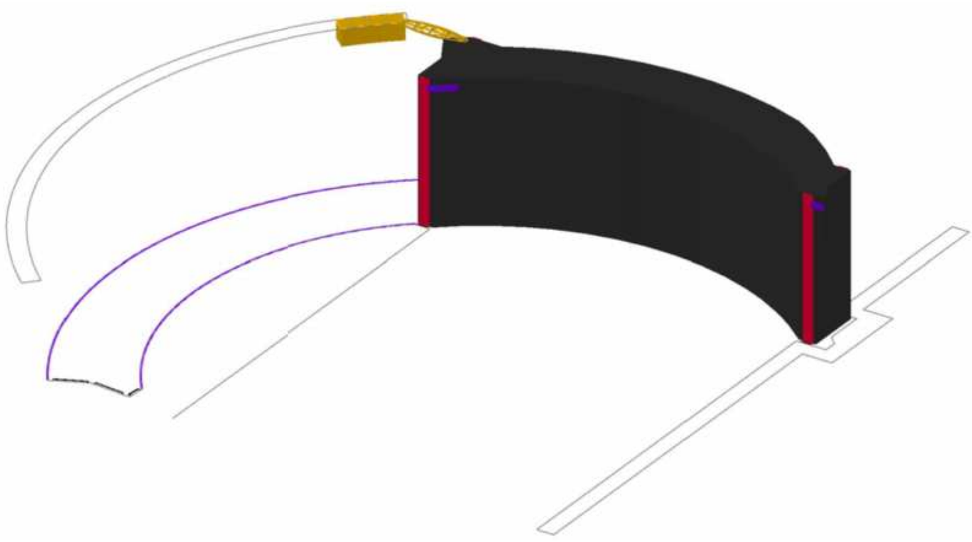


Figure 4-57: 3D impression of the conceptual design (bird eye view hollow side)

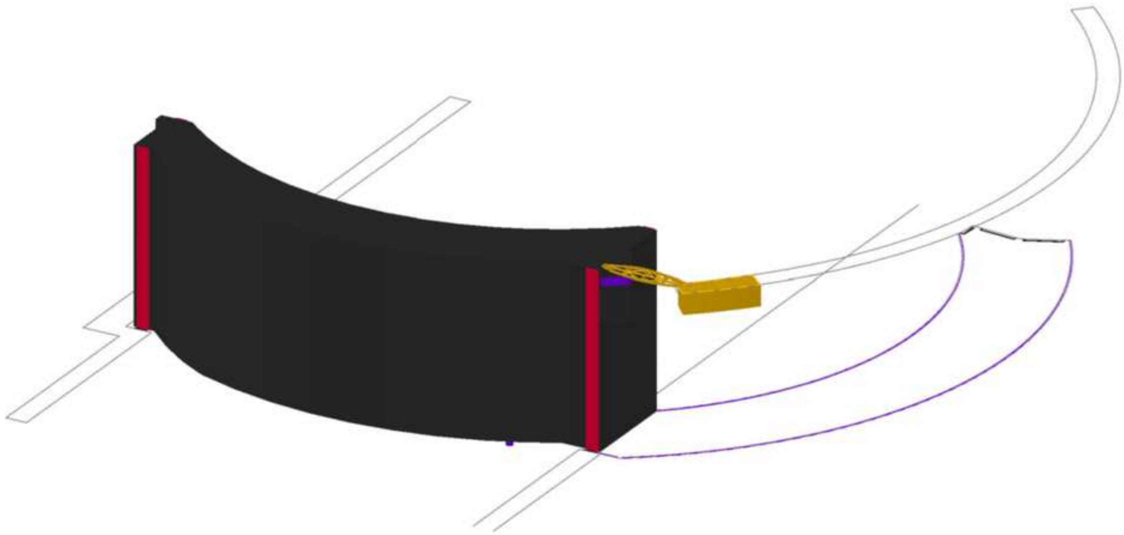


Figure 4-58: 3D impression of the conceptual design (bird eye view convex side)

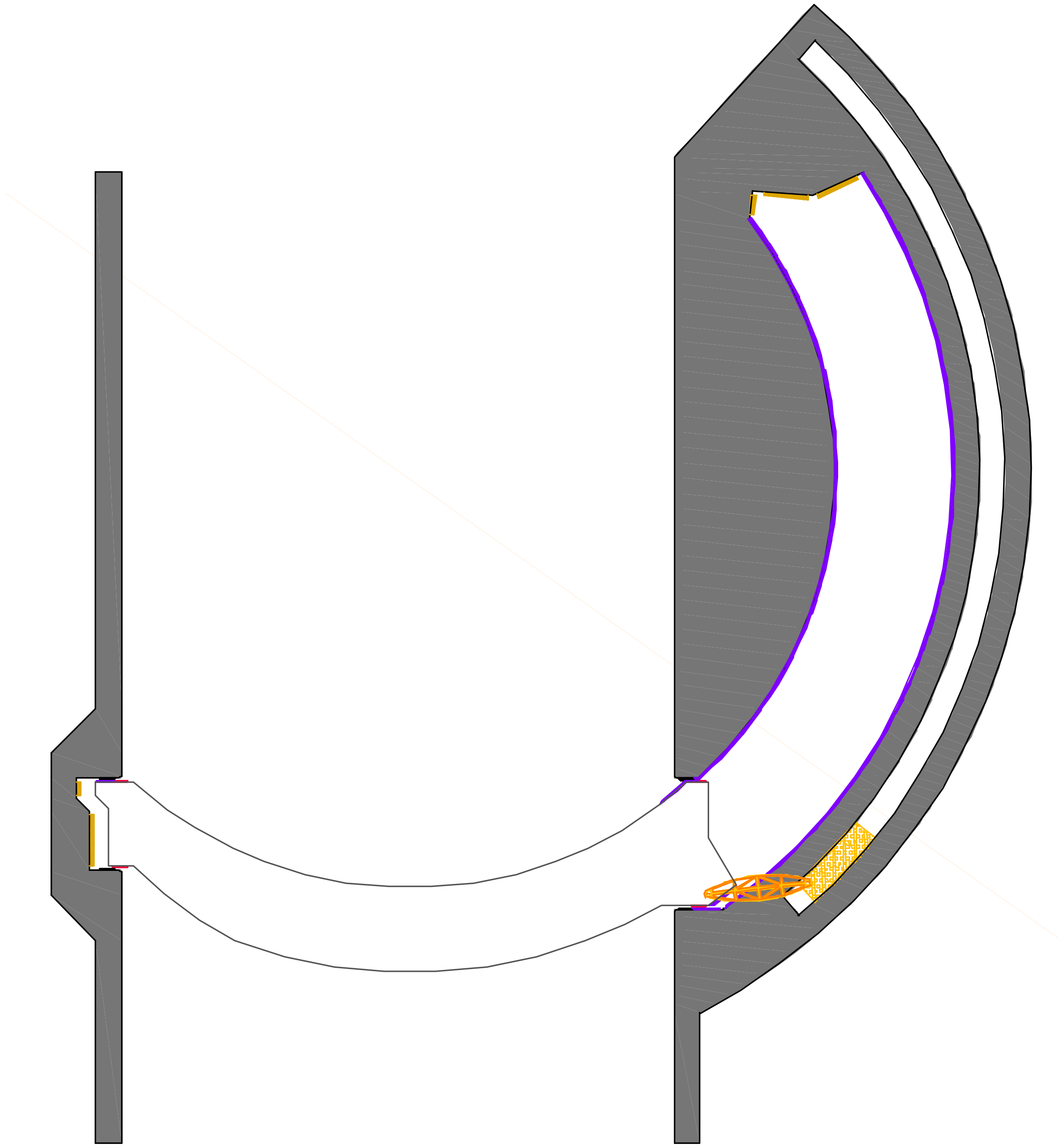


Figure 4-59: Conceptual design (top view)

5 Preliminary design

5.1 Approach

The starting point for the preliminary design is the final conceptual design described in section 0. Main layout is designed based on 2D structural analysis. As recommended in the previous chapter, this stage of design will be more focused on three dimensional structural behavior of the gate. Although detailed design for main elements is given in this chapter, focus of this chapter is mostly the structure of the gate itself. In this manner, a 3D-Model of the structure is studied analytically in terms of behavior accompanied with computer models. 3D-Computer models are used to apply the analysis for more detailed configurations and specifically to quantify the results. section 5.2 describes the structure, its components and boundary conditions that are being used in this study. The modeling approach and model description is given in section 5.3. The structural behavior of the gate is presented by the help of computer analysis in sections 0 and 0 for gate in closed position and gate during daily operation respectively. Detailed design for each element is done in this chapter and can be seen in 5.6. Finally, the design is evaluated in terms of cost and availability at the end of this chapter in 0.

5.2 General description of the Gate Structure

The gate structure consists of various elements; here the most important elements are described, shown and their function is explained. Characteristics and properties of these elements are calculated and presented in sections 5.3.7 and 5.6.8. Figure 5-1 shows an impression of the gate structure with all the important elements. Figure 5-2 to Figure 5-11 show the structural elements separately.

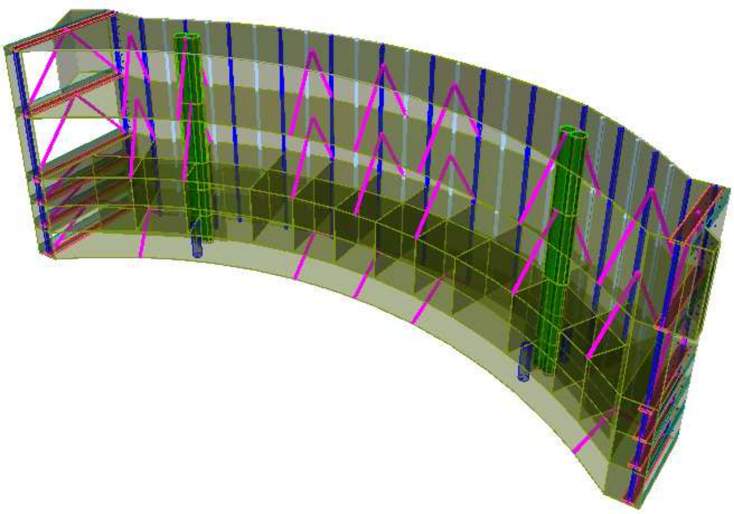


Figure 5-1: General overview of the structural elements

The function(s) of main structural elements are described:

- Skin plates (Figure 5-2 and Figure 5-3) in combination with horizontal plates (Figure 5-6) form a typical cross section (Figure 4-4 from Chapter 4) for resisting the horizontal loads.
- Number of horizontal plates and their distance from each other is a matter of optimization in structural design of the gate. in current preliminary design, only one horizontal plate is used between the top plate (deck) and the top buoyancy chamber plate. This plate is located 7.50m below the deck because the horizontal pressure is at its highest around this level.
- Although preference for decks and horizontal plates (horizontal diaphragms) is a system of frame and bracing, but for simplicity in modeling and calculations in preliminary design, plates are chosen instead. Due to sedimentation problems which can occur at later stages of the gate's life-time, it is recommended to design a system of frames and horizontal bracings instead of plate elements wherever it is possible.
- Two main columns (Figure 5-8) along the hydro-feet (Figure 5-9), skin plates (Figure 5-2 and Figure 5-3) and vertical frames (Figure 5-4 and Figure 5-5) make a structural system for resisting the vertical loads.
- Skin plates, bottom seal and side seals form the retaining system and make the gate watertight. Section 5.6.7 provides details about sealing system of the gate.
- Vertical bracings (Figure 5-10) are for consistent displacement distribution and a consistent horizontal behavior along the vertical direction. Horizontal beams are also present at the position of vertical bracings as well as the inclined elements.
- Hydro-feet (Figure 5-9) are used as bearing system for vertical loads. During operation and movement of the gate, hydro-feet have guidance function. Section 5.6.3 provides calculations and information about the design of hydro-foot.
- Side bearings at lock head are large UHMWPE panels through which the horizontal loads are transmitted to the walls. At the position of these bearing in the gate structure, steel plates are considered for transforming the load to the side bearings. Section 5.6.1 provides detailed drawings and design calculation for side bearings.
- Two pairs of steel shafts at the bottom and three steel panels at the top of the gate form the guidance system of the gate during its movement. Notice that only one out of three top guidances is loaded at any given moment during opening/closing depending on the stage of operation. Section 5.6.4 provides more information about guidance devices of the gate.
- Buoyancy chambers (Figure 5-6) are located between 3.50m and 10.25m from the bottom of the gate. The detailed design of buoyancy chamber's plates and stiffeners is not meant for the preliminary design. However it has to be said that since the buoyancy chambers contain air, direct hydrostatic pressure on the steel plates is considerably larger than other elements of the gate. Therefore thicker plates and larger stiffeners are used at the place of buoyancy chambers and consequently, mass concentration of the structure is higher at the level of buoyancy chambers. See section 5.6.2 for information about buoyancy chambers.
- End frames (Figure 5-7) have one of the most important functions of the gate structure; transmitting the loads from the gate to the bearings. In this manner, end frame consists of several sub-elements to provide the required stiffness and resistance for the gate. As mentioned before, steel panels which are attached to the end frame, transfer the loads on UHMWPE panels of side bearings.
- The driving force is transferred through a connection element from the locomotive to the gate. This element has to be designed such that it can resist the maximum compressive or

tensile driving force during operation. End connection for this element is free to rotate in the horizontal plane and is fixed in the vertical direction. See section 5.6.5 for driving mechanism and connection element.

- Plate elements are always stiffened by plate stiffeners. Section 5.3.7 discusses the stiffeners and their global and local function in the structure.

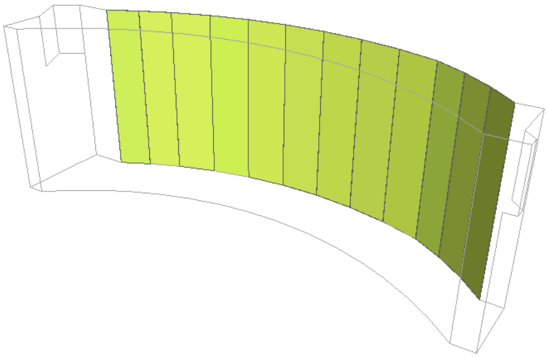


Figure 5-2: Skin plates (Convex side)

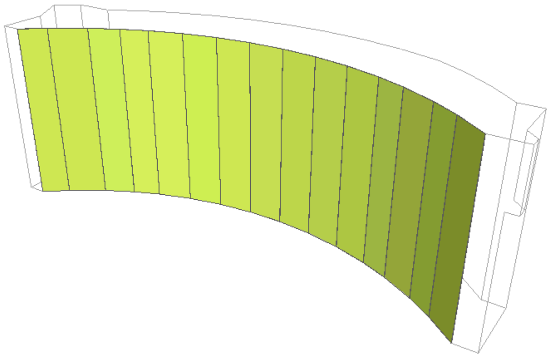


Figure 5-3: Skin plates (Hollow side)

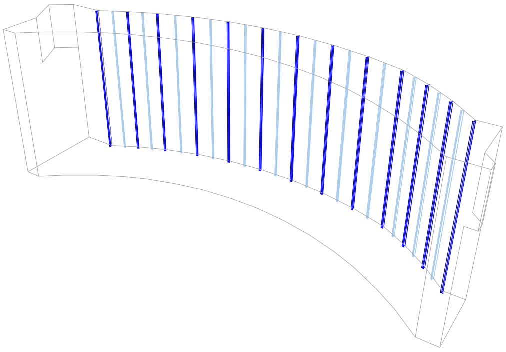


Figure 5-4: Vertical frames (Convex side)

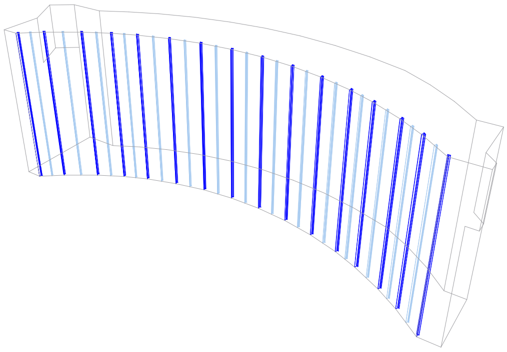


Figure 5-5: Vertical frames (Hollow side)

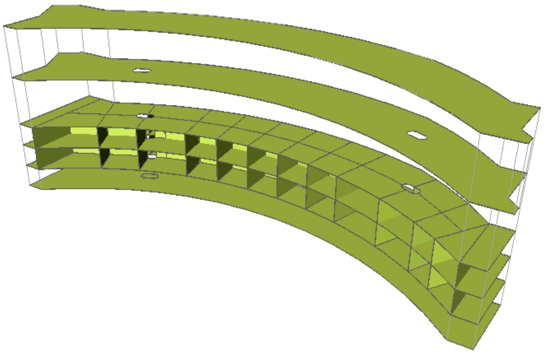


Figure 5-6: Horizontal plates + Buoyancy chamber

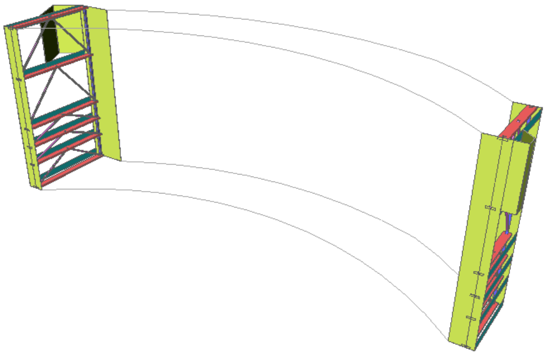


Figure 5-7: End frames

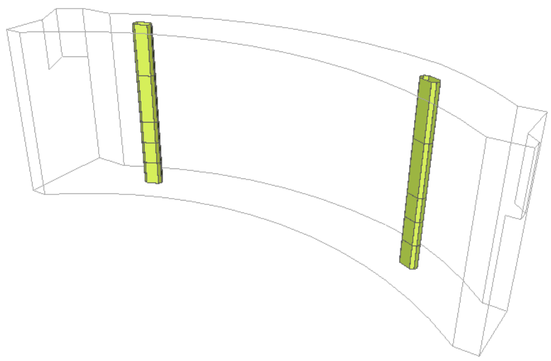


Figure 5-8: Columns

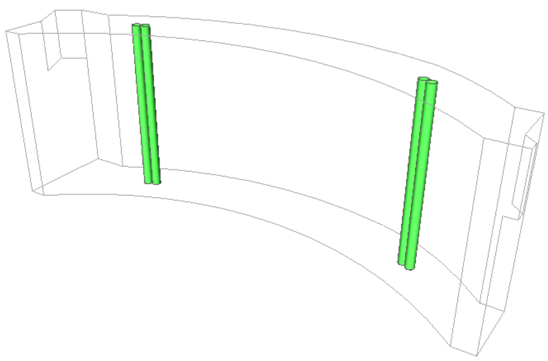


Figure 5-9: Hydro-feet

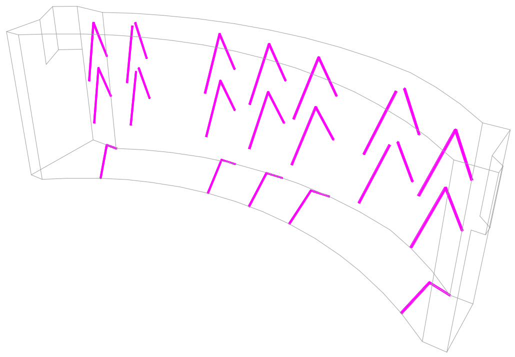


Figure 5-10: Vertical bracings

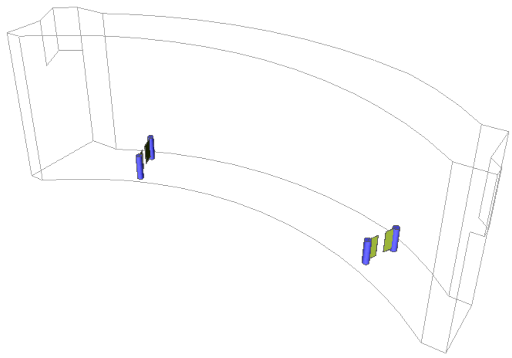


Figure 5-11: Bottom guidance elements

5.3 Modeling

5.3.1 General

A description of 3D-structural model of the gate is given in this section. This model has been defined for "Scia Engineer", a FEM software for structural design and analysis. The structural model is the representation of the curved sliding gate with skin plates on channel side and sea side.

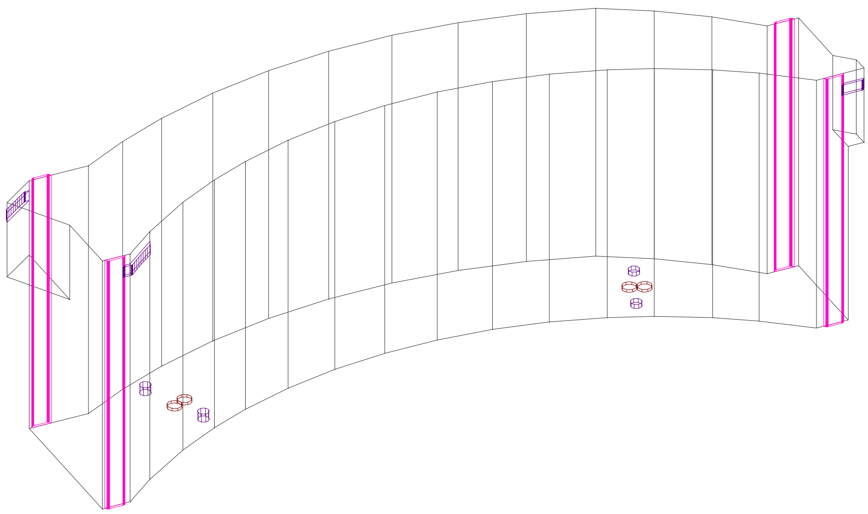


Figure 5-12: 3D overview of gate

5.3.2 *Assumptions*

One model is used for both gates at both ends of the lock chamber; The gate at the channel side (inside gate) and the gate at the sea side (outside gate). The following assumptions and premises are considered:

- For calculations related to positive head, load cases on the outside gate are considered.
- For calculations related to negative head, load cases on the inside gate are considered.
- A linear elastic analysis is done.
- Constrains and boundary conditions are defined according to the relevant load condition and the expected behavior. The validity of constrain definition is checked after structural analysis.

5.3.3 *Coordinate system*

The main coordinate system is Cartesian. In certain cases (Gate during operation) it is convenient to show parameters in Cylindrical coordinate system. Therefore both coordinate systems have been defined in this section.

Since the movement of the gate consists of a rotational turn and a horizontal shift, different coordinate systems are defined to facilitate the modeling process and explanation of the model.

GCaCS (Global Cartesian Coordinate System):

Center-point is located at the rotation axis of the gate during its operation and at the chamber bottom level.

The global X-axis is perpendicular to the centerline of the lock chamber. +X direction is pointed at the opposite side from the main recess.

The global Y-axis is coincident with the centerline of the lock chamber. +Y direction is pointed at the channel side of the lock.

The global Z-axis is a vertical axis coincident with the rotation axis where the +Z direction is pointed upwards.

Alignment of the Global Cartesian Coordinate System is shown in Figure 5-13.

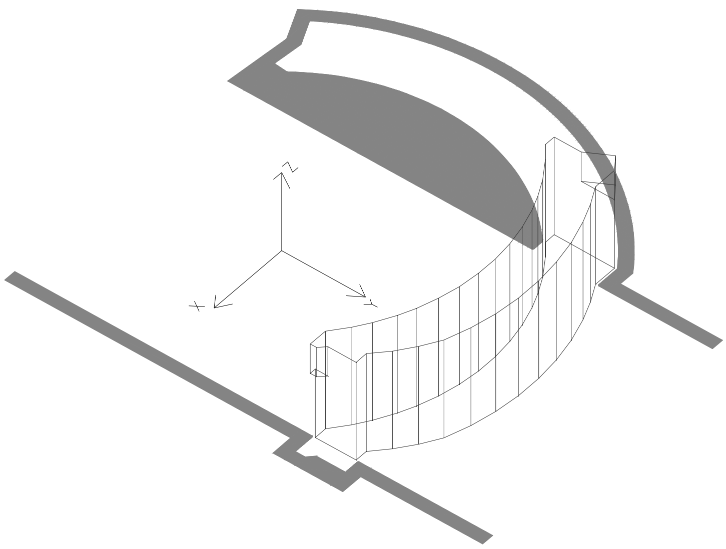


Figure 5-13: Global Cartesian Coordinate System

Transformed GCaCS:

Center-point is located at the center of the arcs of skin plates of the gate when it is closed and at the chamber bottom level. This point is a transformation of the center-point of GCCS in +X direction.

The global X'-axis is perpendicular to the centerline of the lock chamber. +X' direction is pointed at the opposite side from the main recess.

The global Y'-axis is parallel with the centerline of the lock chamber. +Y' direction is pointed at the channel side of the lock.

The global Z'-axis is a vertical axis where the +Z' direction is pointed upwards.

Alignment of the Global Cartesian Coordinate System is shown in Figure 5-14.

GCyCS (Global Cylindrical Coordinate System):

Center-point is located at the rotation axis of the gate during its operation and at the chamber bottom level.

The global Z-axis is a vertical axis coincident with the rotation axis where the +Z direction is pointed upwards.

The global radial distance ρ of any point on the structure is the perpendicular distance of that point to the Z-axis.

The global Azimuth φ of any point on the structure is the angle between X-plane from GCaCS and that point. Positive φ direction is considered counter clockwise.

Alignment of the Global Cartesian Coordinate System is shown in Figure 5-15.

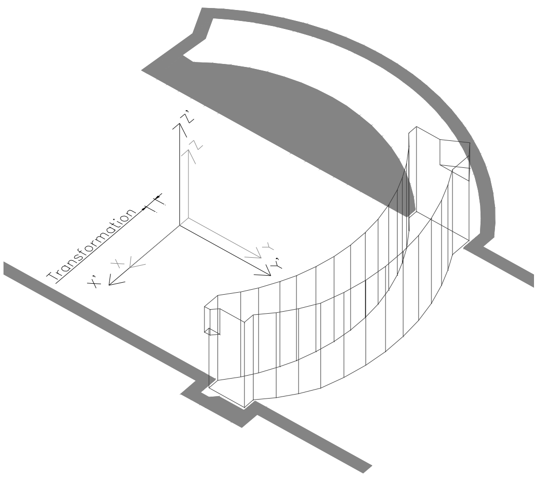


Figure 5-14: Transformed GCaCS

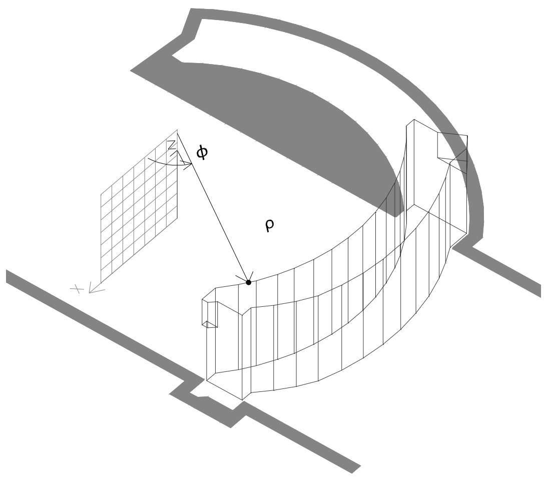


Figure 5-15: Global Cylindrical Coordinate System

5.3.4 *Units*

The SI-unit system is used in Scia model. Basic units are:

Mass [kg], Length [m] and Time [s]

* The Default unit for element dimensions input is [mm]

Presentation of results is done using the following units:

[mm] for Displacements, [m/s^2] for Acceleration, [kN] for Forces, [kN-m] for Moments and [N/mm^2] for Stresses

5.3.5 *Material properties*

Table 5-1 presents the characteristics of the materials that are used for design, analysis and modeling. Notice that some materials are solely defined for modeling purposes and they are used as dummies.

Number	Material	Description	E [N/mm^2]	ν	Density [kg/m^3]
1	Steel	S355	2.1 E +5	0.3	7850
2	UHMWPE	Carbon Black	5.5 E +02	0.42	950

Table 5-1: Material characteristics in model

5.3.6 *Element types*

General element types used in the model are introduced in Table 5-2.

Element Type	Description
3D-Beam (80)	Three Dimensional Elastic Beam
3D-Column (100)	Three Dimensional Elastic Beam
3D-Plate (90)	Three Dimensional Elastic Plate
3D-Plate rib (92)	Three Dimensional Elastic Beam which forms a T-Beam with attached plate

Table 5-2: Element types used in the model

5.3.7 *Simplifications*

In order to avoid time-consuming software calculations the model is simplified. In that manner, horizontal stiffeners of skin plate and in general all the stiffeners for every plate elements are not present in the model, but instead, the equivalent thickness of the plate has been considered in the model. Figure 5-16 shows the actual cross-section of the plate plus stiffeners and the equivalent plate thickness which is being used in the model.

Equivalent plate thickness

It is intended to maintain the total stiffness of the structure at its actual value globally. The equivalent thickness of the plate can be calculated by considering the fact that stiffness of the structure is directly dependent on the moment of inertia of the total cross-section. According to the equations in section 4.2 chapter 4, moment of inertia is mainly affected by the cross-sectional area of skin plate rather than its own moment of inertia. Therefore the equivalent thickness is calculated such that the equivalent area of the plate is equal to the actual area of the plate plus horizontal stiffeners. Notice that the total weight of the structure will also remain the same as the actual value which is an advantage for this simplification.

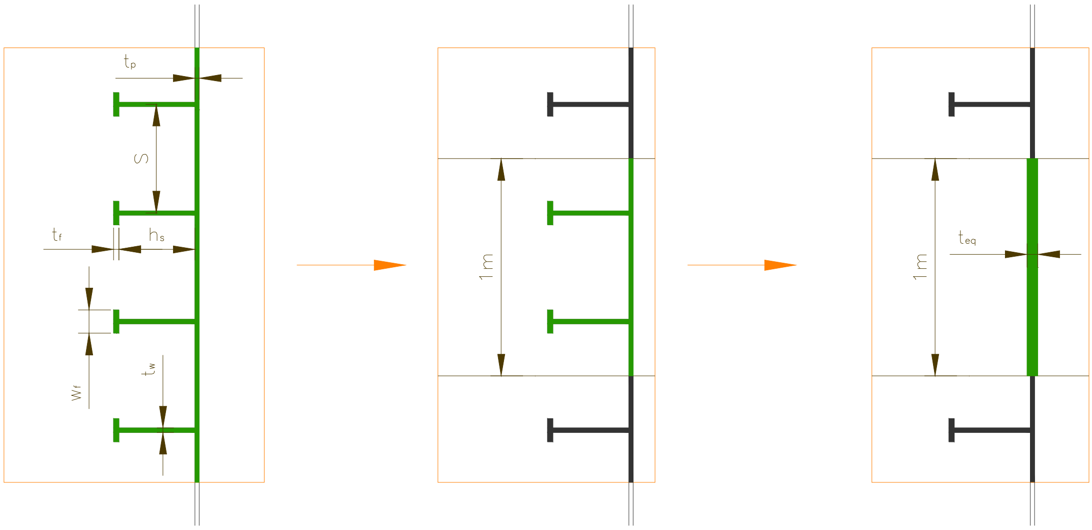


Figure 5-16: Equivalent thickness for plates (Global)

$$A_{plate} + A_{stiff.} = \left(1000 \times t_p\right) + \left(\frac{1000}{S}\right) \times \left(h_s \times t_w + w_f \times t_f\right)\ [mm^2]$$

$$A_{eq} = 1000 \times t_{eq}\ [mm^2]$$

$$A_{eq} = A_{plate} + A_{stiff.} \Rightarrow t_{eq} = \frac{\left(1000 \times t_p\right) + \left(\frac{1000}{S}\right) \times \left(h_s \times t_w + w_f \times t_f\right)}{1000}\ [mm]$$

The disadvantage of this simplification is the local effect of stiffeners on the skin plate. Therefore, two important issues have to be considered.

- Local deformation: Local stiffness of the plate with equivalent thickness is considerably lower than the local stiffness of the actual plate when the above-mentioned method is used. Therefore the local deformations are considerably larger in the model than in reality. The following equations show the equivalent thickness for the purpose of maintaining the local stiffness of the plate:

$$\bar{x} = \frac{\left(1000 \times t_p \times \frac{t_p}{2}\right) + \left(\frac{1000}{S}\right) \times \left(h_s \times t_w \times (t_p + \frac{h_s}{2}) + w_f \times t_f \times (t_p + h_s + \frac{t_f}{2})\right)}{\left(1000 \times t_p\right) + \left(\frac{1000}{S}\right) \times \left(h_s \times t_w + w_f \times t_f\right)}\ [mm]$$

$$E(I_{plate+stiff.}) = E \times \left(\frac{1}{12} \times \left[\left(1000 \times t_p^3\right) + \left(\frac{1000}{S}\right) \times (t_w \times h_s^3 + w_f \times t_f^3)\right] + \left(\bar{x} - \frac{t_p}{2}\right)^2 \times \left(1000 \times t_p\right) + \left(\frac{1000}{S}\right) \times \left[\left(t_p + \frac{h_s}{2} - \bar{x}\right)^2 \times (h_s \times t_w) + \left(t_p + h_s + \frac{t_f}{2} - \bar{x}\right)^2 \times \left(w_f \times t_f\right)\right]\right)\ [mm^4]$$

$$EI_{eq} = \frac{E}{12} \times 1000 \times t_{eq,l}^3\ [mm^4]$$

$$EI_{eq} = E(I_{plate+stiff.}) \Rightarrow t_{eq,l} = \sqrt[3]{\frac{12 I_o}{1000}}\ [mm]$$

Table 5-3 shows an example of how the local stiffness of the plate is being underestimated while the global stiffness is maintained. Notice the difference between t_{eq} and $t_{eq,l}$.

t_p	S	h_s	t_w	w_f	t_f	A	t_{eq}	$\bar{x}$	I_o	$t_{eq,I}$
25	500	350	22	125	25	46650	46,65	124,6	992525146	228,4

Table 5-3: Example for equivalent plate thickness (units in mm)

- Local bending moments: Local load distribution pattern in the simplified model is different than in the actual structure (Figure 5-17). Consider the beam in Figure 5-18. The beam represents the skin plate and the supports are representing the horizontal stiffeners. The bending moment pattern in Figure 5-19 will occur for the skin plate. However in the model, moment line in the vertical direction is completely different and does not include this pattern since the load distribution is mostly in the horizontal direction in the model. Therefore, while interpreting the results, local bending moments between the horizontal stiffeners should be added to the global bending moment which is calculated by the program.

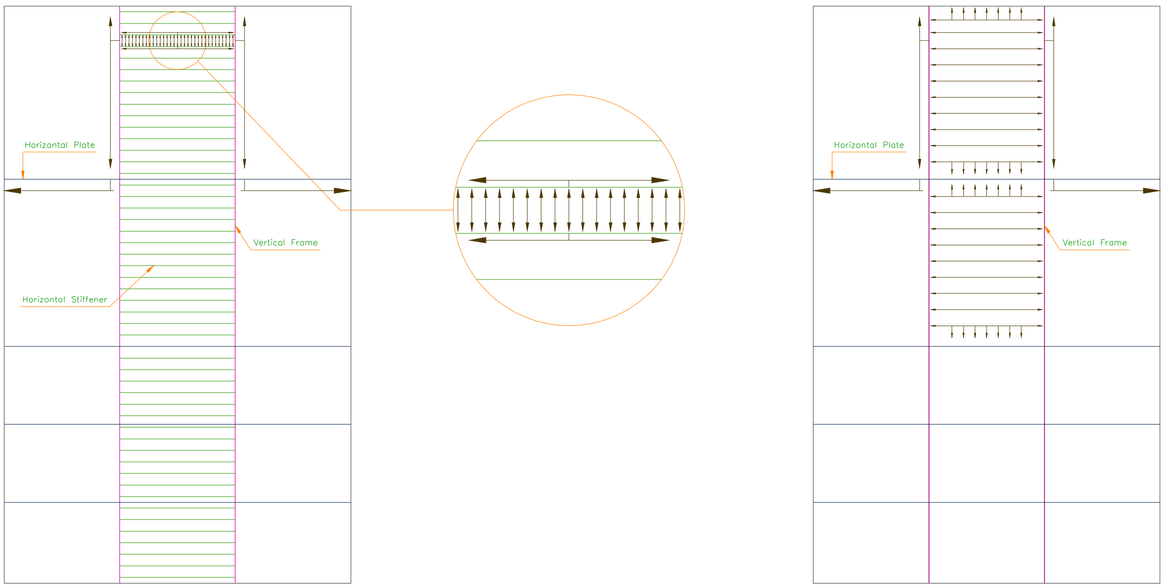


Figure 5-17: Load distribution pattern on skin plates (Left: Actual structure, Right: Model)

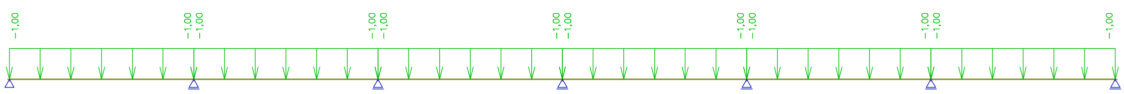


Figure 5-18: Distributed unit load on skin plate

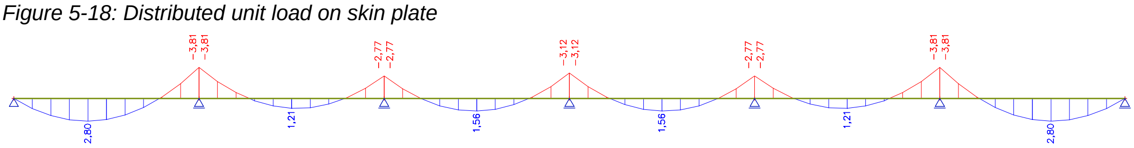


Figure 5-19: Bending moment variation due to a distributed unit load on skin plate

5.3.8 *Main components*

Skin plates

Skin plates are structural elements which retain the water at channel side and sea side. These plates are categorized as skin plates at hollow side (sea side) and skin plates at convex side (channel side). These elements are modeled as 3D-Plate element type. Skin plates are supported by vertical frames and are coupled by the decks, horizontal diaphragms and bracing system.

Vertical frames

Vertical frames are connected to skin plates and are modeled as T-shaped beam. Vertical frames are located at the intersection between two skin plates and at the middle of each skin plate. The vertical frames which are located at the middle of the plates, are modeled as plate ribs.

Decks and horizontal diaphragms

Plate elements are considered for horizontal web plates including deck, diaphragm, bottom plate and buoyancy chambers' horizontal plate. The same method as described for skin plates, is used here for the equivalent plate thickness.

Columns

Columns are modeled as set of plates which are located surrounding the hydro-feet from the bottom of gate structure to the top and are connected to all the horizontal plates.

Bracings

Bracings are modeled as beam elements. The connection of the bracing elements is considered hinged at both ends. Therefore it is anticipated that the only internal force in these elements be the axial force.

Buoyancy chambers

Buoyancy chambers are represented in the model by a set of steel boxes in a row. The number and volume of these boxes represent the real situation with a certain approximation. Notice that in the final design, the plates of buoyancy chambers are stiffened with a vast number of stiffeners which are not present in the model and the equivalent plate thickness is used in the model.

End frames

End frames (as shown in Figure 5-7) consist of 4 different components; Plates, vertical stiffeners, horizontal beams and bracings. The function of these elements is to provide a stiff connection between two sides of the gate (convex and hollow side) at the position of the side bearings and withstand the large bearing loads.

5.3.9 *Boundary conditions*

Definition of boundary conditions is one of the most sensitive steps in the modeling process.

First because the boundary conditions depend on different load conditions. Therefore constrains are defined separately for each load condition.

Second, every bearing has a secondary reaction force caused by friction in addition to its primary reaction force. Applying the concept of friction support in the model is rather cumbersome and it requires iterative attempts to resemble the real situation. The model is only valid when the secondary reaction force (force caused by friction) is not larger than the friction capacity of the

support (friction coefficient (f) * Primary reaction force) and the displacement in the direction of secondary reaction is at its minimum. Therefore the following procedure is considered:
The reaction force which is caused by friction is modeled by a spring (Figure 5-21). The behavior of spring and a friction based support are completely different. However, for small deformations the results are consistent and reliable. In every iteration step, the reaction force of the spring and displacement of structure in the same direction is checked.

- If the reaction force (R_s) is already equal to or smaller than the maximum possible friction force ($f \times R_p$) and the displacement is close to zero, then the assumptions in the model are valid.
- If the reaction force (R_s) is already smaller than the maximum possible friction force ($f \times R_p$) and the displacement is <u>not</u> close to zero, then the spring stiffness needs to be increased.
- If the reaction force (R_s) is larger than the maximum possible friction force ($f \times R_p$) and the displacement is small, then the spring stiffness needs to be decreased.
- If the reaction force (R_s) is larger than the maximum possible friction force ($f \times R_p$) and the displacement is large, then the structure is unstable.

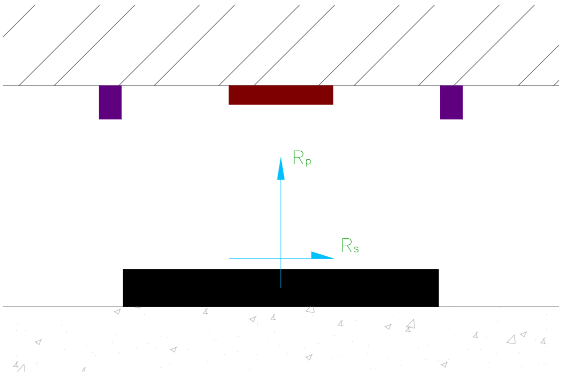


Figure 5-20: Primary and Secondary reaction forces

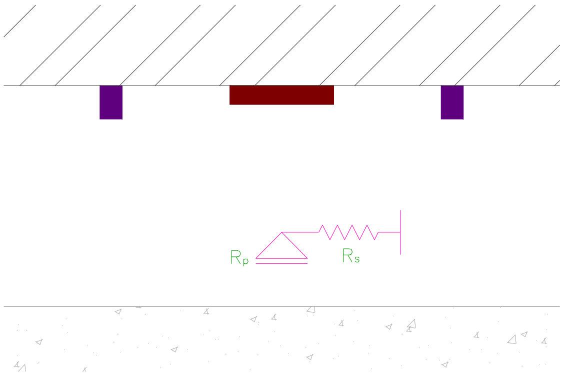


Figure 5-21: definition in model

Constrains

The gate structure has three different support types which are represented by different types of constrains in the model.

1. Side bearings: each of the side bearings are modeled by three line supports on an internal edge of the end plate at the actual position of bearing. All three supports are rigid in Y-direction. The connecting element to the driving mechanism provides the reaction force in X-direction.

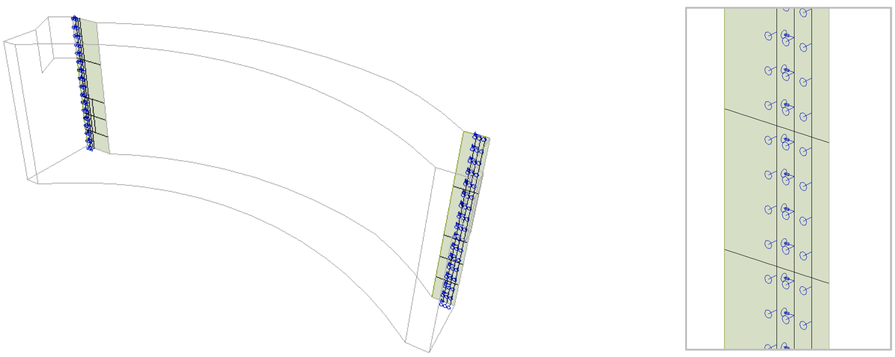


Figure 5-22: Modeling of Side bearings

2. Hydro-feet: Each hydro-foot is modeled as a tubular column element which is connected to horizontal plates at top and bottom of the structure. At the bottom, the hydro-foot column is constrained in Z-direction by a node support and a circular line support (Figure 5-23). Depending on the load condition, an extra spring support (as described earlier in this section) may be used in Y-direction.

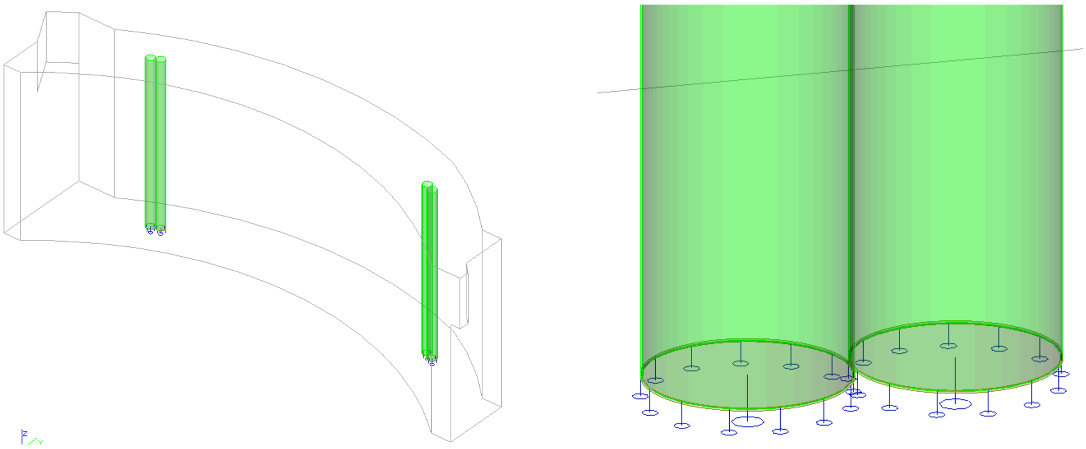


Figure 5-23: Modeling of hydro-foot supports

3. Guidance: Bottom Guidance devices (guiding elements) are modeled as steel elements which are constrained at the very bottom in Y-direction by a node support. Top guidance devices are modeled as internal edges on plate elements. Depending on the load condition, line supports will be applied on these edges. The support will be rigid in the Local Z-direction which is perpendicular to the plane of the plate.

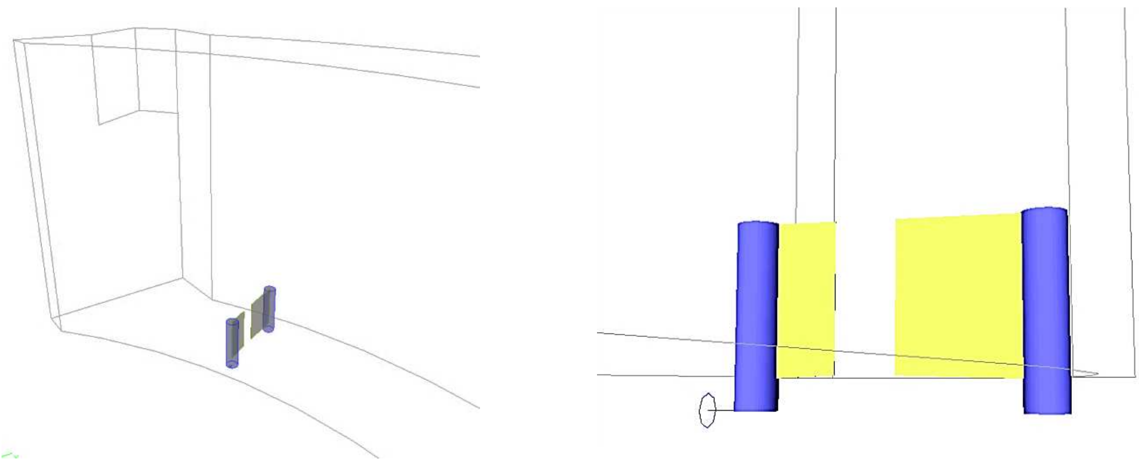


Figure 5-24: Modeling of (bottom) horizontal guidance

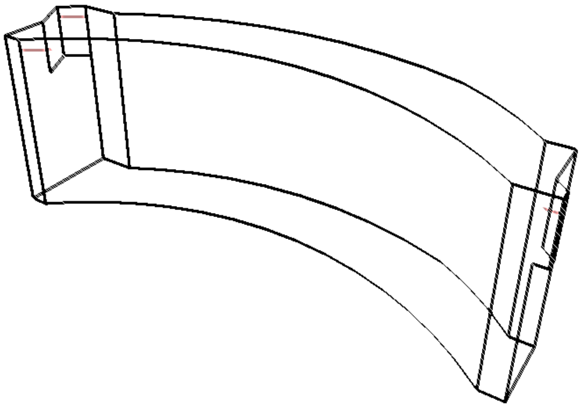


Figure 5-25: Internal edges (Red lines) representing the top guiding elements

5.3.10 Loads

Load cases

The following load cases are defined in the model:

- Hydraulic loads: Hydraulic loads consist of water level differences and all the wave loads. All the hydraulic loads are applied as surface loads directly on the plates.

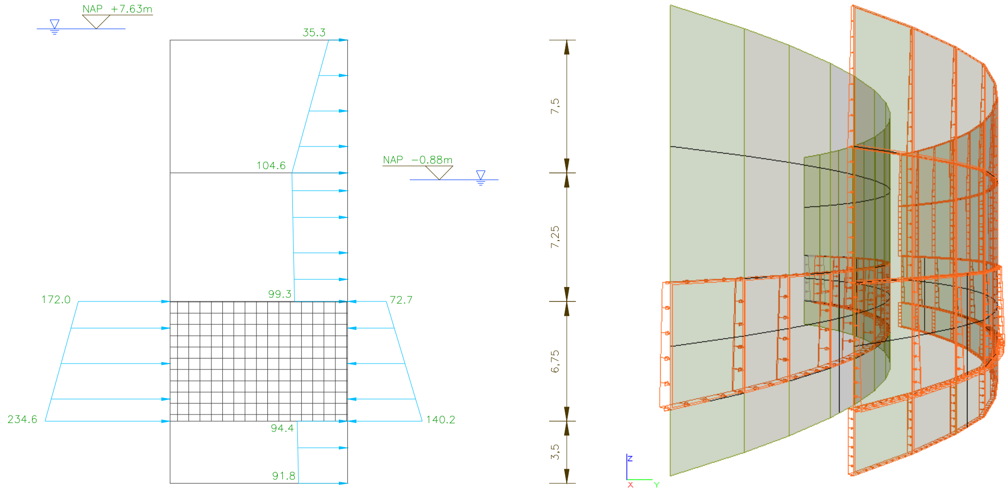


Figure 5-26: Hydraulic loads on skin plates (Positive head)

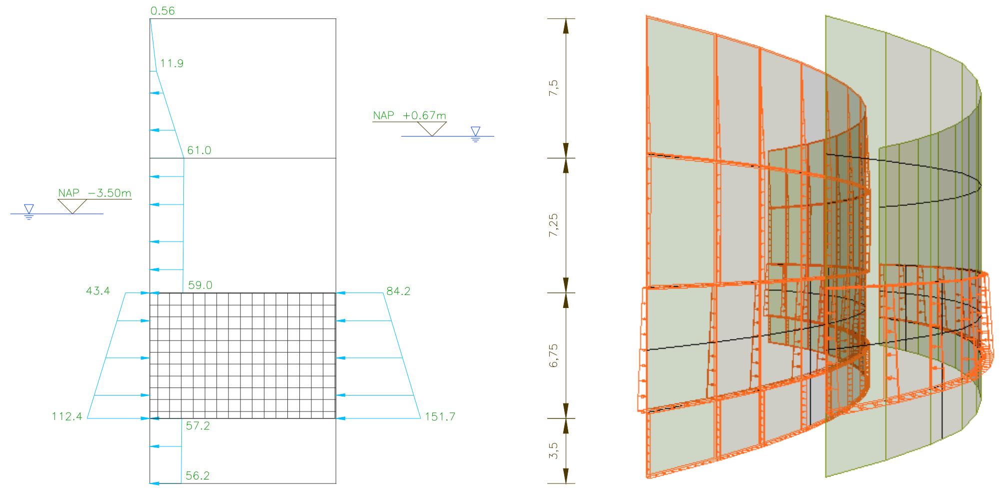


Figure 5-27: Hydraulic loads on skin plates (Negative head)

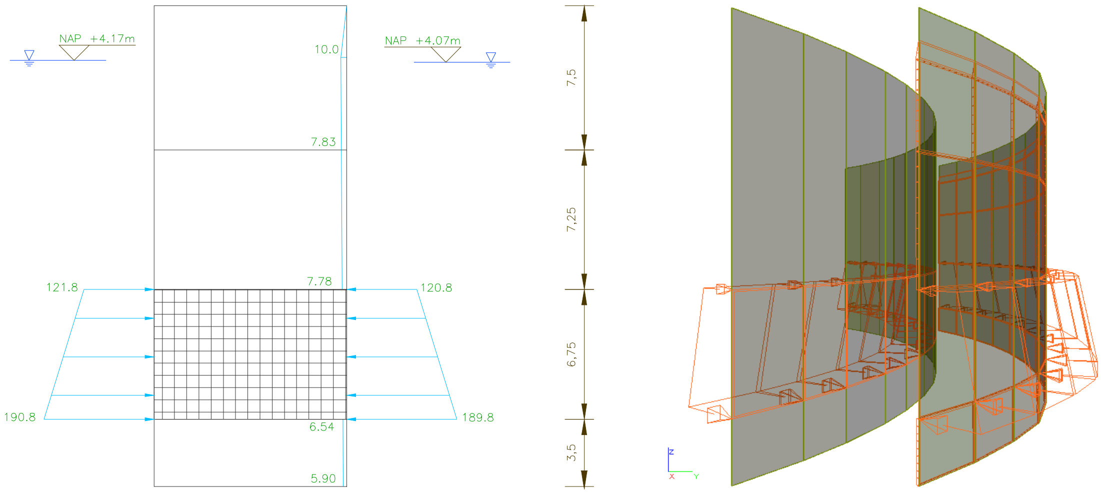


Figure 5-28: Hydraulic loads on skin plates during operation at maximum water level

- Buoyancy: Buoyancy is divided into two different load cases. First one represents the buoyancy force caused by buoyancy chambers. In other word, the loads are hydrostatic loads on the buoyancy chambers. In the case of trim and ballast tanks, the weight of the water inside the tank is added in the model.

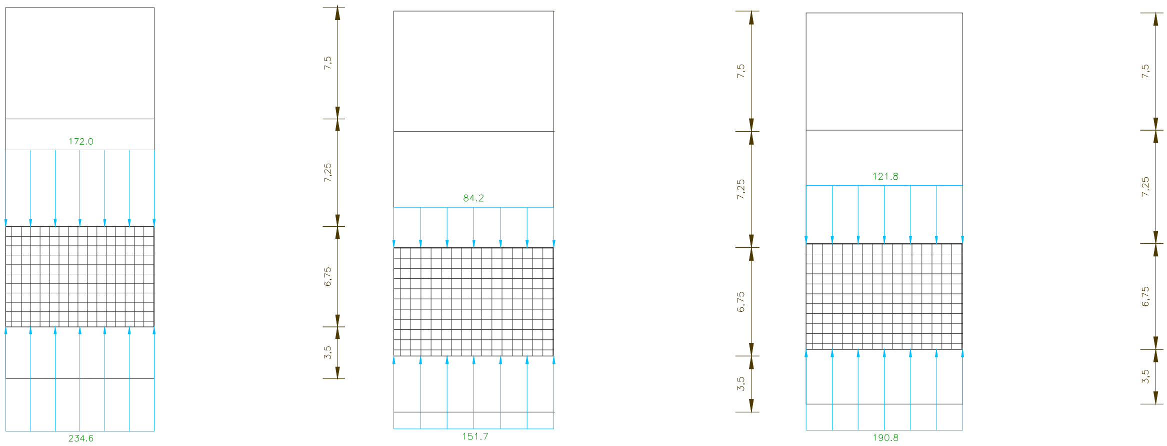


Figure 5-29: Hydrostatic load on buoyancy chambers (Left: Positive head – Middle: Negative head – Right: During operation at maximum water level)

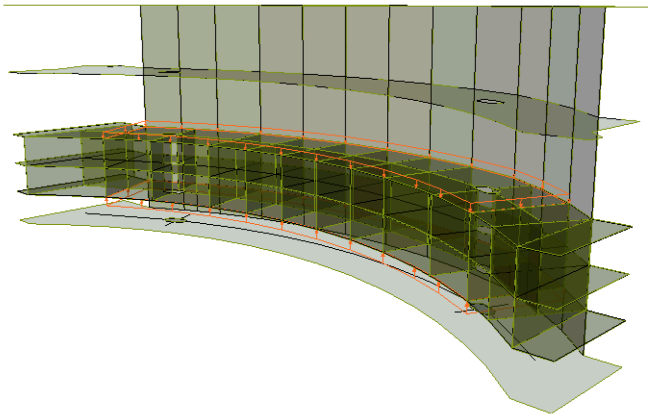


Figure 5-30: Hydrostatic load on buoyancy chambers in the model

- Second load case represents generally the buoyancy force which is applied on the submerged materials itself. This load case is applied as an upward surface load on all the submerged elements (excluding buoyancy chambers which were treated previously). The magnitude for distributed load is calculated as such:

  $q_b = \gamma_w \times t_e$ $\qquad$ $Where\ t_e\ is\ the\ loaded\ element's\ thickness$

- Self-weight: Self weight of the structure is automatically calculated by the program.

- Driving force: Driving force is applied as a point load on the specific element in the end frame.

Load combinations

Following load combinations are considered in the model:

- **Extreme water retaining from seaside**: Hydraulic loads on skin plates (positive head) + Hydrostatic load on buoyancy chambers (positive head) + Buoyancy + Self-weight
- **Extreme water retaining from channel side**: Hydraulic loads on skin plates (negative head) + Hydrostatic load on buoyancy chambers (negative head) + Buoyancy + Self-weight
- **Operating in maximum water level**: Hydraulic loads on skin plates (operation in maximum water level) + Hydrostatic load on buoyancy chambers (operation in maximum water level) + Buoyancy + Self-weight + Driving force
- **Operating in minimum water level**: Hydraulic loads on skin plates (operation in minimum water level) + Hydrostatic load on buoyancy chambers (operation in minimum water level) + Buoyancy + Self-weight + Driving force

Load input

Loads can be defined by different methods in the model. In this study, hydraulic loads and buoyancy loads are applied on the structure as surface loads. As an alternative method, these loads could also be applied as line loads on the edge of the plate elements and/or on the beam elements. The first method is rather more accurate and realistic however it has a disadvantage. As it is described in section 5.3.7, equivalent plate thickness can only resemble the global behavior of the plate and stiffeners. But when it comes to the local deformation and local forces in the plate, the results of the model do not represent the actual behavior. In order to overcome this complication, a test model is made to examine the effects of stiffeners on the local behavior of some of the plates in gate. In the test model, for some of the plates (which have the largest deformations) the actual plate thickness is used and stiffeners are modeled. This test model is used in interpretation of local behavior in sections 5.4.

5.4 3D Structural Analysis: Gate in closed position

5.4.1 General description

Loads

Main load condition is extreme water retaining from sea side. Figure 5-26 and Figure 5-29 show the loads on gate structure.

Coordinate system

Transformed GCaCS is used for 3D analysis of gate in closed position.

Boundary condition

Loads in extreme water retaining load condition are transferred to the lock head by side bearings and hydro-feet. In case of high water from sea side, the gate is being pushed towards the side bearings at the convex side and the bearings at the hollow side are not constrained.

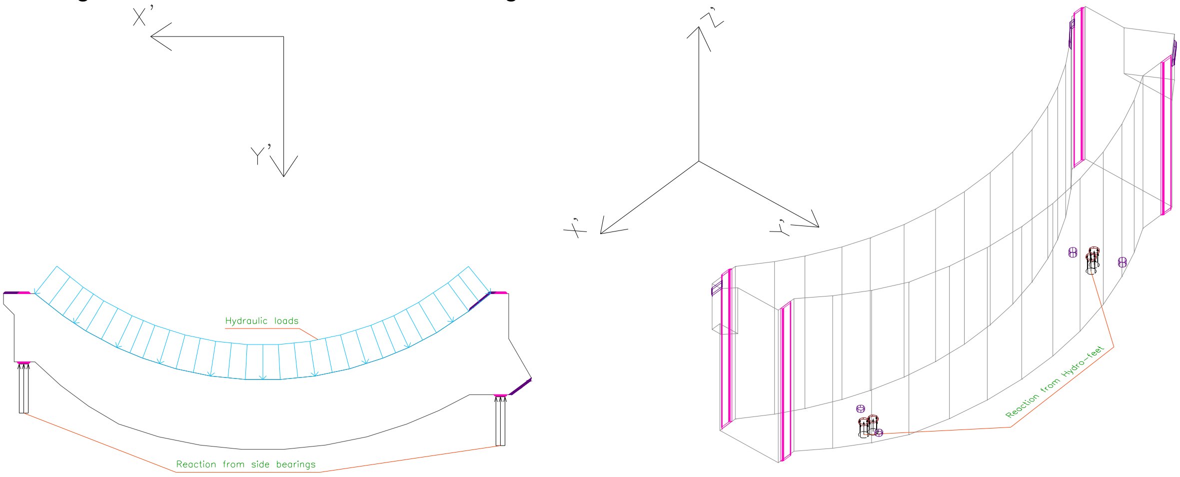


Figure 5-31: Gate in closed position (Notice that the loading pattern in this figure is only for illustration of the direction of loads and the load distribution in Figure 5-26 should be considered)

5.4.2 *Overview of the behavior*

This section gives the results of the 3D analysis for the gate in closed position while retaining extreme hydraulic loads from sea side. These results are used in section 5.6 for design of various elements of the gate.

Reactions

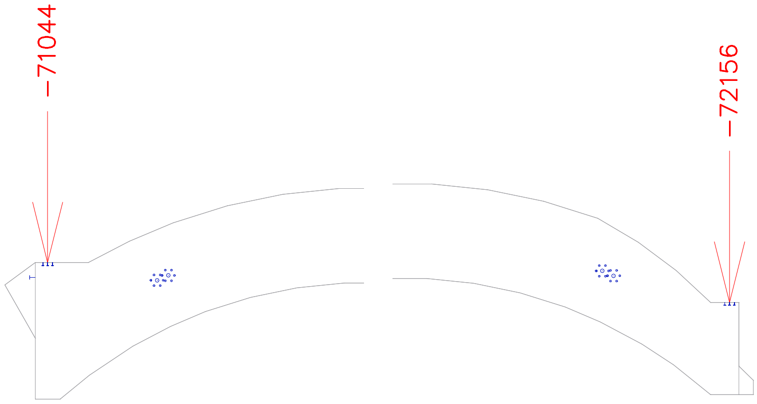


Figure 5-32: Reaction forces in Y direction [kN]

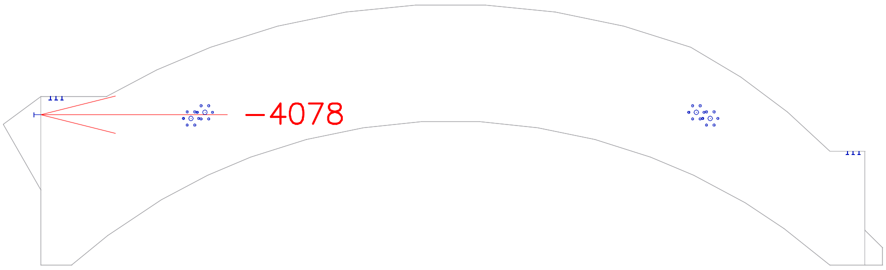


Figure 5-33: Reaction forces in X direction [kN]

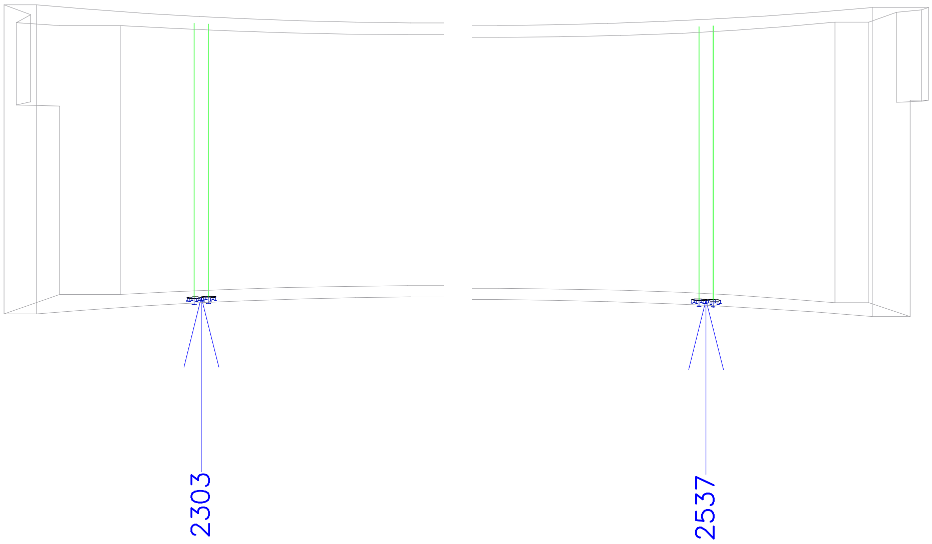


Figure 5-34: Reaction forces in Z direction [kN]

Deformation

General deformation pattern of the gate in X and Y direction is shown in Figure 5-35 in an exaggerated scale. Maximum displacement in Y-direction is 35 mm which occurs at the middle top of the gate. Maximum displacement in X-direction is 25 mm which occurs at top of the gate at the location of side bearings on hollow side. Maximum displacement in Z-direction is 8 mm and it occurs at the middle top of the gate. Detailed information on displacements are given in the following paragraphs.

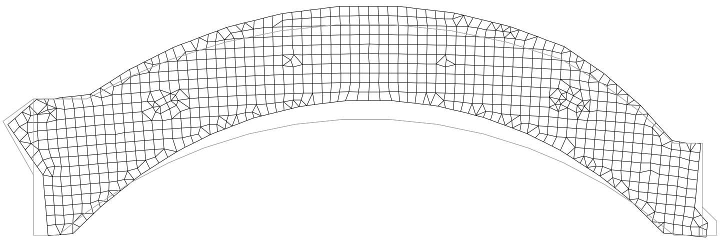
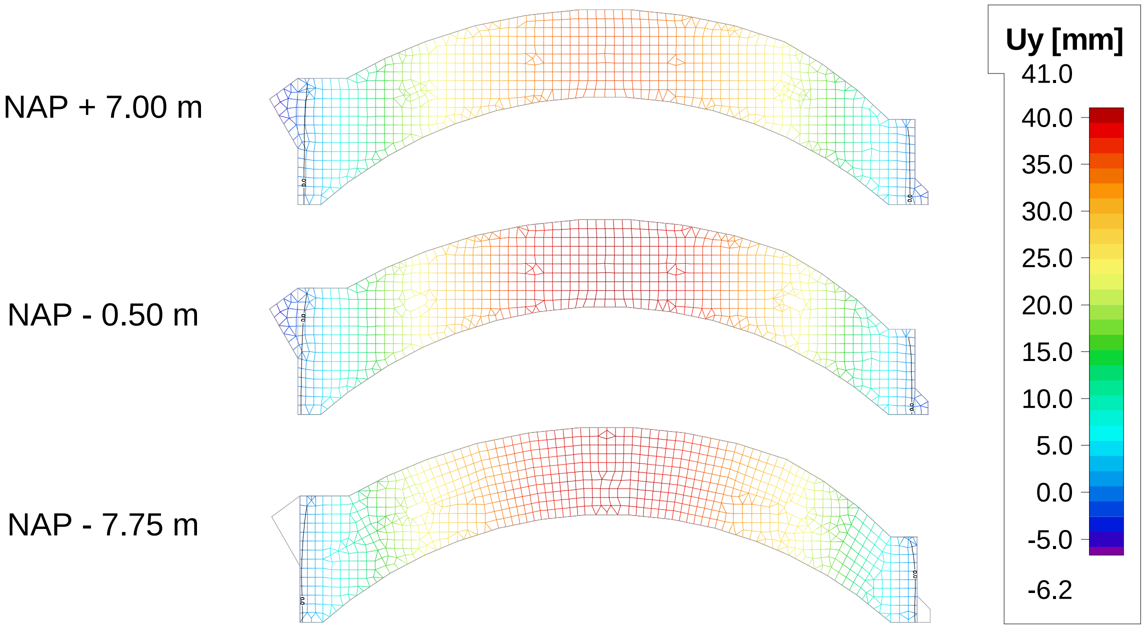


Figure 5-35: General deformation pattern (closed position)

- Deformation in Y-direction: Figure 5-36 shows that deformation in Y-direction is largest at the top of the gate and it decreases towards the bottom. It can also be seen that deformation in Y-direction in any horizontal level, decreases towards the side bearings. Figure 5-36 shows the displacement in Y-direction for horizontal plates in the given elevations.



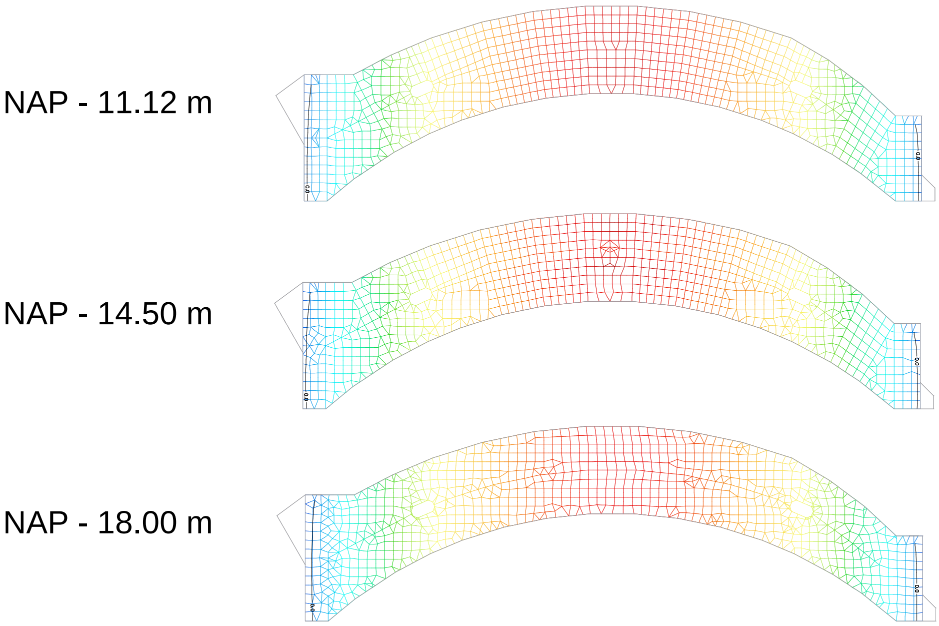
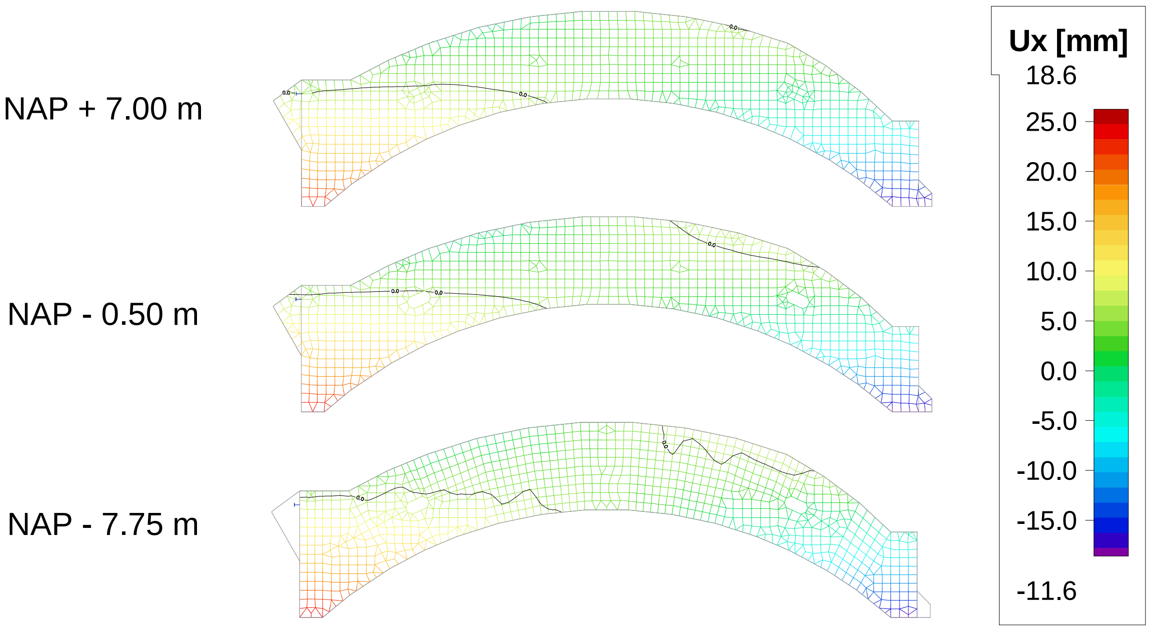


Figure 5-36: Deformation in Y-direction (Notice the black line shows the line with zero displacement)

- Deformation in X-direction: Contour lines in Figure 5-37 show that the gate structure does not deform symmetrically in X-direction and deformations are slightly larger in the left end where the main recess is situated. Positive displacement implies that the point is moving to the right and negative displacement implies that the point is moving towards left.



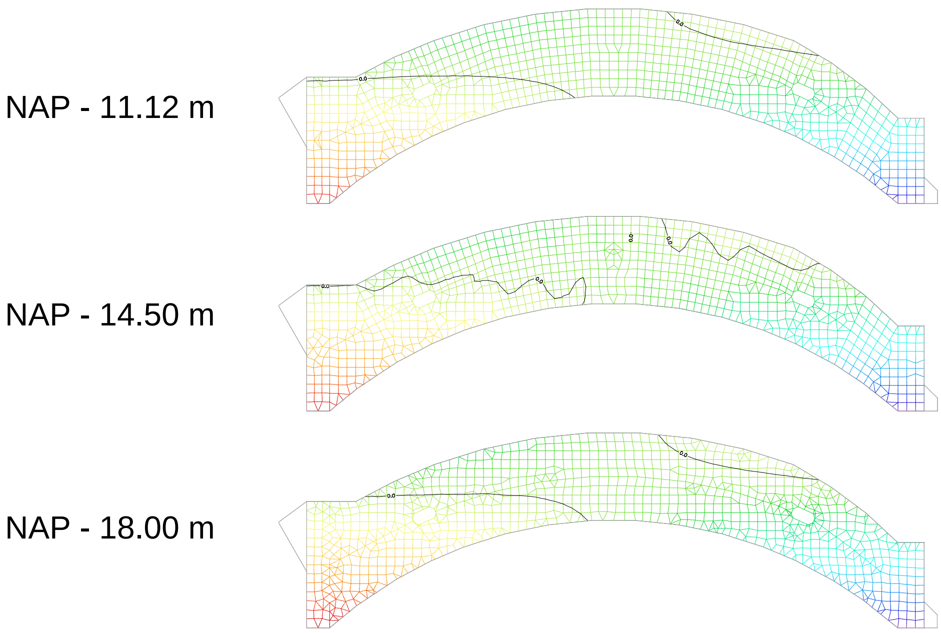
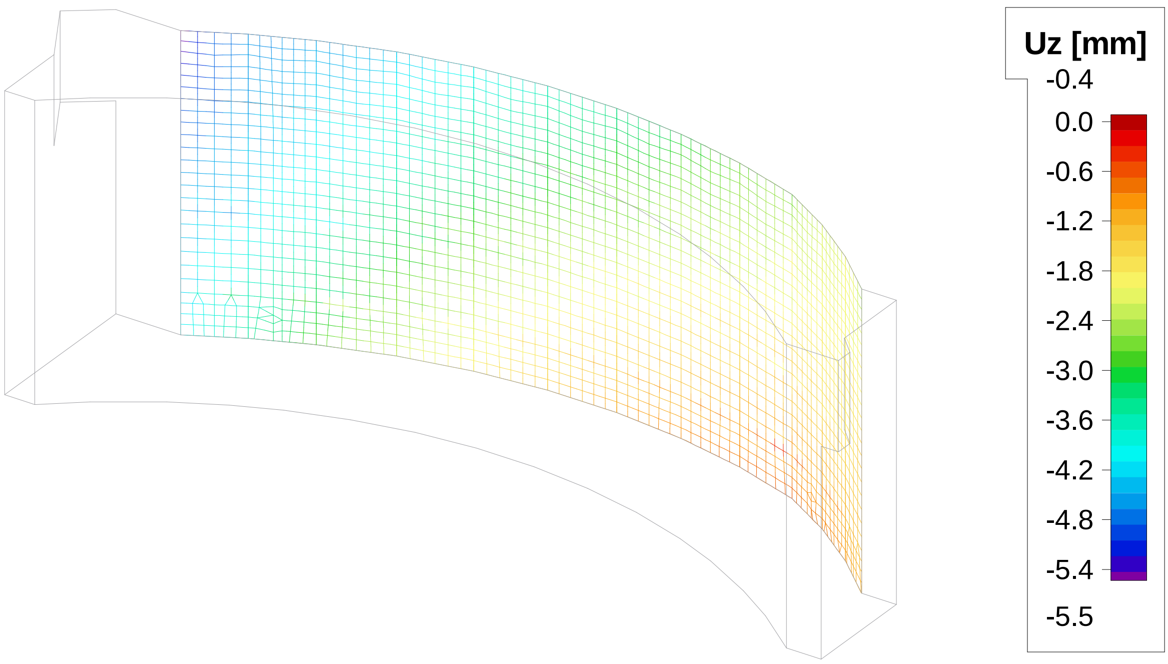


Figure 5-37: Deformation in X-direction (Notice the black line shows the line with zero displacement)

- Deformation in Z-direction: Figure 5-38 shows that the gate is slightly rotated to its convex side. In other words, the skin at the convex side is moving downwards and skin at the hollow side is moving upwards on average.



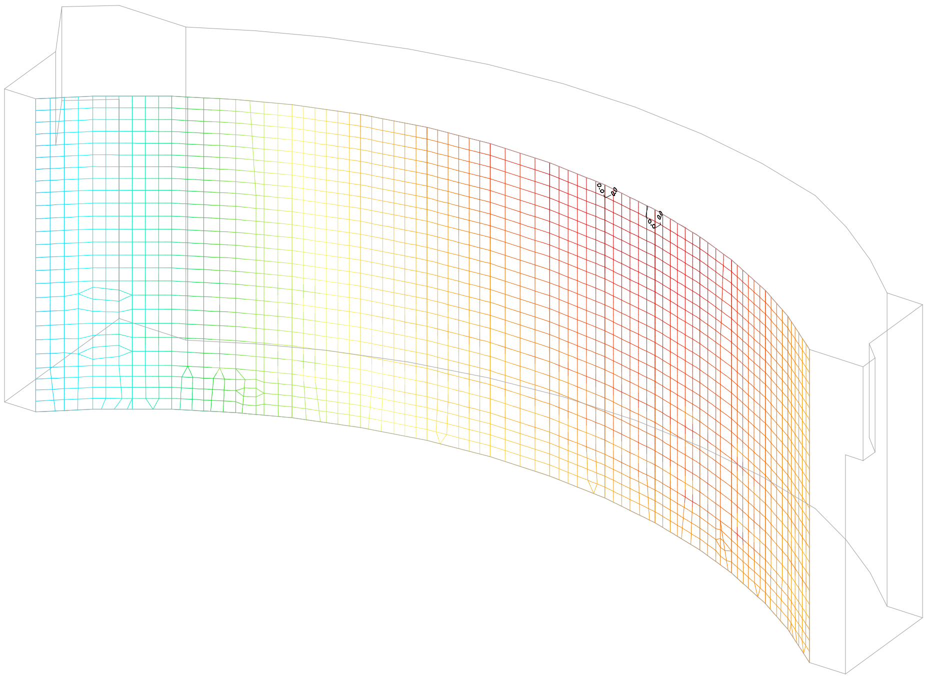


Figure 5-38: Deformation in Z-direction (Top: Convex side – Bottom: Hollow side)

5.4.3 Forces and stresses

All the forces and stresses can be seen as the result of the Scia-engineer analysis output in appendixC.

5.5 3D Structural Analysis – Gate during operation

5.5.1 Operation procedure, loads and boundary conditions

Loads

Main load condition is operation in maximum water level. The most dominant phase of operation for gate structure is initiation of opening. Figure 5-28 and Figure 5-29 show the loads on the structure. Notice that during operation, loads are considerably smaller than the loads in section 5.4 and consequently, internal forces and displacements of the gate are considerably smaller than the previous section. Therefore, the focus of this section is on the driving force.

Coordinate system

GCaCS is used for 3D analysis of gate during operation.

Boundary condition

Boundary conditions are different for different phases of the operation. However, since the gate is modeled at the most dominant phase (initiation of opening), the boundary condition is as follows; Side bearings at the convex side provide the horizontal reaction for horizontal hydraulic loads. Hydro-feet are active and able to slide over the track with the friction coefficient of *0.01*. none of the guidance devices are in contact with their UHMWPE track.

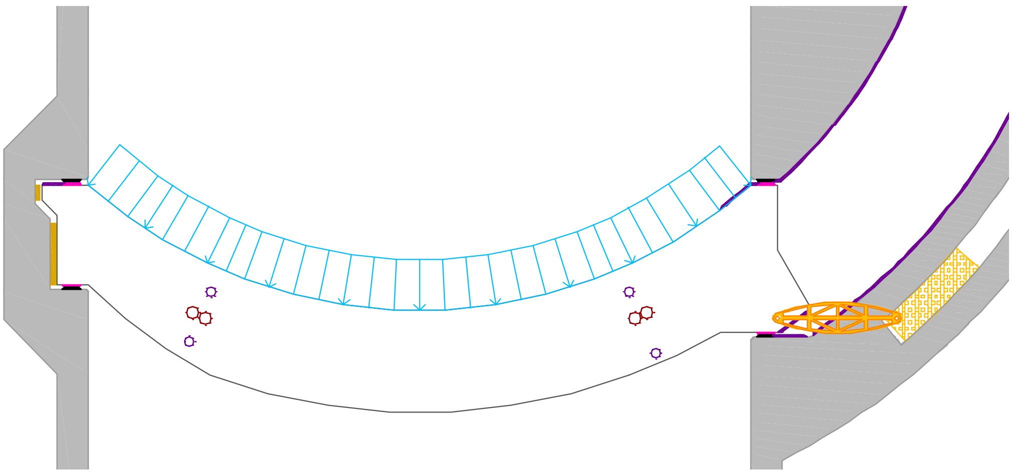


Figure 5-39: Gate at the phase "initiation of opening"

5.5.2 Overview of the behavior

This section gives the results of the 3D analysis for the gate during operation in maximum water level. Computer models are used occasionally in this section. Since the operation of the gate is a dynamic process, it needs to be modeled in a computer program which can provide a dynamic environment. Use of such programs is out of the scope for this study. However, the structure is modeled in the same way that it is modeled in the closed position. The model can only provide results for global structural behavior of the gate at the beginning of opening. For analyzing the behavior of the gate during operation, results from hand calculations are considered as the basis for design. These results are used in section 5.6 for design of various elements of the gate.

Reactions

Reaction forces during operation are not dominant for design. The importance of reaction forces during operation is calculation of driving force and the friction forces at the bearings. It is understood that at the moment when the gate starts to move, the guidance devices are not loaded and the reaction forces are being provided by the side bearings. More importantly all the horizontal reactions are unidirectional which implies that if the total reaction force is known, the total friction force in the perpendicular direction can be calculated. Notice that all the contact surfaces have the same friction coefficient. Therefore, the sum of the reactions are calculated as below:

According to Figure 5-28, Total hydraulic load per meter width on the skin plate of the gate is **177.44** kN/m. Total length of the gate in X-direction is **58.4** m.

$$Total\ reaction\ force\ from\ hydraulic\ loads\ in\ Y-direction = \sum R_Y = 177.44 \times 58.4 = 10362\ kN$$

No reaction force in Y-direction is considered from driving force. Two possible situation can be considered:

- All the reaction force is provided by the side bearing at the right side (main recess side). In that case, the reaction from driving force will compensate the reaction from hydraulic loads at the right side bearing. Therefore, ignoring the reaction force is conservative.
- The perpendicular component of the driving force will generate a turning moment in the gate which the resulting reaction force from all the bearings in Y-direction will be zero.

$$Total\ reaction\ force\ on\ hydro-feet\ in\ Z-direction = \sum R_Z$$

$$\sum R_Z = Self\ weight - Buoyancy\ (Buoyancy\ chambers) - Buoyancy\ (submerged\ structure)$$

$$\sum R_Z = 40000 - 31400 - 4910 = 3690\ kN$$

Deformation

General deformation pattern of the gate in X and Y direction is shown in Figure 5-40 in an exaggerated scale. Since the static and dynamic boundary conditions in X-direction cannot be properly modeled, the resulting deformation of the gate is basically moving in X-direction which is actually the expected movement of the gate. Maximum displacement in Y-direction is 2 mm which occurs at the middle top of the gate.

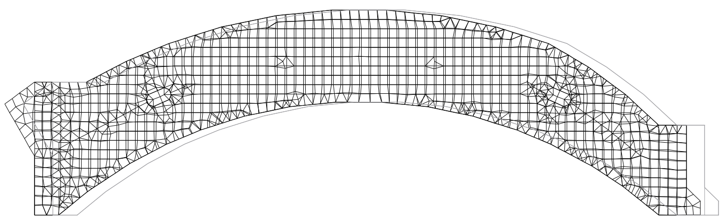


Figure 5-40: General deformation pattern (initiation of opening)

Driving force

Figure 5-41 Schematizes the forces in the beginning stage of opening. S_1 and S_2 are the friction forces resulting from the reactions in Y-direction at the position of side bearings. S_3 and S_4 are the friction forces resulting from the reactions in Z-direction at the contact surface of hydro-feet and the guiding track. The inertia force is also calculated with the acceleration of $4*10^{-3}$ m/s^2 and added mass of

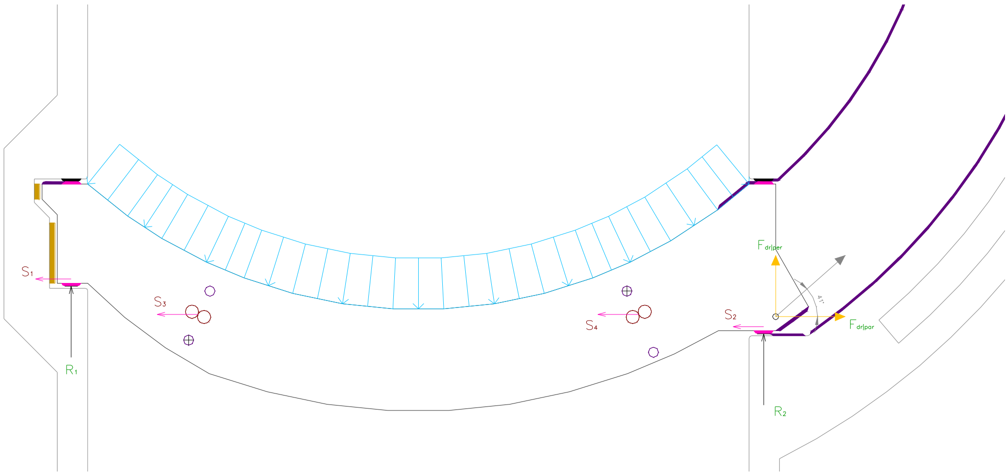


Figure 5-41: Schematization of loads at the initiation of opening

Therefore:

$S_1 + S_2 = 0.17 \times 10362 = 1762\ kN$

$S_3 + S_4 = 0.01 \times 3690 = 36.9\ kN$

$F_a = (4 \times 10^{-3}) \times (4.7 \times 10^{6}) = 18800N = 18.8kN$

$$\sum S = 1817\ kN \quad \Rightarrow \quad F_{Dr|par} \geq \sum S \quad \Rightarrow \quad F_{Dr} \geq \frac{F_{Dr|par}}{\sin 41°} \quad \Rightarrow \quad F_{Dr} \geq \frac{1817}{0.65} = 2771\ kN$$

$$\Rightarrow \quad Required\ driving\ force \approx 3000\ kN$$

Performing the same procedure for the beginning of the rotational movement, the required driving force at that moment is 2000kN at its maximum.

5.6 Design

This section provides calculations and detailed drawings of the preliminary design for main elements.

5.6.1 Side bearings

Governing load condition in design of side bearings is retaining in extreme water level. Figure 5-32 shows the total reaction force on side bearings. however, the reaction force is not distributed uniformly and the maximum pressure on the side bearing should be considered in design of the UHMWPE panels. Figure 5-43 shows the reaction force distribution pattern on the side bearings. Notice that this distribution is not exactly realistic. Due to the large stiffness of the horizontal plates, the reaction force is only distributed at the position of these plates in the model. Since the reaction force will be transmitted to the steel panel on the gate and consequently to the UHMWPE panel, the distribution is more consistent and linear. Therefore a distribution pattern based on the results of the model is considered. The maximum pressure on side bearing, can be calculated by dividing total force over the ratio of total force over maximum pressure.

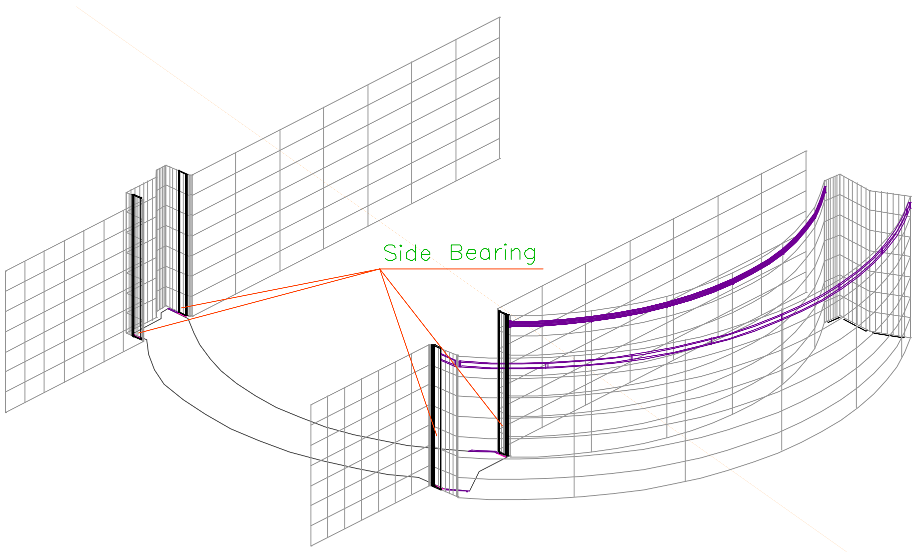


Figure 5-42: 3D-view, Location of side bearings panels on lock head

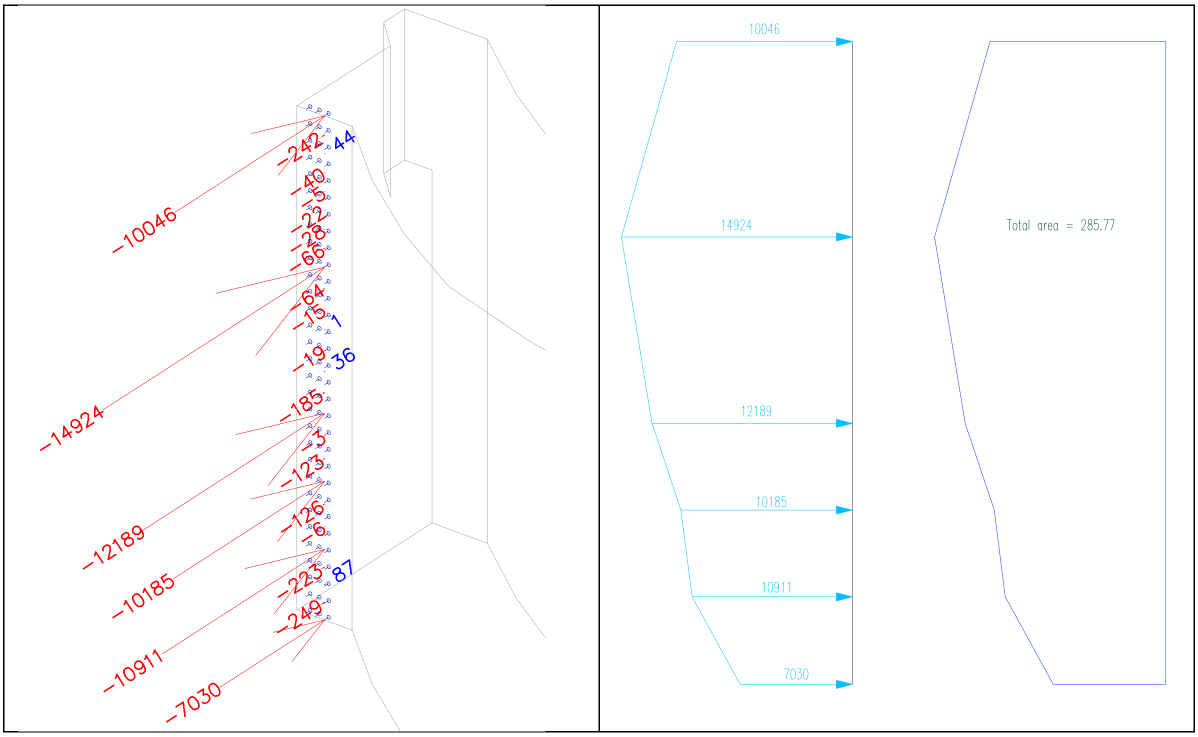


Figure 5-43: Reaction force distribution (model output)

$$Ratio\ of\ the\ \text{“}total\ force\text{”}\ over\ \text{“}maximum\ distributed\ reaction\ load\text{”} = \frac{285.77}{14.97} = 19.15$$

from Figure 5-32, the reaction force = 72156 kN

$$Maximum\ distributed\ reaction\ load = \frac{72156}{19.15} = 3767\frac{kN}{m}$$

$$Minimum\ required\ width\ of\ side\ bearing\ (UHMWPE) = \frac{3767}{12000} = 0.31\ m$$

Minimum width of the UHMWPE panels should be 26 centimeters. Total width of the side bearings is 1.30 meter which is considerably larger than the required width. Notice that 1.30 meter width also accounts for sealing provisions (Figure 5-44).

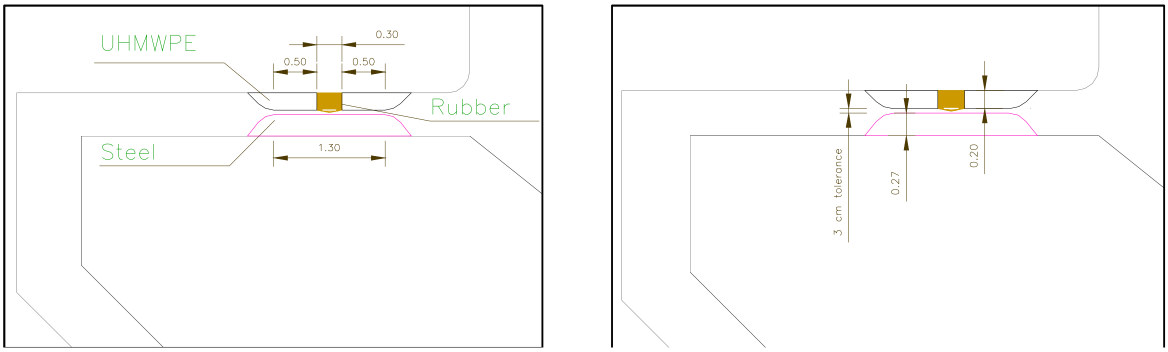


Figure 5-44: Side bearing details [m]

5.6.2 *Buoyancy chambers*

Design of buoyancy chambers is done based on certain criteria.

- All the buoyancy tanks should always be below the water level during the gate lifetime.
- The volume and position of the chambers should be such that the floating stability of the gate during exchange procedure is guaranteed.
- Total volume of the tanks should be designed to be more than the required volume. In that case, the extra volume would be considered as reserve tanks.
- Three different type of tanks are considered: Air tanks, Trim tanks, Ballast tanks.
- Air tanks are normally filled with air during operation.
- Ballast tanks are normally filled with water during operation. In this design, the ballast tanks are also serving as reserve tanks in case an accident cause leakage in one or more of the air tanks.
- Trim tanks are partially filled during operation of gate.
- Total volume of air in the whole chamber is determined by considering two extreme situations during operation and trying to maintain the minimum and maximum bearing force on hydro-feet within the design limits.
- An access chamber should be considered for inspection and maintenance purposes.

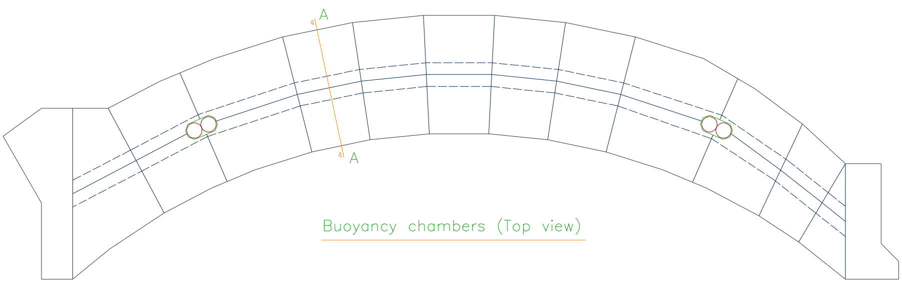


Figure 5-45: Buoyancy chambers (Top view)

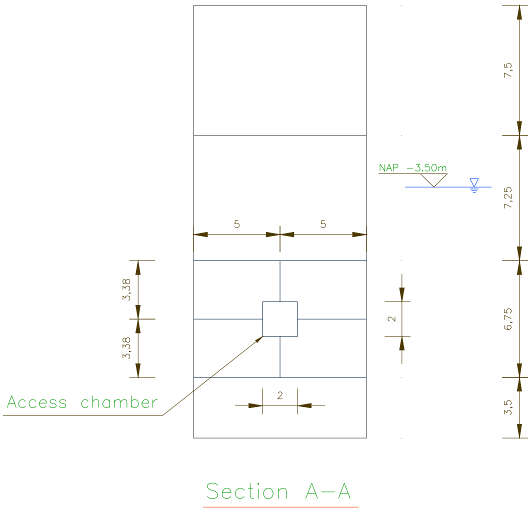


Figure 5-46: Buoyancy chambers and the access chamber (NAP -3.50m is the extreme low water level in 10^6 years)

Details about the design of buoyancy chambers are provided in Appendix D. Table 5-4 shows the main characteristics of the designed buoyancy chambers.

Parameter	Symbol	Value	Unit
Self-weight of the gate	W	40000	kN
Buoyancy upward force during operation	B_{Ch}	31400	kN
Required air volume during operation	$V_{b,o}$	3060	m^3
Buoyancy upward force during exchange	$B_{Ch,ex}$	37697	kN
Required air volume during exchange	$V_{b,ex}$	3760	m^3
Air tanks volume	$V_{a.t.}$	2806.5	m^3
Ballast tanks volume	$V_{b.t.}$	825.5	m^3
Trim tanks volume	$V_{tr.t.}$	952.8	m^3

Table 5-4: General buoyancy chamber specifications

5.6.3 *Hydro-feet*

Design of hydro-feet is mainly done based on recommendations of D. Ros (MRCONSULT B.V.) and the publications (20) as the results of research project done by Rijkswaterstaat and TU Delft within last twenty years. Detailed design calculations can be found in Appendix E. In order to provide a set of input for design, minimum and maximum loads need to be calculated.

Loads

Two main load conditions are considered for the design of hydro-feet

1) Maximum bearing force on the hydro-foot

When the water level is at its minimum [NAP -2.20m] and the maximum driving force is acting on the gate, maximum bearing force occurs for the right support. This force is calculated as below:

$$Maximum\ bearing\ force = \frac{W}{2} - \frac{B_{min}}{2} - \frac{B_{Ch}}{2} + R_{dr,u}$$

$W = Total\ structure\ weight = 40000\ kN$
$B_{min} = Minimum\ Buoyancy\ loads\ on\ structure = 3760\ kN$
$B_{Ch} = Upward\ Buoyancy\ force\ of\ Buoyancy\ chambers = 31400\ kN$
$R_{dr,u} = Upward\ reaction\ force\ caused\ by\ driving\ force = 1570\ kN$

$$\Rightarrow Maximum\ bearing\ force = 20000 - 1880 - 15700 + 1570 = 3990\ kN$$

2) Maximum operational water level

When the water level is at its maximum [NAP +4.17m] and the maximum driving force is acting on the gate, minimum bearing force occurs for the left support. This force is calculated as below:

$$Minimum\ bearing\ force = \frac{W}{2} - \frac{B_{max}}{2} - \frac{B_{Ch}}{2} - R_{dr,d}$$

$B_{max} = Maximum\ Buoyancy\ loads\ on\ structure = 4910\ kN$
$R_{dr,d} = Downward\ reaction\ force\ caused\ by\ driving\ force = 1570\ kN$

$$\Rightarrow Minimum\ bearing\ force = 20000 - 2455 - 15700 - 1570 = 275\ kN$$

Design

The complete theory and design process of hydro-foot is given in Appendix E. The maximum bearing load of 3990 kN is considered to be provided by two hydro-feet which are situated next to each other inside the column element in the gate.

Primarily three alternatives were considered for the hydro-sliding mechanism:

1- One hydro-foot of 1.80m diameter; this was not chosen because the large diameter can become problematic for sliding on the joints of the track. The pressure in that case may not be consistent and cause the sliding to stop.
2- Two adjacent hydro-feet of 1.35m diameter; this option was chosen because of a better performance.
3- One rectangular hydro-fender of 1.00 x 1.30m; hydro-fender was not chosen even though it was theoretically the best solution. However due to lack of sufficient experiments, the reliability of this option cannot be guaranteed.

Provisions for installing and disassembling the hydro-foot are considered. Each hydro-foot, will be connected and fixed to the gate bottom by the help of a locking mechanism similar to a camera lens. Top of the hydro-foot will then be fixed with a set of bolts which are connected to the top deck. There will be no fixed connection in between and the hydro-feet are held by elements at the position of the horizontal plates in order to prevent buckling of the hydro-foot.

Table 5-5 gives the characteristics of the designed hydro-foot.

Parameter	Symbol	Value	Unit
Design load	$F_{hyd,max}$	2000	kN
Outer radius	R_O	0.66	m
Pocket radius	R_i	0.47	m
Effective area	A_{eff}	1.006	m^2
Dimensionless pressure ratio	β	0.7	---
Dimensionless radius ratio	γ	0.716	---
Pump pressure	P_p	3.0	Mpa
Minimum film thickness	h_{min}	$12x10^{-4}$	m
Average film pressure	P_r	2.15	Mpa
Required flow	Q_f	19.6	m^3/hr
Restrictor diameter	d_o	0.016	m
Required pump power per hydro-foot	P_{pump}	32.7	kW

Table 5-5: Hydro-foot design parameters

5.6.4 Guidance devices and tracks

Track

Figure 5-47 shows an overall view of the guiding track. Track is made of UHMWPE material due to its advantageous characteristics (discussion on choice of UHMWPE in chapter 4). The guiding track is designed in two different levels. The main track has a constant width of 4.25 meters and height of 0.60 meters. The secondary track is considered only for one of the bottom guidance elements. It has a width of 1.30 meters and height of 0.35 meters.

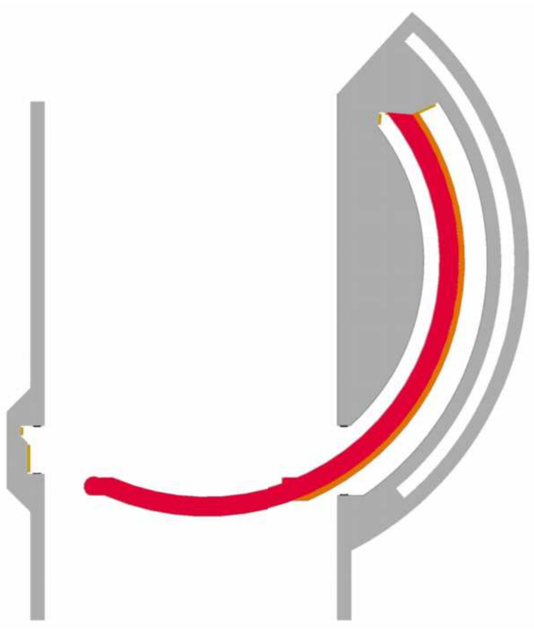


Figure 5-47: Guiding track (Top view)

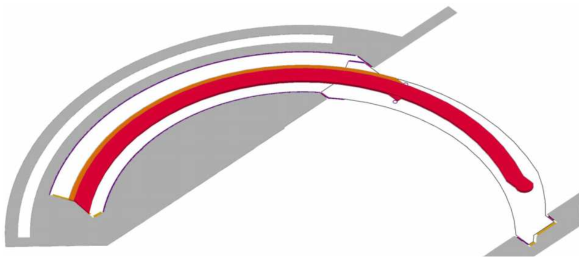


Figure 5-48: Guiding track (3D view)

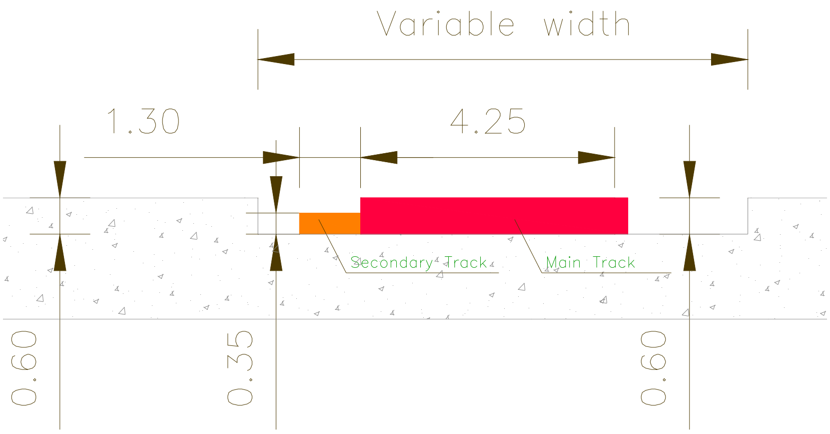


Figure 5-49: Guiding track (cross-section)

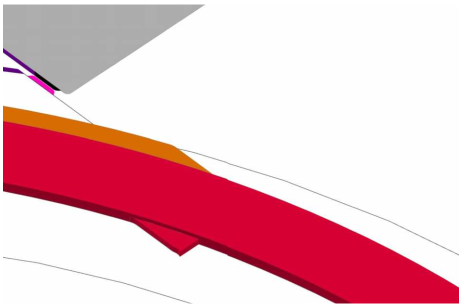


Figure 5-50: Secondary track along the main track

Bottom guidance

Bottom guidance are steel shafts which slide over the track at the bottom of lock head. The minimum contact height is considered to be 0.25 meters. Front set of bottom guidance are located higher and are in contact with the top 25 centimeter of the main track. Rear set of bottom guidance are located lower and the contact height varies during the operation of the gate. Figure 5-51 to Figure 5-58 show the guidance devices in different phases of operation.

An important practical matter is the stability of the guidance system. Notice that the 25 cm contact length seems relatively small compared to the main dimensions of the gate. It is noted that the maximum upward and downward displacements are within a few centimeters (3 centimeters). However, a comprehensive stability analysis should be done in order to verify the stability of the gate during operation.

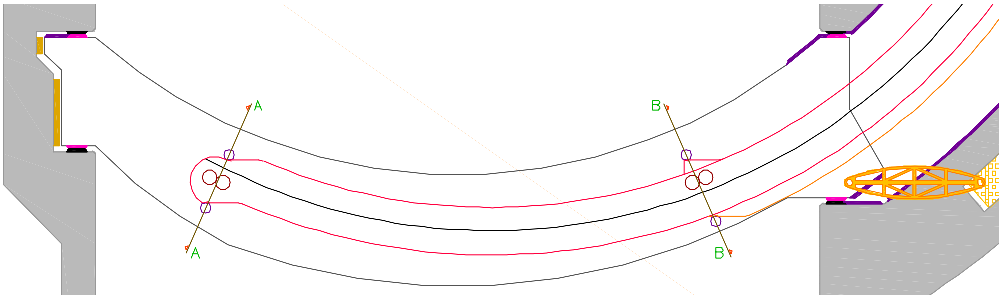


Figure 5-51: Initiation of horizontal movement

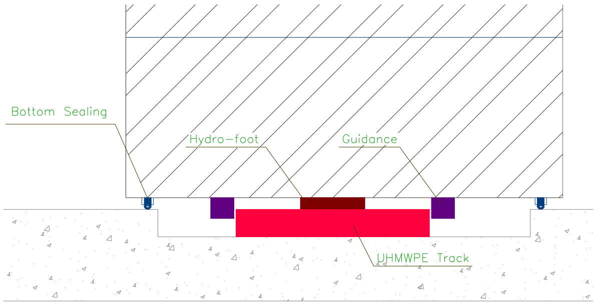


Figure 5-52: Cross-section A-A from Figure 5-51

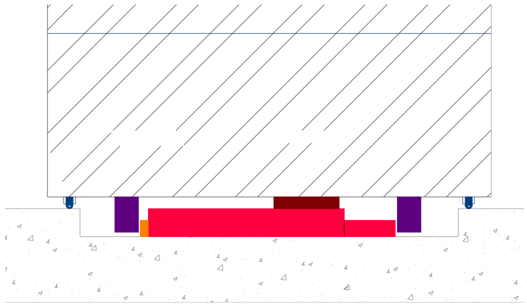


Figure 5-53: Cross-section B-B from Figure 5-51

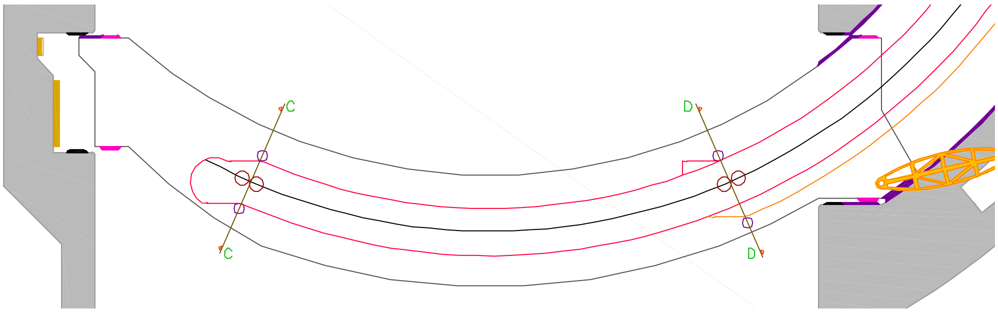


Figure 5-54: End of horizontal movement / Beginning of rotation

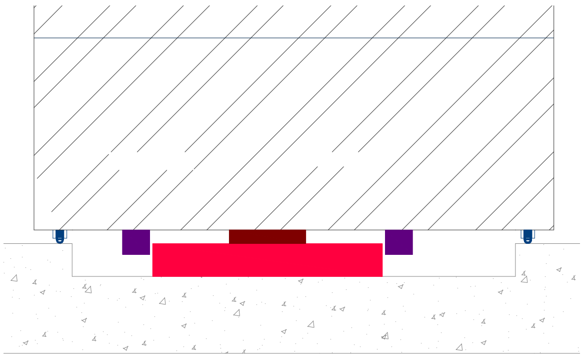


Figure 5-55: Cross-section C-C from Figure 5-54

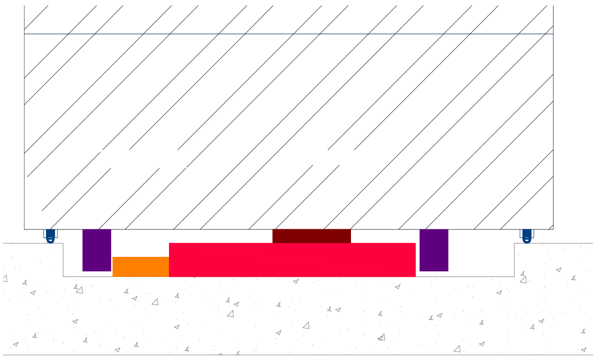


Figure 5-56: Cross-section D-D from Figure 5-54

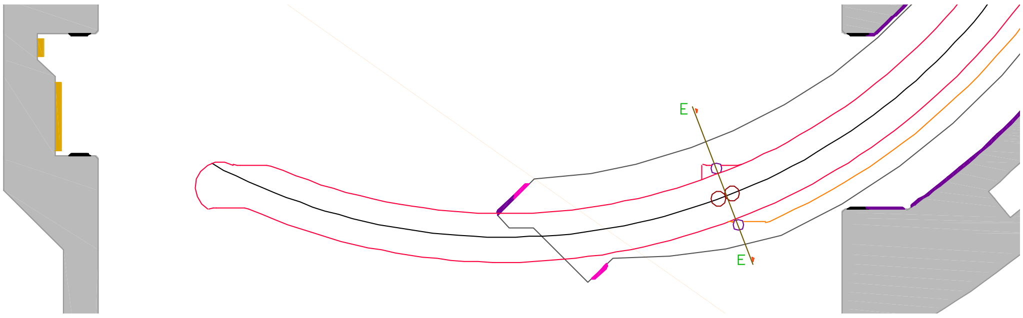


Figure 5-57: During rotation when the left guidances pass through the secondary track

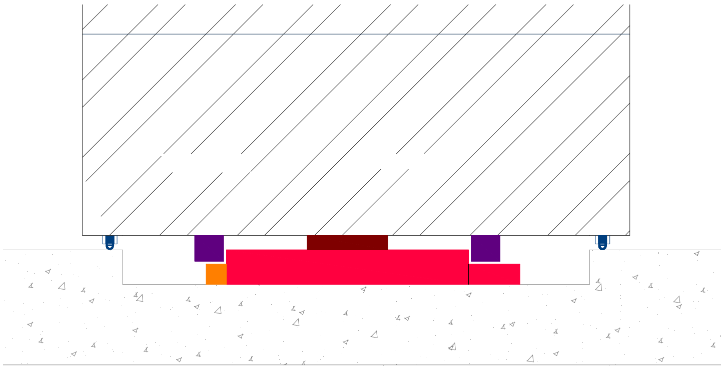


Figure 5-58: Cross-section E-E from Figure 5-57

Top guidance

Figure 5-59 shows the position of top guidance devices on the gate. Figure 5-62 to Figure 5-67 show the first few steps of opening. The importance of these figures is to realize the stability of the structure is guaranteed by top guidance devices. In each stage, at least one guidance is present to prevent overturning of the gate in each direction. Graphs of Figure 5-60 and Figure 5-61 show the effective contact area at each moment for the top guidance devices.

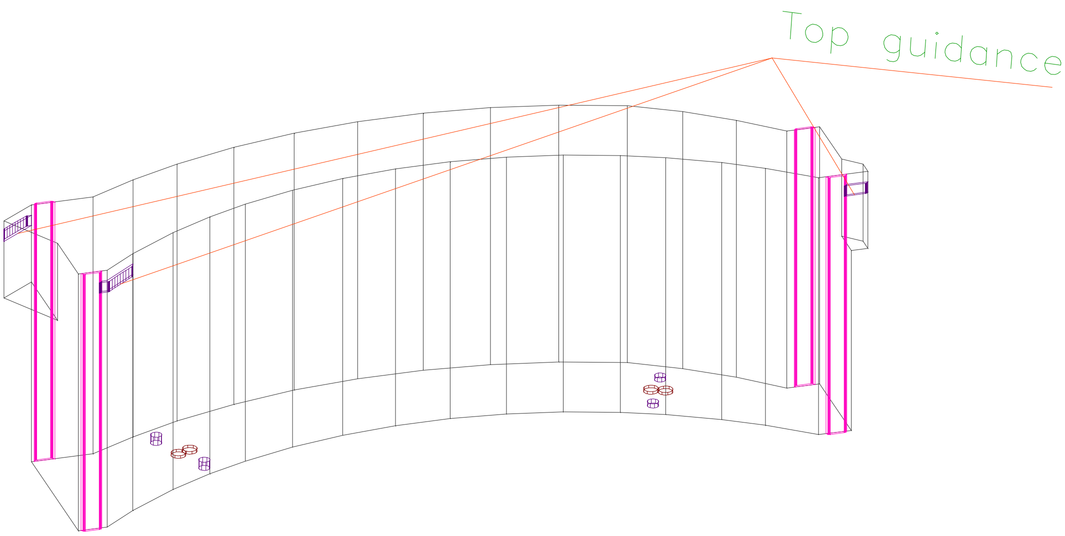


Figure 5-59: Position of top guidance devices

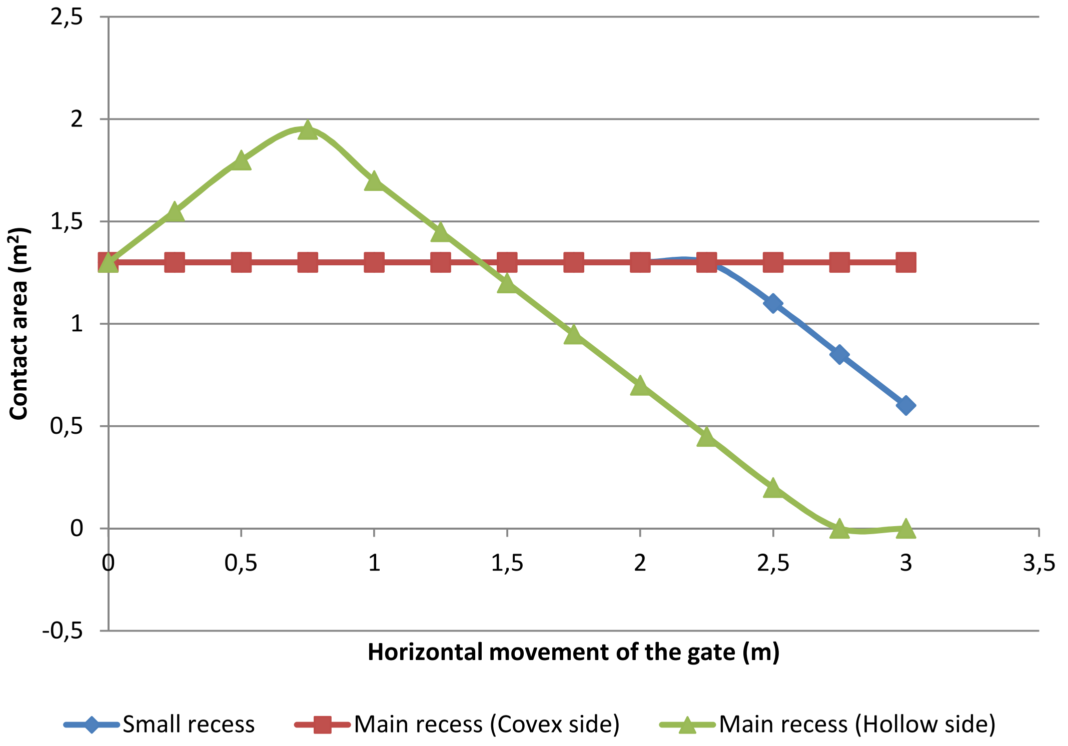


Figure 5-60: Effective contact area of top guidance devices during horizontal movement

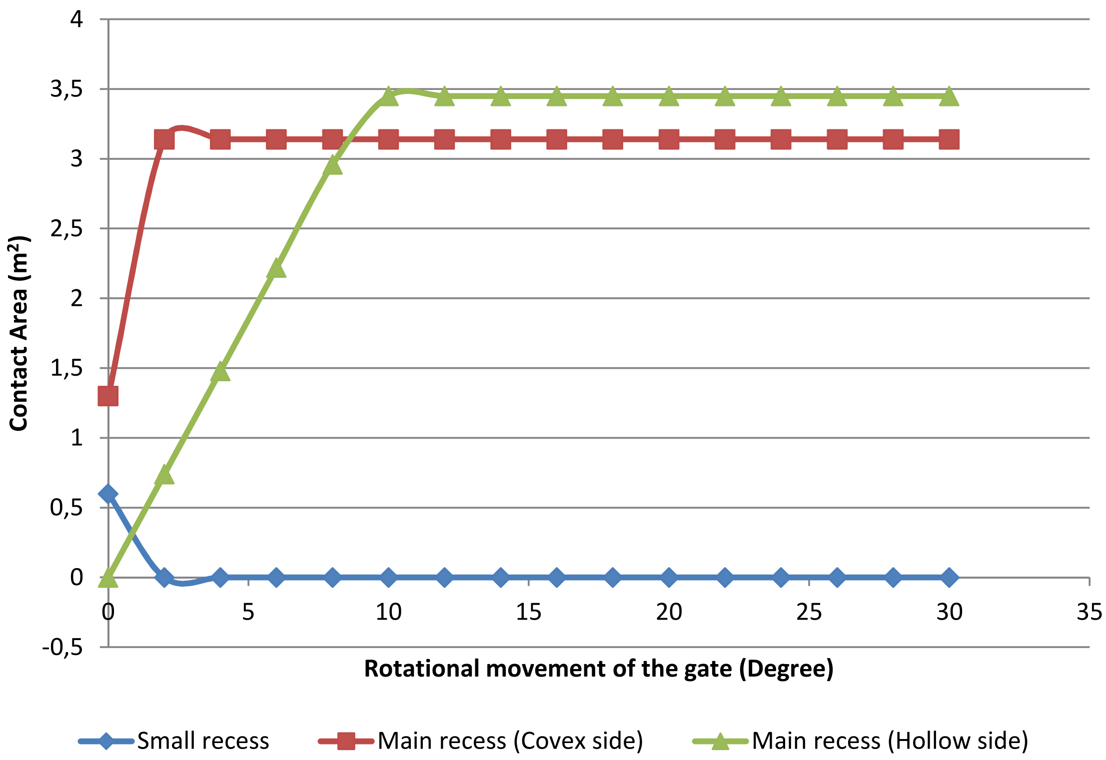


Figure 5-61: Effective contact area of top guidance devices during rotational movement

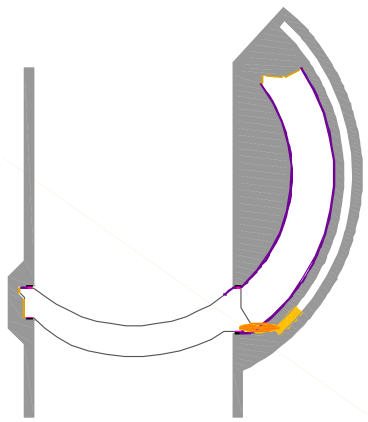


Figure 5-62: Beginning of movement

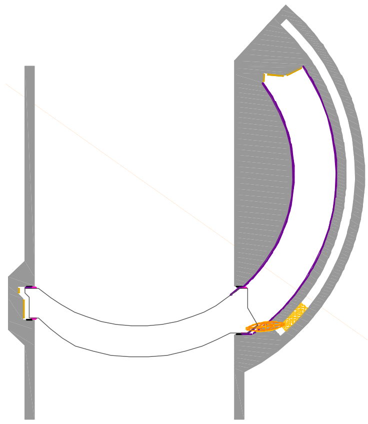


Figure 5-63: 1.5m (50%) horizontal movement

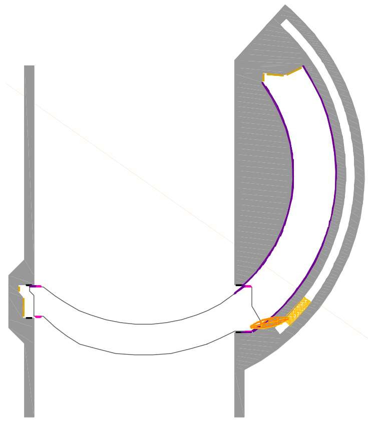


Figure 5-64: 3m (100%) horizontal movement

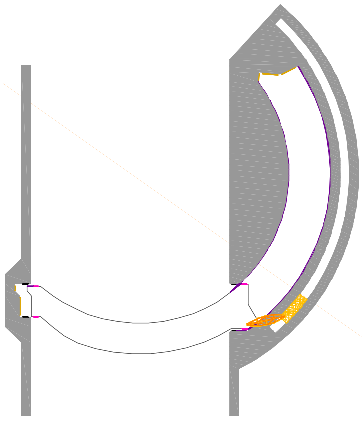


Figure 5-65: 0.5° rotated

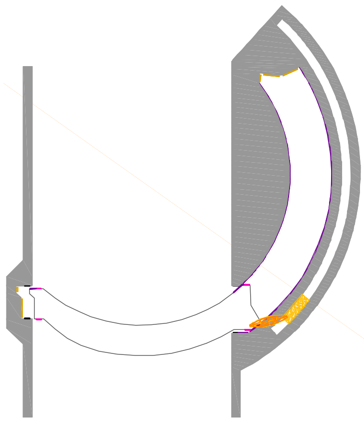


Figure 5-66: 1° rotated

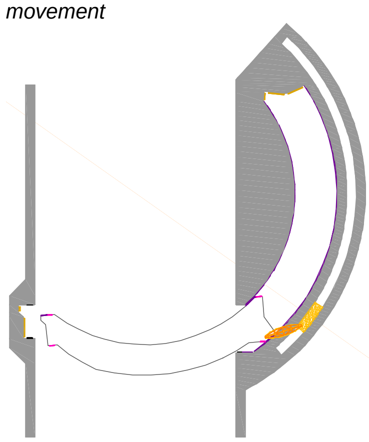


Figure 5-67: 5° rotated

5.6.5 Operation equipment

Design of operational device is limited to design of the engines and first estimate on the dimensions of the elements for locomotive as been done in section 4.5.3. Notice that the operational device is designed for the worst operational load conditions. In normal situations the required power and force is considerably less. Therefore the design is redundant for normal situations.

Locomotive

Detailed information regarding the design of the locomotive operating system can be found in

Parameter	Symbol	Value	Unit
Number of pinions	N_p	8	---
Required driving force	F_{Dr}	3000	kN
Required driving force per pinion	F_{rep}	375	kN
Pinion diameter	D_p	0.5	m
Required driving torque per pinion	M_{rep}	93.75	kN.m
Nominal motor speed	n_m	1300	Min^{-1}
Nominal motor torque	M_m	679	N.m
Required motor power per pinion	P_m	92.4	kW
Total required motor power	$\sum P_m$	740	kW

Table 5-6: Characteristics of the operational equipment

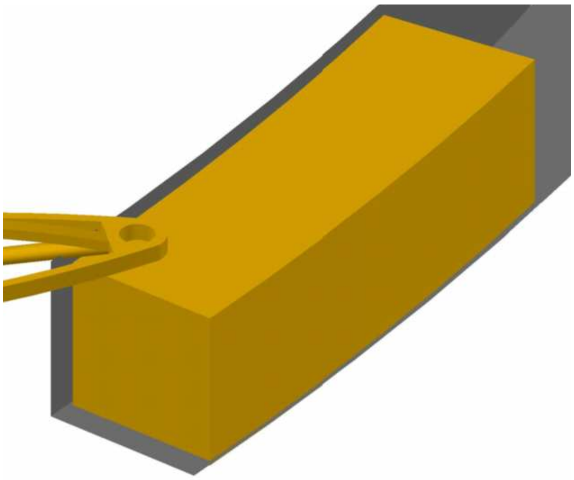


Figure 5-68: General view of the locomotive at its recess. The position of the connection device can be seen at top of the locomotive

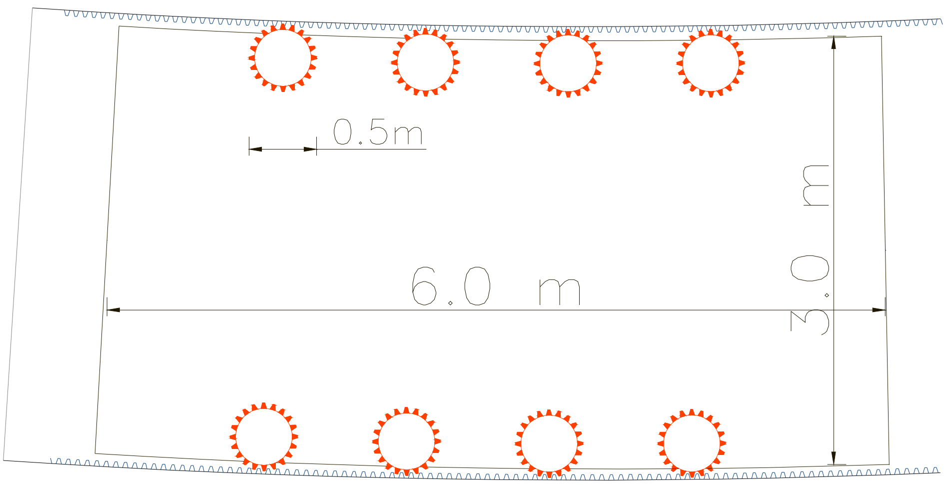


Figure 5-69: General dimensions and position of the pinions inside the locomotive (top view section)

Connecting element

The layout of the connection device is shown in Figure 5-70. The important factors in design of this element are axial force, buckling and unsupported length with regard to buckling. Total length of this device is 13 meters.

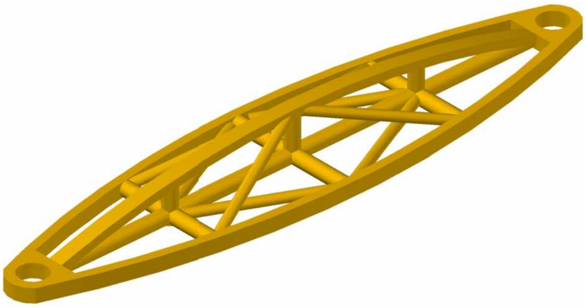


Figure 5-70: Connection device between the locomotive and the gate

5.6.6 *Lock head*

Allowable stresses are checked for concrete as followed by the design for side bearings. Furthermore, required reinforcement should be provided and calculated for resisting all the loads on the lock head including the shrinkage and temperature loads. Figure 5-71 shows the overall layout of the lock head.

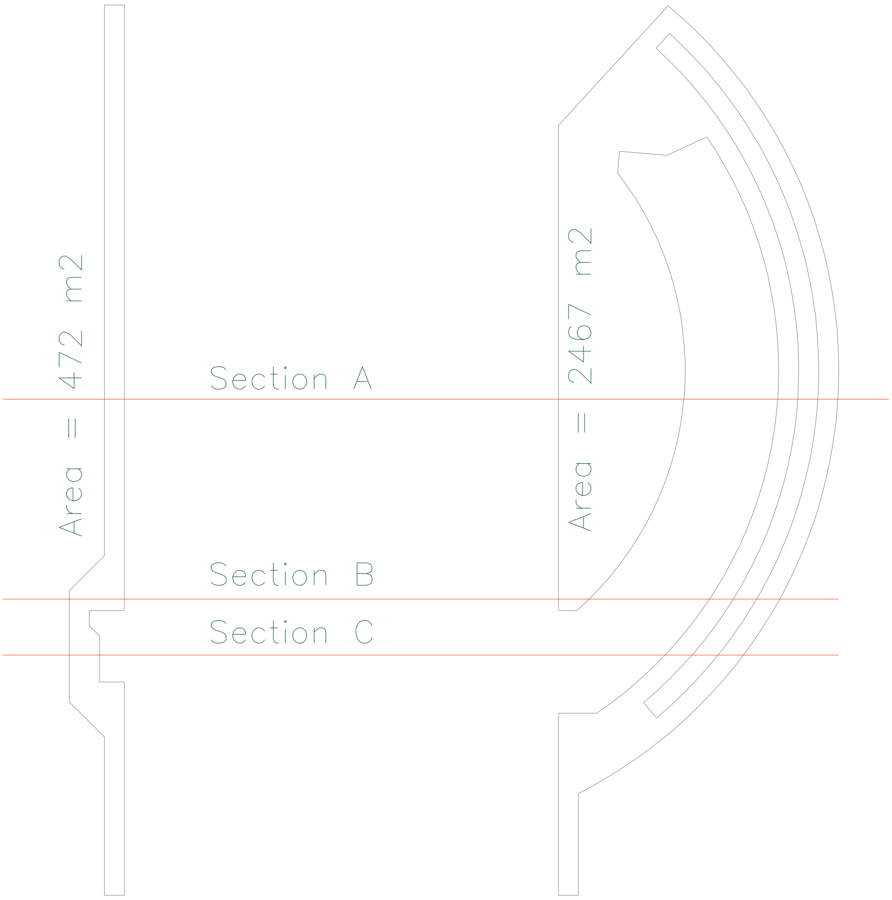


Figure 5-71: Lock head (Top view)

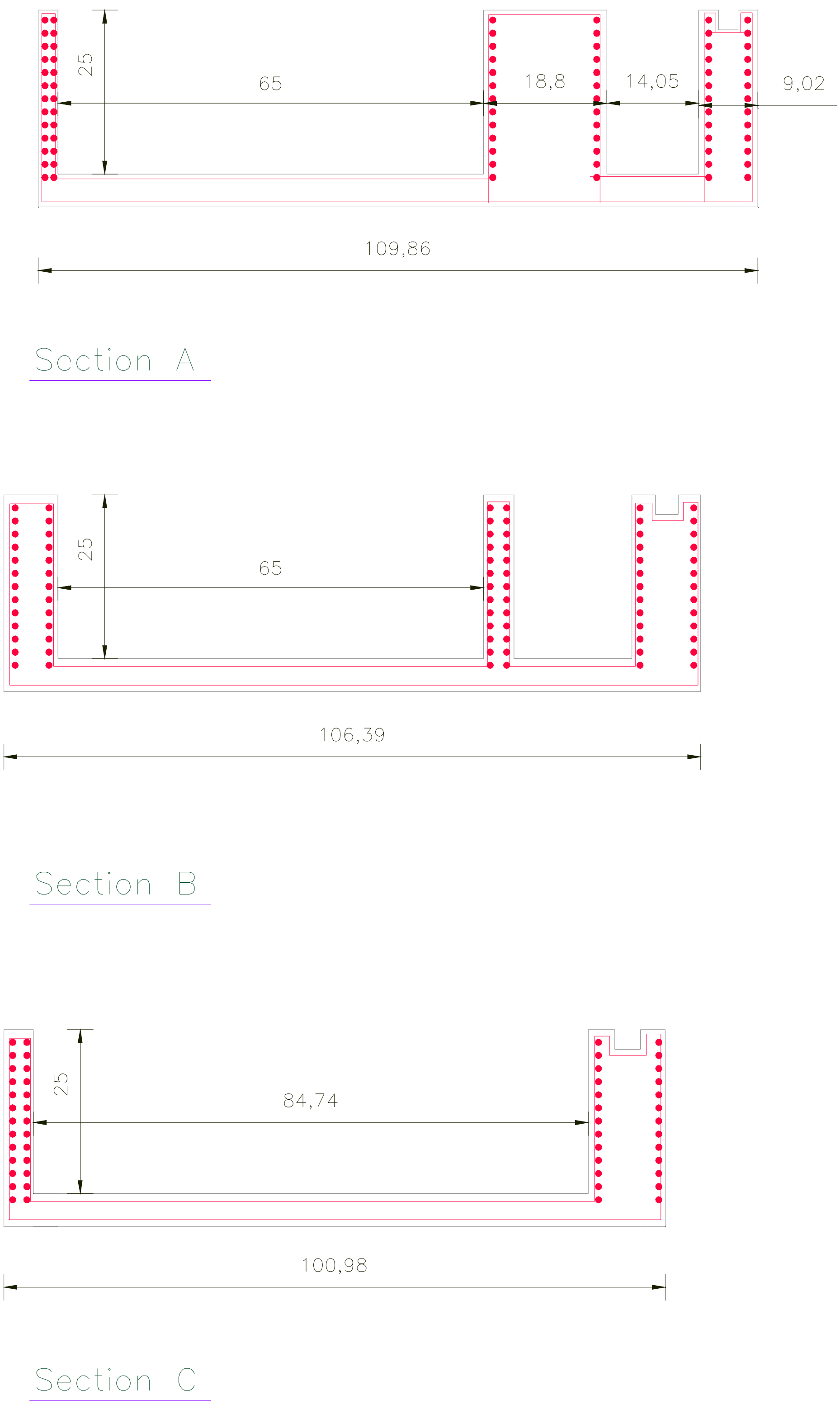


Figure 5-72: Lock head Cross-section and reinforcement patterns

5.6.7 Sealing

Bottom sealing

Bottom sealing is a floatable rubber controlled by the hydrostatic pressure. When the water head is zero, the rubber is floating and there is no contact with concrete surface of the bottom. When there is a water level difference, the rubber is pushed downwards by the hydraulic head and will seal the surrounding area. The rubber and its case have to be protected from possible sand and mud that could get stuck in the sliding surface of rubber and its case.

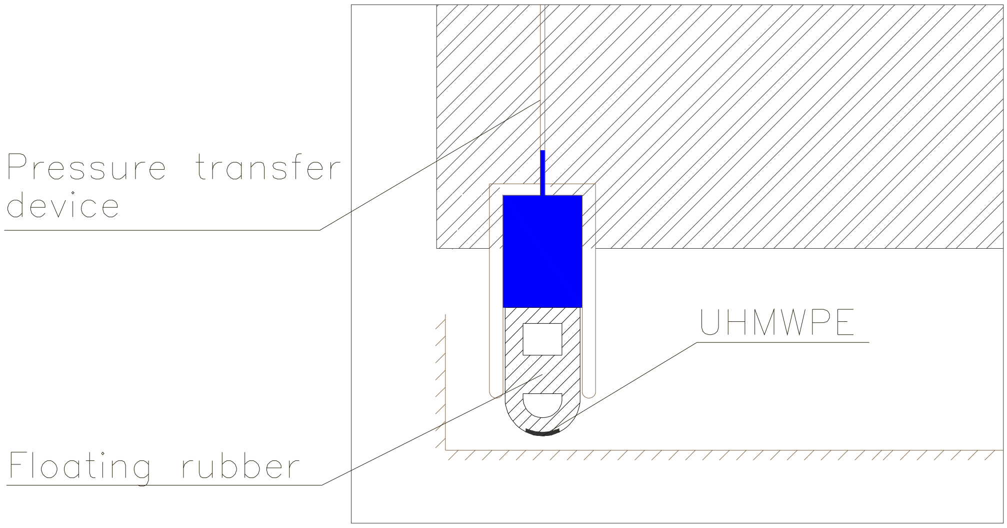


Figure 5-73: Bottom sealing cross-section

Vertical sealing

Vertical sealing consists of a rubber which lies inside the side bearing on the lock head. The rubber is coated with a thin layer of UHMWPE to prevent wear for rubber due to friction. Figure 5-74 shows the general layout of the vertical sealing.

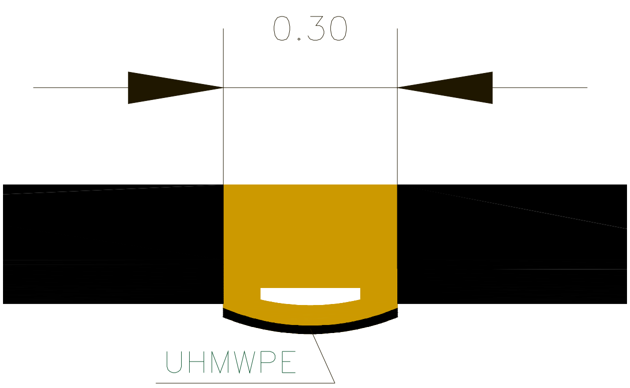


Figure 5-74: Scheme for vertical sealing in combination of side bearing

Notice that the vertical sealing has to be connected to the bottom sealing at the corresponding interface. This can easily be achieved since the bottom seal and the vertical seal are situated at both sides.

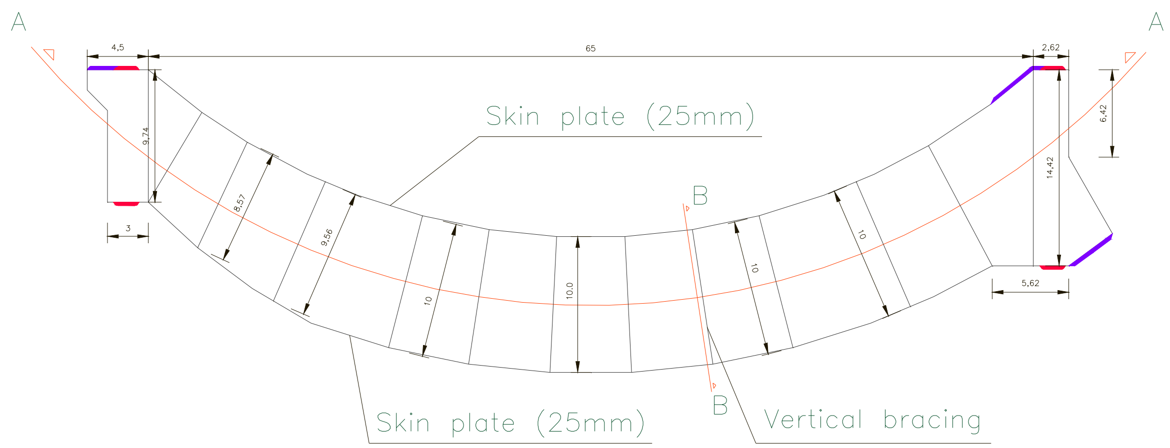
5.6.8 Gate structure - ULS

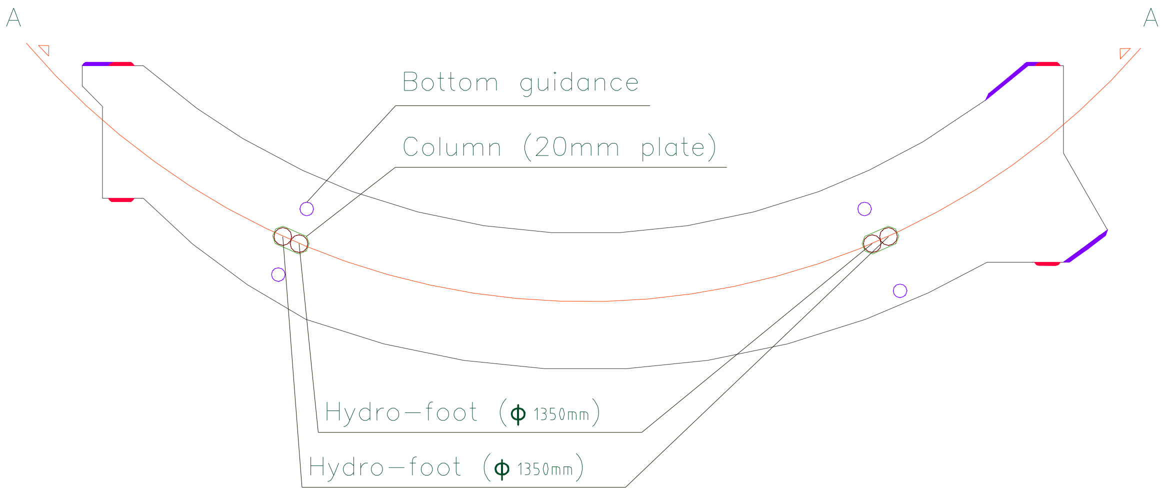
Graphs and output from Scia in the appendix C showing stress levels. Table 5-7 shows the dimensions for plates and the stiffeners. t_m is the thickness of the plate in the model and t_p is the actual thickness of the plate in the structure. The same symbols as Figure 5-16 are used for this table.

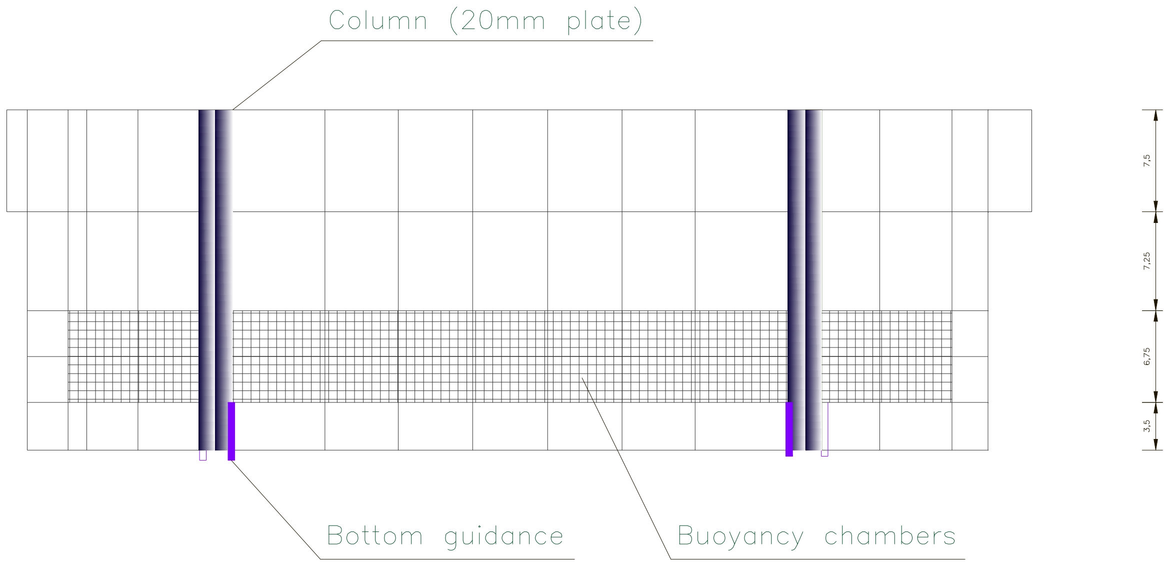
Element	Location	t_m	t_p	S	h_s	t_w	w_f	t_f	t_{eq}
		[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
Skin Plate	Convex side	48	**25**	500	350	22	150	25	47,9
Skin Plate	Hollow side	48	**25**	500	350	22	150	25	47,9
Horizontal plate	1 (top)	60	**25**	500	500	22	250	25	59,5
Horizontal plate	2	50	**25**	500	400	20	200	22	49,8
Horizontal plate	3 (Buoyancy top)	50	**25**	500	400	20	200	22	49,8
Horizontal plate	4 (Buoyancy middle)	40	**25**	500	250	22	100	20	40
Horizontal plate	5 (Buoyancy bottom)	50	**25**	500	400	20	200	22	49,8
Horizontal plate	6 (bottom)	40	**25**	500	250	22	100	20	40
Vertical plates	Buoyancy chamber	40	**25**	500	250	22	100	20	40
Columns		25	**18**	500	150	15	100	15	25,5
Skin plates	End frame	40	**25**	500	250	22	100	20	40

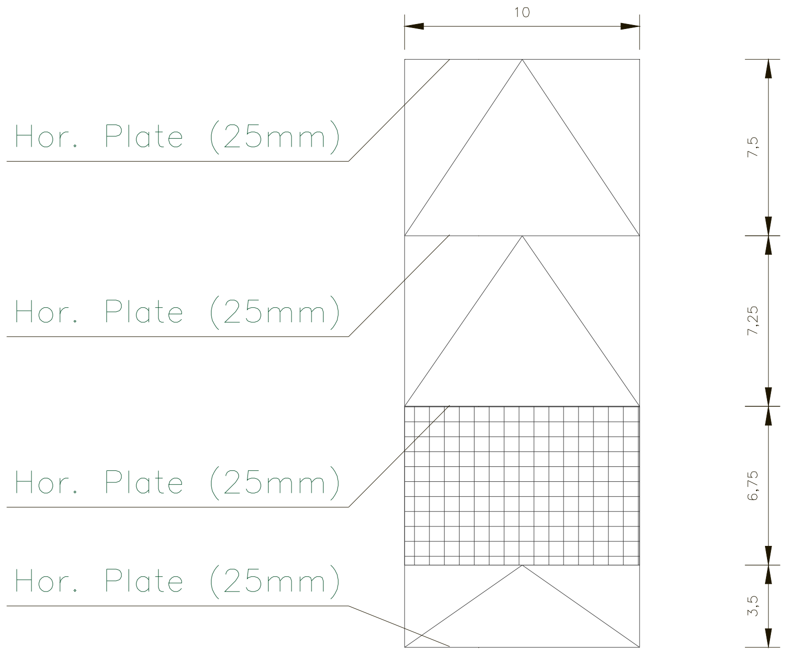
Table 5-7: Properties of designed plates and their stiffeners

Design Summary




A
A
Bottom guidance
Column (20mm plate)
Hydro−foot (ϕ 1350mm)
Hydro−foot (ϕ 1350mm)


Column (20mm plate)
7,5
7,25
6,75
3,5
Bottom guidance
Buoyancy chambers



5.6.9 Floating stability / Gate exchange

For the purpose of exchange and transport, the gate has to be first floatable and second statically stable during floating. For static stability, rotation of the element should be compensated by a righting moment caused by the buoyant force and the weight of the element. This is the case where the Metacentric height (h_m) is positive. In practice, h_m > 0.50 m is recommended. Detailed calculation of metacentric height is given in Appendix F. This height for the current design is 0.68m. The exchange process of the gate is illustrated in Figure 5-75.

Provisions should be considered for placing the bottom guidance within the acceptable tolerances. Handling the gate in such scale is extremely difficult within the allowable tolerance ranges. Therefore sensitive components of the gate are subject to impact or undesired forces during the placement of the gate. further design improvements should consider these elements.

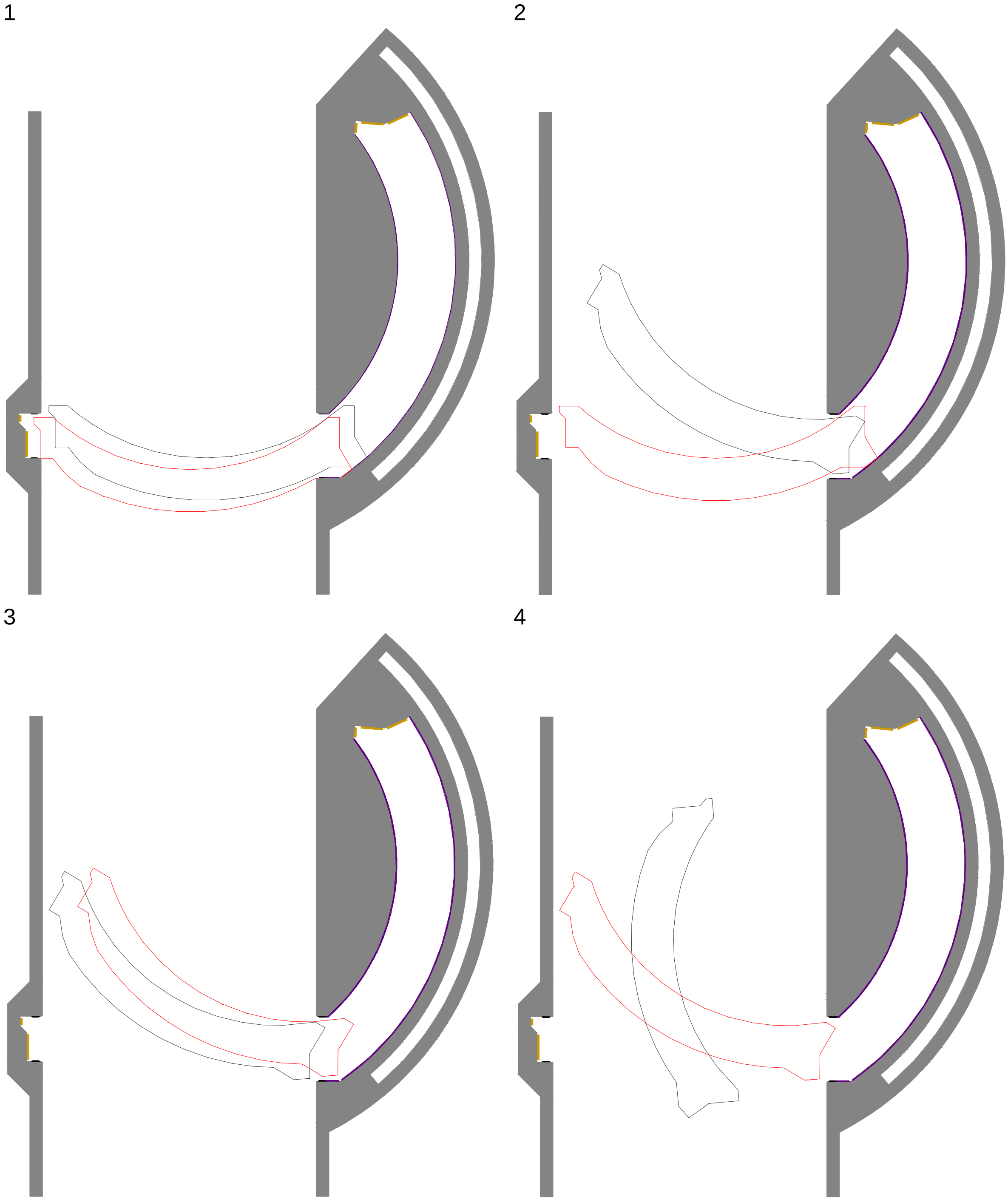


Figure 5-75: Gate exchange procedure (the red gate shows the position of the gate in previous step)

5.7 Costs and RAMS Analysis

As a closing argument for this chapter and in general for the design process, this section provides a cost estimation and cost comparison between the competing alternatives. A comprehensive evaluation is given afterwards in the form of RAMS analysis. Due to complications of quantification, the analysis is done qualitatively.

5.7.1 Cost Estimation

The costs for construction of gate and operating system is estimated and presented in Table 5-10. In calculation of the costs, unit prices are retrieved from the archive calculations for the preliminary design of IJNZ in Iv-Infra. Notice that determination of costs for some of the elements and equipment is very difficult, since the producer companies do not provide that information for public. For instance, predicting a realistic price for bottom sealing in current design is difficult, because the sealing has to be built specially for the project and the producer will only give the price to a serious client after proper calculations. In current cost estimation, the costs for construction of lock head are not calculated precisely but a rough estimation shows a value of 14.8 million Euros for an assumed volume of 80000 m^3 concrete and 1% reinforcement. Finally notice that the costs for maintenance of the gate are not calculated as they are more difficult to estimate realistically.

In Table 5-8 and Table 5-9 the costs for the gate and for the operating system are compared for different alternatives. The calculation method and items for the other alternatives are the same as the curved sliding gate and therefore, the price comparison is valid. An important missing item in comparison of the costs is the space usage. One of the advantages of the curved sliding gate is that is occupies a small area, during the operation in addition to open and closed position (Figure 5-76).

Alternative	No. of gate sets incl. reserve	Tonnage per gate set	Total price (excl. operating equip.)	Price per Gate set	Price per Ton
	sets	Tons	Euros	Euros	Euros
Mitre Gate (70m)	6	3600	107.413.748	17.902.291	4.973
Sector Gate (65m)	4	4400	90.248.200	22.562.050	5.128
Rolling Gate (65m)	4	3500	70.000.000	17.500.000	5.000
Rolling Gate (70m)	4	3900	78.000.000	19.500.000	5.000
Curved sliding gate (65m)	4	3875	78.451.710	19.612.927	5.061

Table 5-8: Cost comparison between competing gate types

Alternative	No. of equipment sets incl. reserve	Price (operating equipment)	Price per set
	sets	Euros	Euros
Mitre Gate (70m)	5	27.740.000	5.548.000
Sector Gate (65m)	4	26.350.000	6.587.500
Rolling Gate (65m)	4	16.600.000	4.150.000
Rolling Gate (70m)	4	17.600.000	4.400.000
Curved sliding gate (65m)	4	24.207.750	6.051.938

Table 5-9: Cost comparison for operating equipment between competing gate types

Item	Quantity	Unit	Unit Price	Total Price
Construction of gates (2 sets and 2 reserve sets)				
Koop staal tbv deuren (4 stuks) inclusief bruggen over deurkas in landhoofd	15.500,00	ton	€ 1.100,00	€ 17.050.000
Knip/Snij verlies staal deuren	775,00	ton	€ 1.100,00	€ 852.500
Samenstellen stalen deuren in bouwdok	15.500,00	ton	€ 2.300,00	€ 35.650.000
Handling staal op bouwlocatie / kraanhulp etc.	15.500,00	ton	€ 50,00	€ 775.000
hulpconstructies tbv opbouw deuren in bouwdok	82.000,00	m^3	€ 15,00	€ 1.230.000
Conservering deuren op locatie/preconservering (4 stuks) (geconditioneerd)	118.344,00	m^2	€ 68,75	€ .136.150
Slijtlaag op deuren ivm rijweg incl bruggen over deurkas in landhoofd	4.320,00	m^2	€ 100,00	€ 432.000
Voorzieningen schuiven aan deur (frames / rubbers / geleiding / etc.)	16	set	€ 25.000,00	€ 400.000
Aanslagen op de deuren (afsluiting raakpunt deuren)	104,00	m	€ 800,00	€ 83.200
Afdichting op deuren tpv drempel (afsluiting tegen drempel)	582,80	m	€ 2.000,00	€ 1.165.600
Afdichting op sluishoofd tpv wanden sluishoofd	100,00	m	€ 900,00	€ 90.000
Voorzieningen (bumpers op deuren) tbv bescherming bij stand in kassen	208,00	m	€ 750,00	€ 156.000
Frame / bevestigingsconstructie (staal) op deur tbv aanslagen / afdichtingen(demontabel)	890,80	m	€ 600,00	€ 534.480
Voorzieningen afdichtingen tbv beton hoofden	890,80	m	€ 750,00	€ 668.100
Transport deuren naar sluiscomplex	4	No.	€ 47.520,00	€ 190.080
Invaren / Inhijssen deuren in kolken	2	No.	€ 76.240,00	€ 152.480
Invaren / Inhijssen reservedeuren in opslagdok / deurenbergplaats	2	No.	€ 59.520,00	€ 119.040
Afmonteren deuren na inhangen / inhijsen	2	No.	€ 41.300,00	€ 82.600
Maintenance Provisions				
Droogzetvoorzieningen voor kolkbreedte 65m (input IV Infra SO-fase).	1	set	€ 1.325.000,00	€ 1.325.000
Aanbrengen vloer (stortsteen & colloidaal beton) deurenbergplaats (buitenzijde)	800,00	m^2	€ 750,00	€ 600.000
Lev + aanbr Pompen in gekromde roldeuren (4 st tbv drijflichamen, incl 4 reserve)	34	st	€ 60.000,00	€ 2.040.000
Lev reservepompen tbv opdrijven (4 st tbv balanslichamen, incl 1 reserve)	4	st	€ 50.000,00	€ 200.000

Operating system equipment (2 sets and 1 reserve set)				
Leveren en aanbrengen pennenbaan op deur	233,00	m	€ 35.000,00	€ 8.155.000
Leveren en aanbrengen bonkelaar	16,00	No.	€ 350.000,00	€ 5.600.000
Leveren en aanbrengen aandrijving ("tractor ") bonkelaar	2	set	€ 800.000,00	€ .600.000
Leveren en opslaan reserve bonkelaar & aandrijving etc.	2	set	€ 3.600.000,00	€ 7.200.000
Leveren en opslaan overige reserve onderdelen	2	pst	€ 250.000,00	€ 500.000
UHMWPE sheets for side bearings	200,00	m^2	€ 1.354,79	€ 270.958
UHMWPE sheets for Guidance	342,50	m^2	€ 1.354,79	€ 464.015
UHMWPE sheets for Bottom track	1.512,20	m^2	€ 1.354,79	€ 2.048.711
Direct construction costs				**€ 97.770.914**
After detailing the construction costs	5,00%	-	€ 97.770.914	€ 4.888.546
Direct construction costs				**€102.659.460**

Table 5-10: Detailed cost estimation for preliminary design

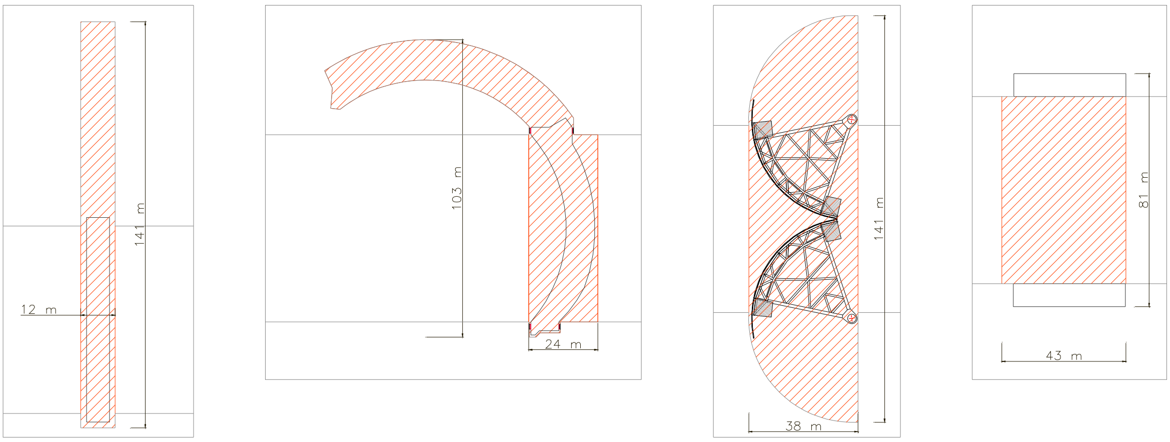


Figure 5-76: comparison of the required space between the alternatives

- The sliding curved gate is advantageous in sense of *less space consumption in lock chamber* (less required length) compared to sector gate and mitre gate.
- The sliding curved gate is advantageous in sense of *less space consumption in lock head* (less required width) compared to straight rolling and sector gate.
- The sliding curved gate is advantageous in sense of *total costs for gate construction* (incl. reserve sets) compared to sector gate and mitre gate.
- The sliding curved gate is advantageous in sense of *total costs for operating equipment* (incl. reserve sets) compared to sector gate and mitre gate.

5.7.2 *Reliability*

In order to investigate the reliability of the structure, first the failure mechanisms of the gate in current design are discussed. As described in chapter 3, when the reliability of a system is evaluated, the functions of the components and the structure have to be considered. A defect or fault in a component of the gate, can lead to failure in main functions of the gate. Throughout the realization of the function failures, the causes and the possibility of those failures and the preventive measures will be discussed.

Function Failures

Two main functions of the gate are water retaining and marine navigation. Faults in the components can cause failure in any of these main functions depending on the function of the component. Figure 5-77 and Figure 5-78 show the basic design related causes of failure in lock gate. Notice that general causes of failure such as human error and natural or human intended disasters are not included in this evaluation of reliability. However, simplicity was one of the main design objectives of the gate and the probability of human error was reduced in the design.

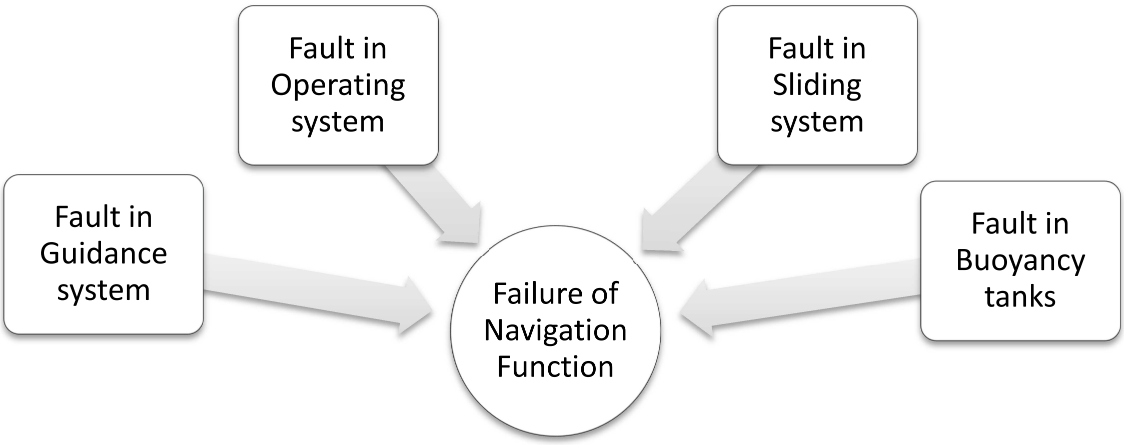


Figure 5-77: Primary simplified fault tree for Marine Navigation Function

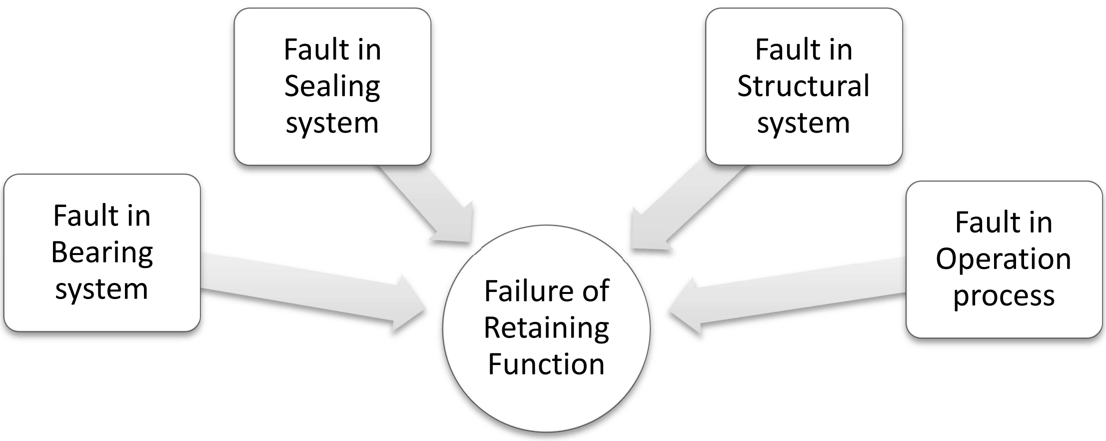


Figure 5-78: Primary simplified fault tree for Water Retaining Function

Preventive Measures

Redundancy, inspection and periodic maintenance are main strategies in increasing reliability.

- *Redundancy*

  Since the design is benefiting from new technologies and innovative concepts, it is important to compensate for the decrease of reliability due to unknown and unpredicted causes of failure. Current design consists of several measures in order to make the final product redundant. In general, the gate is considered to be redundant and it can be seen in the next section that this principle is noticed well in the components of the gate especially with the components which there is less experience.

- *Role of inspections and periodic maintenance*

  In any engineering system, there are failure mechanisms which can be spotted before their occurrence by their specific signs. In that manner, regular inspections are an effective way to increase the reliability of the gate. Therefore, the possibility of being easily inspected is considered an advantage in sense of reliability for an element. In this section, the possibility and need of inspections for components are evaluated as a contributing aspect for reliability.

  Due to inevitable wear and tear of the elements in the gate and the limited life-time of the components, periodic maintenance is necessary to guarantee the reliability for components of the gate. In addition, by performing preventive maintenance procedure, the chance of corrective maintenance necessity will be decreased and the downtime of the structure and total maintenance costs can be decreased in long-term.

Evaluation

The following paragraphs provide a brief evaluation of reliability for each of the functional systems.

- **Guidance system**: The guidance system of the gate as described in section 5.6.4, provides a minimum of three guiding points at all the times. The bottom guiding devices are designed for the maximum operational loads and the contact length of the guidance in normal situations is 25 centimeters. The fluctuations of the gate during operation are considered to be within a few centimeters which gives the guidance system a minimum of approximately 20 centimeters of contact length.
  Top guidance devices are sufficiently large for providing enough contact length during the operation. The only critical phase is the beginning of rotational movement during opening as shown in Figure 5-64. In this phase, the top guidance at the hollow side of the gate will come in contact with its track in the main recess gradually from zero to its full capacity during the first few degrees of rotation. However, when the contact length is zero, the top guidance at the other end of the hollow side is in full contact with its track at small recess. Therefore the fluctuations of the gate can be expected to be maximum at start of the rotation within the first one degree of rotation. Since the contact length increases from this point forward, the stability of gate will not be disturbed by this behavior.
  The tracks are made from UHMWPE which according to the descriptions in section 4.4.2 are reliable and durable materials. Experiments (20) show very little wear and damage during the

life-time of UHMWPE tracks. In addition, the design of the tracks and the chamber bed implies on low sedimentation likelihood due to self-cleaning characteristic of hydro-foot.

Inspection and maintenance of top guidance devices and top guiding tracks is easy. On the other hand, bottom guidance devices and the guiding track are always below the water and inspection and maintenance requires divers for In conclusion, the reliability of guidance system is high and the probability of failure caused by fault in guidance system is relatively low.

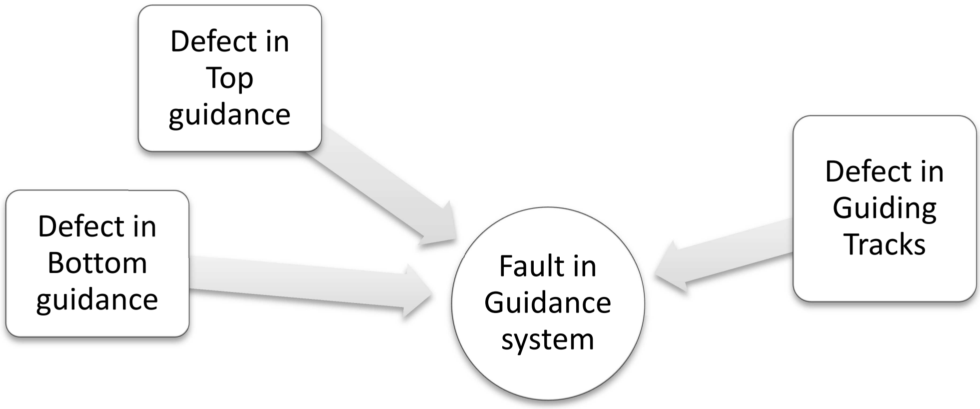


Figure 5-79: Primary simplified fault tree for Guidance system

- **Operating system**: The locomotive operating system has never been used for lock gates before. However, locomotives are a common choice for operating system of draw bridges. The locomotive is designed to provide the required driving force for the maximum operational loads as described in section 5.5. During the life-time of the gate, the maximum load situation happens very rarely (frequency of 10^{-1} per year) and the rest of the times, the loads are considerably lower on the locomotive. Consequently the number of pinions and engines is redundant for 99% of the time. In addition, the locomotive is separated from the gate and is operating in its own recess which has two advantages. First, a good quality of sealing can be achieved for the equipment in locomotive. Secondly, since the racks and pinions are working in a protected environment, the fluctuations of the system are considerably lower than the fluctuations of the gate. Therefore the likelihood of wear decreases substantially and the effective contact of the pinions' teeth is preserved during the operation process. Furthermore easy inspection and periodic maintenance of locomotive is made possible because of this separate recess.

  The connection element between the gate and locomotive is also designed for the maximum required driving force. The structural design of the element itself is not done for this study; however, a general layout is suggested for this element in order to show the considerations for buckling of the device. It is understood that design construction of such element is not an unusual engineering issue and it can be done within the current knowledge and technology. The critical part of the design is the hinged connection of the element to the gate and to the locomotive. Based on the practical examples of such connection in existing bridges, it can be said that providing a reliable connection is not an obstacle for current design.

  Functionality of electrical equipment is an everlasting issue in design of all lock gates. Study of these components is out of the scope of this graduation work. However it can be said that the sealed environment of operating system slightly decreases the chance of defect in electrical equipment.

In conclusion, high reliability can be achieved for operating system by realizing the critical elements and situations.

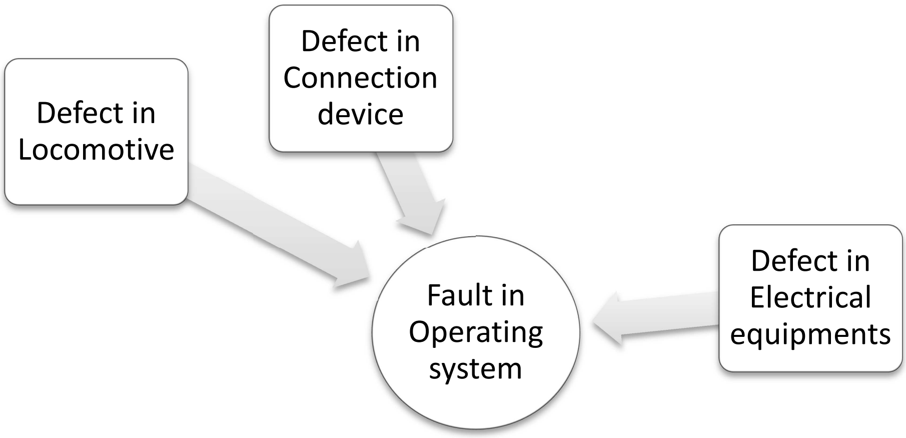


Figure 5-80: Primary simplified fault tree for Operating system

- **Bottom Support / Sliding system**: Use of hydro-foot as bottom support system is a subject of discussion in new generation of lock gates. In general, the concept of hydro-foot has passed all the experimental tests successfully and it has proven to be reliable in practice in case of "Prins Willem Alexander" lock in "Oranjesluizen". Current design has considered the maximum required force to be provided by the hydro-feet. This maximum force only applies to a situation which happens with a considerably lower frequency than 10^{-1} per year. Based on the same given arguments for the operating system, it is concluded that use of two hydro-feet at each supporting point is considered redundant for 99% of the time.

  Chance of failure for the hydro-foot device and for the restrictors is relatively low based on the outcomes of relevant experiments (20). The pressure distribution, self-cleansing mechanism and corrective behavior of the hydro-foot makes it a reliable support during the operation of the gate. However, the critical part of this principle is water installation and most importantly the pumps which provide the required water pressure. In this design, it is considered that even one pump can provide sufficient water pressure under the bearing pad for creating effective film thickness. Therefore, the second pump can alternatively take part in the operation and is considered redundant.

  Use of UHMWPE track is evaluated in section 4.4.5. It is worth repeating the facts that wear is very low in this type of track and the friction coefficient and waviness of the track decreases gradually after each cycle of operation. In addition, the maintenance and replacement of the track is relatively easy compared to steel rails.

  In conclusion, the design of current gate provides enough measures for increasing the reliability of bottom support system. However, although construction of hydro-foot with a diameter of 1300 mm is theoretically possible, a hydro-foot with such dimension and such anticipated bearing force has never been built which makes it less reliable in practice. In general the inspection of the feet and the track has to be done by divers but the installations can be monitored digitally with the help of particular devices. The periodic maintenance of the pumps can also be done easily since they are located above the usual water level.

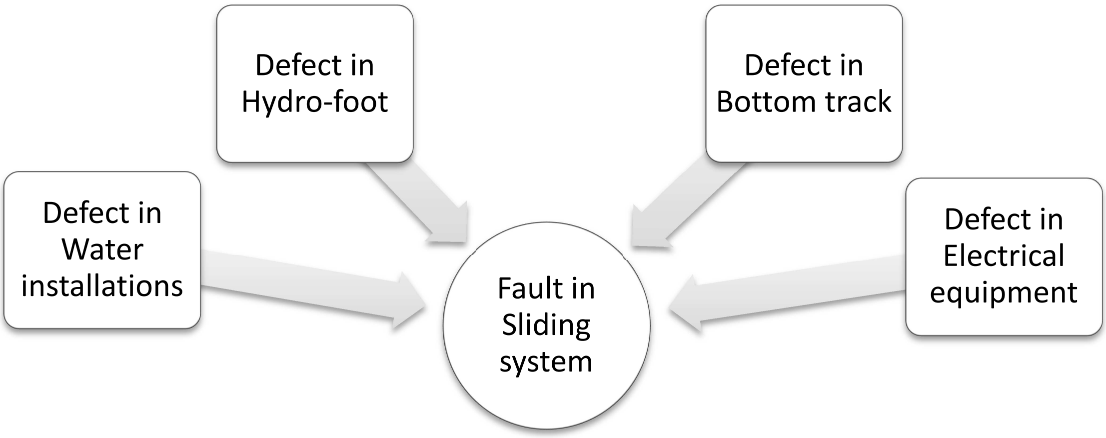


Figure 5-81: Primary simplified fault tree for Support system

- **Buoyancy tanks**: Design of buoyancy tanks is done similar to the existing lock gates and no special innovation was intended for buoyancy chambers. Possibility of leakage always exists in buoyancy chambers and this design is not an exception. Therefore this has been foreseen in the design and extra tanks are considered as reserve and ballast tanks. The main problem occurs when the leakage in buoyancy tanks cannot be compensated by the water installations. Then the structure falls out of balance or the expected bearing reaction increases on the support system and the operation process may be stopped. Inspection of the buoyancy tanks and the water installations is made possible by the predicted inspection chambers inside the buoyancy chambers and a dry access approach to the inspection chamber.
  In general, the reliability of the buoyancy tanks is comparable to the existing locks.

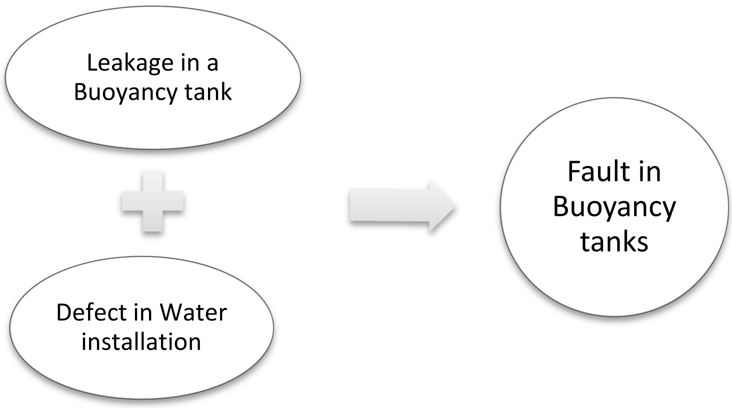


Figure 5-82: Primary simplified fault tree for Buoyancy tanks

- **Bearing system**: As it was intended in the design objectives, the use of movable components is minimum in this design. The bearing system of the gate is a fixed structure in the lock head. The required strength and stiffness is easily provided by the lock head and can be improved by several measures such as prestressing.

Bearing panels of the gate are made from UHMWPE material which has been evaluated positively in previous sections in sense of low wear. The inspection and maintenance procedures are easy for these bearing panels.

The structural analysis of the gate structure has been done in section 5.4 and based on the results, the stresses in the gate structure during the maximum load condition are relatively low compared to the allowable stress levels.

In general, the bearing system of this gate is comparable to a straight rolling gate. Notice that most of the other alternatives for curved sliding gate need movable devices for providing the bearings. These devices have lower reliability than a fixed bearing and are considered the weak link in the design. In other words, one of the main advantages of this design is the high reliability of its fixed side bearings.

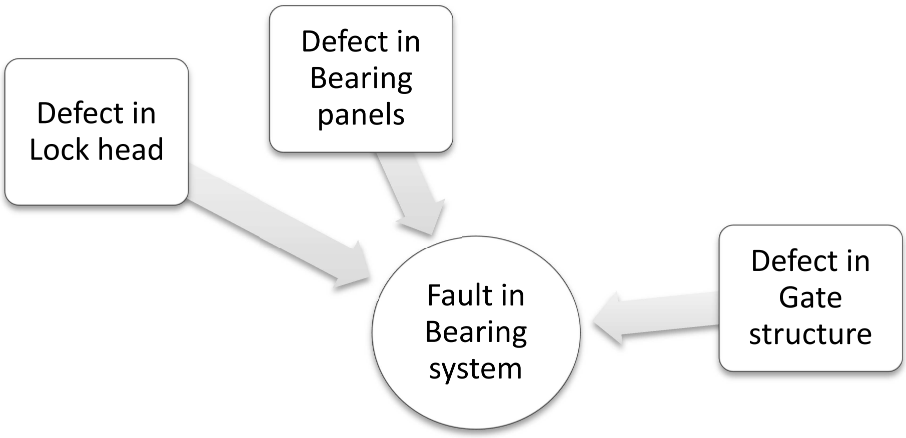


Figure 5-83: Primary simplified fault tree for Bearing system

- **Sealing system**: The vertical sealing of this design has been used for a number of existing lock gates and has been proven to be reliable within its requirements. However, the bottom seal needs more investigation and attention as it has not been used in lock gates. Reportedly, a sample of this type of sealing has been used in a lock structure in United States. Further information on the history of this type of sealing is not available. Nevertheless, the large length of the required sealing at the bottom of the gate implies on uncertainties for effectiveness of this type of sealing. There is a possibility of malfunctioning for the hydraulic drive system of this type of sealing. On the other hand, the advantage of this seal element is very low possibility and vulnerability of wear. Inspection and maintenance of the bottom sealing is also difficult and it has to be done by divers under water. In general, the reliability of the sealing system remains a matter of question since the concept is reliable in theory but has not been evaluated in practice. The main concern in practice is the possibility of sand and mud penetration inside the system which can cause the rubber part to get stuck and stop functioning properly.

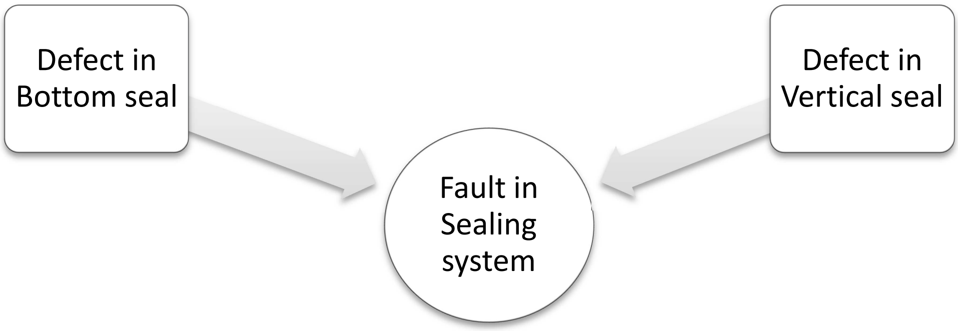


Figure 5-84: Primary simplified fault tree for Sealing system

- **Structural system**: Structural system of the gate has been analyzed thoroughly in section 5.4. As it can be seen, the stress levels are relatively low for all the elements of the gate and possibility of collapse is consequently low for the elements. The design load condition is an extreme situation with a probability of occurrence less than 10^{-4} per year for the lifetime of the gate. Global stability and resistance of the gate is consequently high even for the situations worse than the design situation. Additionally, the fatigue loads are considerably low because the number of cycles in the lifetime of the gate is relatively low for fatigue to become dominant.
  Maximum deflection of the gate is limited to 40 millimeters and the maximum possible slip of the gate through the bearing points at the sides is 25 millimeters for the extreme situation. Therefore, it can be said that the structural system of the gate delivers a reliable design based on the analyses of this study. Notice that since the connections of the gate are not designed in this research work, they cannot be evaluated here.

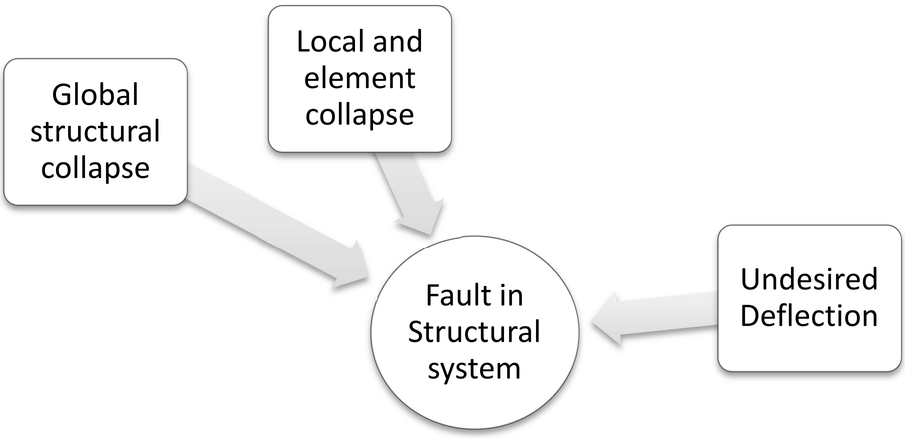


Figure 5-85: Primary simplified fault tree for Structural system

5.7.3 *Maintainability*

Maintainability of the structure is studied in three sub-categories of Inspection, Preventive maintenance and Corrective maintenance. Each sub-category in this section has a different way of contribution to maintainability and eventually the availability of the new design. Notice that the maintenance procedure is rather complicated and description of the whole procedures and determination of required time is out of the scope of this study. Therefore, this section provides qualitative information regarding the provisions for maintenance of the gate.

Inspection

As stated before, regular inspection and system monitoring provide valuable information regarding the functional state of the gate structure. It indicates if a component needs repair or replacement or other provisions in order to prevent the defect from further development. This information gives the advantage of more efficient time-management in maintenance policies of the gate. Additionally, the anticipated time for maintenance can be predicted and long delays and preparation times before the maintenance can be avoided. In this manner, possibility and convenience of inspection is an important criterion for maintainability of a component. The following components of the gate have this advantage:

- Operating system including the locomotive and the connection device
- Top guidance devices and tracks
- Water installations
- Buoyancy chambers

The following components need divers for inspection:

- Bottom guidance devices and tracks
- Hydro-feet and sliding track
- Bearing system
- Sealing system

Inspection of the structural elements of the gate which are very specific tests and procedures has to be done both under water and above the water.

Preventive Maintenance

Preventive and periodic maintenance have been discussed in the previous section. In this section, the possibility of performing these maintenance procedures is evaluated. Another important aspect in this type of maintenance is the time-management. The preventive maintenance approach is considered beneficial as long as it does not imply more downtime than the corrective maintenance. Therefore, the possibility of performing preventive maintenance within the desired time can contribute to the maintainability of the gate.

Corrective Maintenance

Corrective maintenance is regarded to the repair and replacement procedures for the defected or faulted component. It can be categorized to minor repairs and major repairs:

- Minor repairs

Minor repairs are regarded to the maintenance procedures in which the component can be repaired or maintained at location within a short time period (few hours). Some components of the gate have this advantage and provisions are considered for performing minor corrective repairs.

- Major repairs

Major repairs are necessary when the defect in the component cannot be corrected in its location or within a few hours. In that case, the component needs to be replaced. Therefore, provisions for replacement of any component should be considered. The ultimate replacement is considered to be gate exchange in case of serious damage.

Evaluation

Table 5-11 evaluates various systems of the gate in sense of maintainability.

	Inspection	Minor repair	Replacement
Guidance system			
Top guidance	Advantageous	Possible	Possible
Bottom guidance	Diver required	Only small repairs	Possible but difficult
Guiding track	Diver required	Only small repairs	Advantageous
Operating system			
Locomotive	Advantageous	Advantageous	Advantageous
Connection device	Advantageous	Possible	Advantageous
Electrical equipment	Advantageous	Possible	Possible
Sliding system			
Hydro-foot	Diver required	Possible but difficult	Advantageous
Water installations	Advantageous	Only small repairs	Possible
Sliding track	Diver required	Only small repairs	Advantageous
Electrical equipment	Advantageous	Possible	Possible
Buoyancy tanks			
Leakage control	Advantageous	Only small repairs	Not possible
Water installations	Advantageous	Only small repairs	Possible
Bearing system			
Lock head	Diver required	Possible but difficult	Not possible
Bearing panels	Diver required	Only small repairs	Possible
Sealing system			
Bottom seal	Diver required	Only small repairs	Possible but difficult
Vertical seal	Diver required	Only small repairs	Possible
Structural system	Specific procedure	Only small repairs	Possible in 24 hours

Table 5-11: Qualitative Maintainability evaluation

5.7.4 *Availability*

As it is defined in chapter 3, availability is related directly to reliability and maintainability of the structure. However, the degree of availability and estimation of the percentage of the time which the gate is available is rather complicated and requires analyzing the failure scenarios thoroughly. In this section, the very general form of the availability is considered and a simple scenario analysis is provided for the main elements of the design. But before, non-availability condition is described and uptime and downtime are explained. Notice that availability of the gate is both related to natural conditions like waves or water levels and also on the reliability of the components. Here, the availability of the gate is only studied for the functional systems of the gate. The non-availability of the gate due to natural conditions can be calculated by considering the design loads and the frequency of occurrence.

Non-availability

The failure mechanisms have been described in evaluation of reliability. It can be seen that the faults in functional systems of the gate can result in failure of the main functions of the gate. However, failures in functional systems do not necessarily result in non-availability of the gate. In that manner, the uptime of the gate is regarded to the situation where the main functions of the gate can still be delivered weather all the systems are available or not. As mentioned above, failure scenarios need to be analyzed in order to calculate the availability of the gate precisely. The following paragraph provides a number of scenarios in which the failure (or fault) in one functional system does not cause failure in the whole system of the gate. In addition, critical failures are also mentioned.

Failure Scenarios

This paragraph explores the failure mechanisms and their consequences on the gate functions. In this manner a number of scenarios are considered:

- Defect in guidance devices or tracks will definitely lead to failure in the guidance system and consequently in navigation function of the gate

- Total failure of operating system will cause failure in navigation function of the gate. However when there is a defect in the locomotive, for example, one out of the eight engines is malfunctioning, the locomotive would still be able to operate with seven engines in overloading mode.

- If the sliding system fails and the water installations would not be able to provide water film at the contact surface of the hydro-feet and the track, the hydro-feet will slide on the track with a considerably higher friction coefficient (15~20 times higher) but the operating system would still be able to provide enough driving force if the maximum possible hydraulic loads are not present.

- Leakage in the buoyancy tanks can lead to increase of total weight and reaction on the hydro-feet. Consequently, the water film thickness will decrease and the friction coefficient will increase. Therefore the required driving force increases due to increase of friction forces. However, the operating system would still be able to provide enough driving force if the maximum possible hydraulic loads are not present.

- Although it is very unlikely for the bearing system to fail, but the failure in the bearing system will lead to total system failure for the purpose of water retaining function. However, small defects like wear or partial tear of the bearing pads can still be tolerated as the UHMWPE bearings are designed with a high safety factor.

- Defects in sealing system will cause leakage trough the supposedly sealed areas while the water retaining function is intended. This can mean failure for the main function, but notice that small tolerances are accepted for the sealing system.

- Structural system of the gate delivers principally the most important function of the gate. Availability analysis for structural system is complicated due to presence of several different element types in the structure. Nevertheless, the structural system of the gate has a higher availability than structural system of an arched sliding gate which relies on mechanical bearing point. It can be said that the current structural design can deliver almost the same availability as straight rolling gates in sense of the structural system.

Evaluation

A realistic evaluation of total availability of the structure can only be made after the exact calculation of reliability and maintainability of the gate and determining the accurate uptime and downtime of the gate. In general it can be said that since the availability of the gate was one of the basic criteria in the design, the concept of curved sliding gate, can prove to satisfy the high anticipated availability levels once the preliminary design gets improved and more detailed.

5.7.5 *Safety*

In order to evaluate the safety of the innovative gate design, the acceptable risk levels have to be determined. Safety of the design is related to the reliability of the gate and damage avoidance policies. In reliability analysis, the function failures were introduced and evaluated. Yet, for the safety analysis and evaluation, only the critical failures should be considered. In other words, a number of functional failures do not decrease the safety level of the design though they decrease the availability. By the end of this section, a brief evaluation on the safety level of the design is given based on stability and resistance off the gate and failure consequences.

Acceptable Risk Level

As a basic definition for risk, the probability of critical failure and the magnitude of the damage or loss will determine the value for risk. In current design, the damages are in terms of financial loss and life loss. Determination of the probability of critical failure is complicated due to complication of the system and it needs a through probabilistic study. Determination of acceptable losses both in financial terms and human life is also very difficult and it requires an agreement between the shareholders. Therefore, the accepted risk level can only be described qualitatively as very low life loss (theoretically zero) and reasonable financial loss which is justified in the municipal or national scale.

Critical Failure

A critical failure in life-time of the gate is considered a substantial damage to the gate and lack of ability to perform essential measures (such as maintenance) within a determined time. In that manner, structural failure of the gate such as instability or collapse of the main elements of the gate is considered as a critical failure for the function of water retaining during the extreme hydraulic situation. In addition, any critical situation which leads to the failure of the operation process is also considered critical since it would result in unexpected financial losses.

Evaluation

The structure of the gate is analyzed to withstand the ultimate limit state forces in extreme situations and the results of those analyses show that the stress levels for the elements of the gate are considerably lower than the plastic limit of the materials and therefore the possibility of residual strains is nearly zero. However, the gate is not designed for the accidental ship collision or for that matter any other accidental loads which are in the same magnitude. Therefore, it can be said that the total safety of the gate is decreased due to the risks involving the unexpected loads.

Furthermore, the stability of the gate is guaranteed for the extreme load conditions and the deformations of the gate in those situations are very small compared to the size of the gate and also dimensions of the bearing areas. In that manner, the stability of the gate is assured during the extreme conditions. As for the accidental and unexpected loads, if the collision does not result in global distortion of the layout of the gate, then the stability of the gate is still intact due to its special curved shape which makes it stable regardless of the position on which the gate is standing. As a result, the consequences of the damage are not large and the risks are low.

Safety of the gate in sense of navigation function can be evaluated by considering the reliability and maintainability of the gate in addition to the financial loss rate due to non-availability of the gate for navigational purposes. Although a high reliability can be achieved for the design and fast and effective maintenance procedures can be managed to be performed, the large loss rate and non-availability fines, increases the risks perhaps to above the acceptable risk levels. Therefore, a better knowledge of the financial losses can improve the realistic estimation of the gate safety.

6 Conclusion and Recommendation

This report is the product of the research study as a master thesis. The study initiated in Iv-Infra and got developed by the author with the supervision of experts in Iv-Infra and scholars from TU Delft. This chapter provides the outcomes of this study followed by a number of recommendations for future studies. The conclusions and recommendations solely refer to the main subject of study which is the design of an innovative lock gate later depicted as the curved sliding gate.

6.1 Conclusions

Conclusions of this study are presented in the form of a comprehensive and descriptive answer to the main research questions which were illustrated in chapter 1. The principle matters of investigation in current study were aimed at *feasibility* and *applicability* of the proposed innovative design of Curved Sliding Gate.

6.1.1 Feasibility

As the preliminary design of the gate has been made, it is implied that design of a curved sliding gate is theoretically possible. However, a number of considerations have to be given in order to answer the feasibility question vividly.

- Based on the evaluation system in the form of RAMS analysis, the design is evaluated as feasible in the sense of reliability, availability, maintainability and safety.

- It is also concluded that the preliminary design of the curved sliding gate has to be improved in all those terms to assure the feasibility of the design.

- Within the development of the design, a number of technologies have been applied in the design which are either very recent or has never been used for lock gates. These technologies are hydro-foot support and sliding system, locomotive operating system, combined movement guidance system and hydraulic pressure based sealing system.

- The chosen technologies are designed within the current practical limits and according to existing references. Therefore the field of innovation is relatively safe for this study. However, the main causes of non-availability in gate structure are traced back to the unknown revenue of these technologies. In order to assure the feasibility of current design, improvement of employed technologies is required.

- As stated above, use and combination of new technologies is evaluated in theory. Now, the concept of curved sliding gate with all the accompanied technologies needs to be evaluated through an experimental study to approve the outcomes of this study and get a better understanding of the behavior of such design.

- The acceptable tolerances in design of curved sliding gate are very small compared to the global dimensions of the gate and in practice are difficult to achieve but yet possible.

In conclusion it can be said that by keeping the above considerations in mind, the results of this study show that design for the concept of curved sliding gate is **feasible**.

6.1.2 Applicability

As the innovative concept of curved sliding gate passes the feasibility check, the question of applicability and competitiveness of the gate as an alternative in design can be answered through the following points.

- The design of the curved sliding gate is applicable for the lock structures with high water retaining height requirements.

- In addition to the considered height as boundary condition, the lock chamber for design of the curved sliding gates is considered to be wide.

- The result of the cost comparison shows that the final cost for this type of gate is considerably higher than cost of straight rolling gates.

- In comparison to other competing alternatives, the curved sliding gate has lower construction cost than sector gate and mitre Also the advantage in use of less space makes the curved sliding gate a better choice.

- Concept development of this type of gate has been done on the basis of a number of design objectives which one of them was innovation. Therefore it has to be considered that opting for other alternatives may lack the innovation element but has other advantages.

- Based on the evaluation of Availability in section 5.7.2, the design can deliver the anticipated availability once applied by certain improvements.

In conclusion, it can be said that the current design of curved sliding gate is **applicable** for the situations where the space limitation is a critical problem. The main conclusion of this study is:
Unless the space limitation problem does not exist, application of curved sliding gate cannot be justified.

6.2 Recommendations

As the nature of the study implies, the research is carried out within a certain resource and time limitation. Therefore, there is always room for improvement of the results of the study and possibilities for further scientific, experimental and practical investigations. This chapter provides a number of recommendations for the future researchers who want to continue the search for a better innovative design. The recommendations are divided into four categories:

- **Areas of design improvement**

1. The weakest link in the reliability analysis for the navigational functionality of the gate, considered to be the guidance system. Therefore, improvement on the design of the guidance devices especially the bottom guidance devices can increase the reliability of design.

2. Since the operating system of the gate is a mechanical device, the detailed design of the equipment and the locomotive in general, deemed out of the scope of this study. Consequently the reliability of operating system can be increased and the properties of the elements can be improved by providing sufficient knowledge from the mechanical engineering sector.

3. Maintenance procedures have not been determined or described in current study. Although a number of provisions are considered for the maintenance of the gate such as component replacements and gate replacement. For acquiring a better design with an assurance on high availability, basic maintenance procedures need to be determined.

4. As stated in preliminary design stage, the design procedure has been done only for a single design loop. In order to achieve an efficient structural design, further design loops should be considered. Additionally, more detailed analysis models can improve the understanding of the behavior of the structure.

- **Room for experimental study**

The following items have been designed based on the existing data and theory. It is recommended that the reliability and behavior of the gate be evaluated via experiments on the components which the amount of existing data is not sufficient to guarantee the expected results.

5. Guidance system: The special three dimensional layout of the guidance system needs to be studied with a powerful simulation tool or controlled laboratory test.

6. Operating system: Functionality of the operating system and its effects on the gate structure during the movement of the gate should be verified by proper laboratory tests.

7. Sealing system: The applicability of the bottom sealing in large dimensions of this curved sliding gate can be investigated through experimental studies.

8. Hydro-fender: As stated before, use of hydro-fender instead of hydro-foot gives several advantages. However, due to lack of experimental data, the use of hydro-fender in practice remains on hold. Reliable laboratory results can contribute severely to the concept of hydro-sliding for the lock gates on general.

- **Further design investigation**

9. In section 5.5 it was mentioned that since the loads on the gate halfway through the opening are not large, the global torsional behavior of the gate will not be studied. However, for broadening the field of application of the curved sliding gate, the torsional behavior of the gate should be studied and evaluated.

10. The global stiffness of the gate in the vertical plane perpendicular to the lock chamber axis is relatively low especially in comparison to straight rolling gates. Further investigations can illustrate that if this low stiffness can lead to a serious problem or not. This has been only a realization through the course of the study and it did not introduce any problems in the design process.

11. Study of fatigue loads has been ignored in current design due to low number of operation cycles. However, since the fatigue breaking mechanism is considered as a dangerous collapse mechanism, and considering the lifetime of the gate structure, further structural analysis for fatigue can contribute to the reliability of design.

12. Section 5.7.4 provides a simple availability analysis for the design of curved sliding gate. A detailed scenario analysis and accurate calculations are required for estimation of real availability. Since the availability of the gate is one of the most important requirements, performing this study and in general a probabilistic study of the design is recommended.

13. The choice of geometrical characteristics of the curved gate was based on the general arguments of the chapter 4 which determined a set of starting point for design. However, finding the best proportions of geometrical characteristics like the radius of the gate can result in a more efficient design.

14. Best option for the number and location of hydro-feet can be found by performing a sensitivity analysis for the performance of the hydro-feet.

15. Considering the ship collision condition in design is recommended for large projects.

16. Detailed design of lock head for the bearing loads and leveling chambers can better determine the final costs of the construction.

- **Practical improvement**

  17. For the applicability of the design in practice, refer to the section 6.1.2.

  18. The focus of current study was the feasibility study and investigating the applicability of the curved sliding gate in practice. However this study lacks reliable construction provisions and further study on the construction procedures, manufacturing and assembling can contribute to the consistency and integrity of the design.

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APPENDICES

A Loads (Zeetoegang IJmond)

The following loads are considered for the design of the curved sliding gate:

- Self-weight and buoyancy

Weight of the gate is one of the most important loads especially for the stability in the design aside from the horizontal loads. The total dry weight of the gate is estimated to be around 2700 Tons based on first hand calculations. Use of self-weight and buoyancy should be done very carefully in the design since they can be favorable in stability of the structure. Notice that mud and marine growth should be also included in the loads.

- Hydrostatic water pressure/water level differences

Water level differences should be considered in two different situations; Storm surge barrier function and Navigation function:

1) Large water level differences, when the gate is closed. This is most probably the largest load on the gate. Based on the report "Uitgangspunten Civiele Constructies" [2], the water levels will be considered as follows:

Extreme positive head

Water level at North Sea:	NAP + 7.63 m
Water level at North Sea Channel:	NAP - 0.88 m

Extreme negative head

Water level at North Sea:	NAP - 3.50 m
Water level at North Sea Channel:	NAP + 0.67 m

2) Small water level differences should be considered during gate movement which represents some tolerances for leveling operations. This water level difference is determined to be 0.10 m (for outside gate) or 0.15 m (for inside gate) [2]. Water levels during operation will be as follows for outside gate:

Maximum head during operation (opening)

Water level at North Sea:	NAP + 4.17 m
Water level at North Sea Channel:	NAP + 4.07 m

Maximum water level at North Sea:	NAP +4.17 m (including sieges)
Minimum water level at North Sea:	NAP -2.20 m
Water level at North Sea Channel side:	NAP -0.88 m

 Notice that the water levels are meant for hydrostatic pressure calculations and they are accounted for sieges, sea level rise, set-up/set-down and robustness [3].

The following tables shows the selected values as design points for frequency of 10^{-4} per year:

Parameter	Value
Extreme high water level (North Sea)	NAP +5.44 m
Extreme low water level (North Sea)	NAP -3.00 m
Extreme high water level (North Sea Channel)	NAP +1.30 m
Extreme low water level (North Sea Channel)	NAP -0.70 m
Set-up and set-down (North Sea Channel)	+/- 0.30 m

Governing positive head:

Water level North Sea side incl. set-up Water level North Sea channel side Set-down North Sea channel side	6.86 m + NAP -0.58 m + NAP -0.30 m
Head (without robustness) 10% Robustness	7.74 m 0.77 m
Head	**8.51 m**

Governing negative head:

Water level North Sea side Set-down North Sea side Water level North Sea channel side	-3.00 m + NAP -0.11 m -0.07 m + NAP
Head (without robustness) 10% Robustness	-3.34 m 0.33 m
Head	**-3.67 m**

- Wave loads

Wave loads are divided into two categories; swell and wind wave. Due to presence of breakwaters the swell has small amplitude compared to wind waves (0.12 m compared to 2.24 m) and its effect is negligible. Wave loads should be considered as hydrodynamic pressures on the gate. For this purpose, calculations based on “Goda Method” are used from the design of sector gates [4]. Here are characteristics of design waves [3]:

Extreme situation:
Hs = 2.24 m
Ts = 5.00 s

Normal operation situation (Sea side):
Hs = 0.90 m
Ts = 2.60 s

Normal operation situation (Channel side):
Hs = 0.40 m
Ts = 2.00 s

For translation waves, the amplitude is 0.10 m for sea side and 0.20 m for channel side. The steepness is 0.10 m/min for both.
Waves generated locally by ship movements and leveling operations may also be included. More deliberation will be provided on the next stages of design.

- Wind

Wind load would act as a pressure on the surface of the gate. Since it is known that wind load won't be dominant, then no more data will be provided at this stage. For more information see the report “Update hydraulische ontwerpvoorwaarden ter plaatse van de Nieuwe Zeesluis te IJmuiden”.

- Water density

Water density for the North Sea and North Sea channel is different and should be noticed during calculations.

Salt water density (North Sea) =	10.22 kN/m3
Sweet water density (North Sea Channel) =	10.00 kN/m3

- Leveling

Leveling of the lock chamber, may introduce forces on the gate, however, it is decided to carry out the leveling of the lock through culverts at the sides of the lock wall rather than filling/emptying via the gate itself. It is worth mentioning that the leveling time for normal water levels is 12 minutes and for extreme water levels (maximum water level difference in operating situation) is up to 19 minutes. However, these values may be optimized in the design process.

- Acceleration (driving forces)

Acceleration forces will act on parts of the gate and are very dependent on the choice of moving mechanism.

- Friction

Friction acts mostly as a reaction (or better said as a secondary effect which gets triggered by other forces especially horizontal forces) but yet it is the most troublesome force in the design of curved rolling gate. Friction coefficient would be determined based on the choice of material.

- Ice

Ice loads can be applied as line loads. But, what is more important than the shape and magnitude of the load, is the possibility of blocking the moving path or freezing in the areas where can disturb the function of the gate. The following are the ice loads which should be applied at the most unfavorable location:

In case of salt water:	250 kN/m
In case of sweet water:	400 kN/m

Horizontal point load of 1.5 MN

- Collision

Gate has to withstand the ship collision forces to a certain level. This load case will not be treated in the report thoroughly, because the primary focus of the study is the reliability of the gate under normal situations. However, special cases like ship collision will be studied in sense of stability of the structure and availability requirements.

- Temperature

Temperature changes should be considered in design of the gate for expansion and shrinkage, especially for the moving devices and guidance facilities. In general, the gate structure should not be sensitive to temperature changes such that it gets stuck or the operation of the gate faces any difficulties. Design temperature for this project is 10 ℃.

Minimum temperature = -25 ℃

Maximum temperature = 30 ℃

- Water displacement

Effects of water displacement such as water-gate friction, extra pressures due to the trapped water in the recess.

- Currents

During the operation of the gate, there will be a transportation of the water due to possible small water level difference.

- Earthquake

Earthquake loads will not be treated in this study.

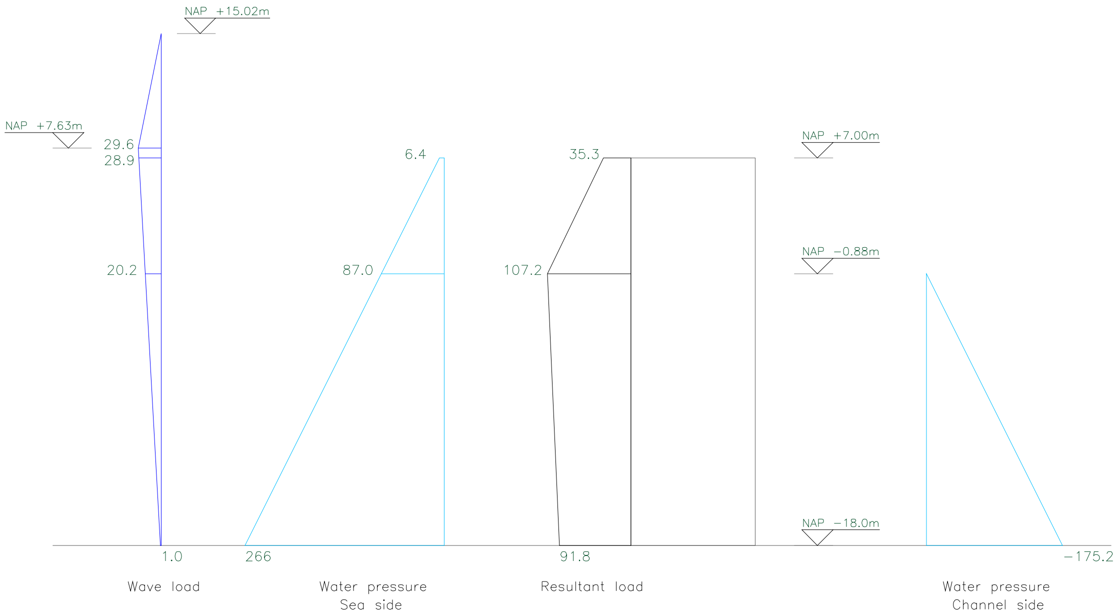


Figure A 1: Load schematization for positive head

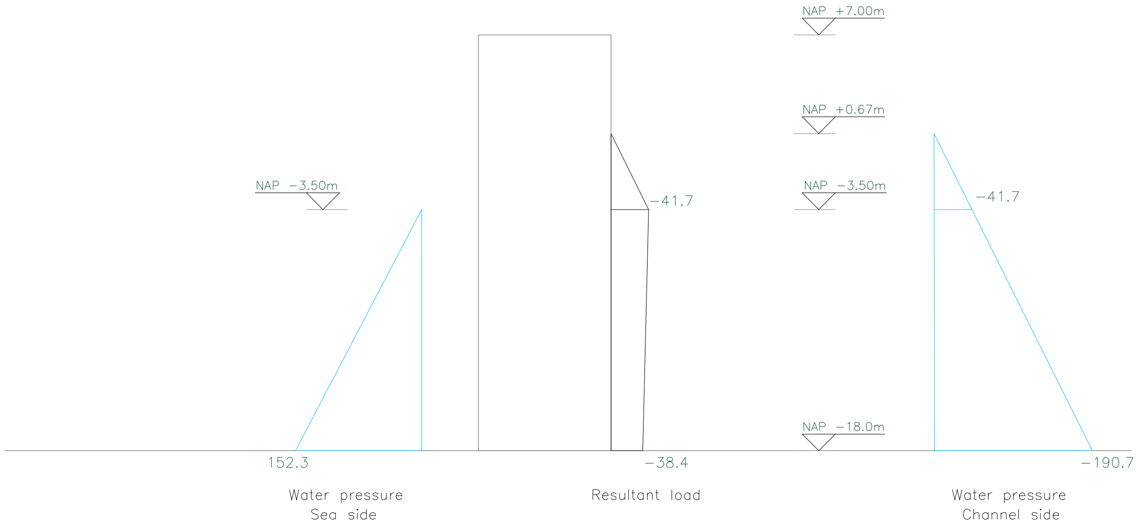


Figure A 2: Load schematization for Negative head

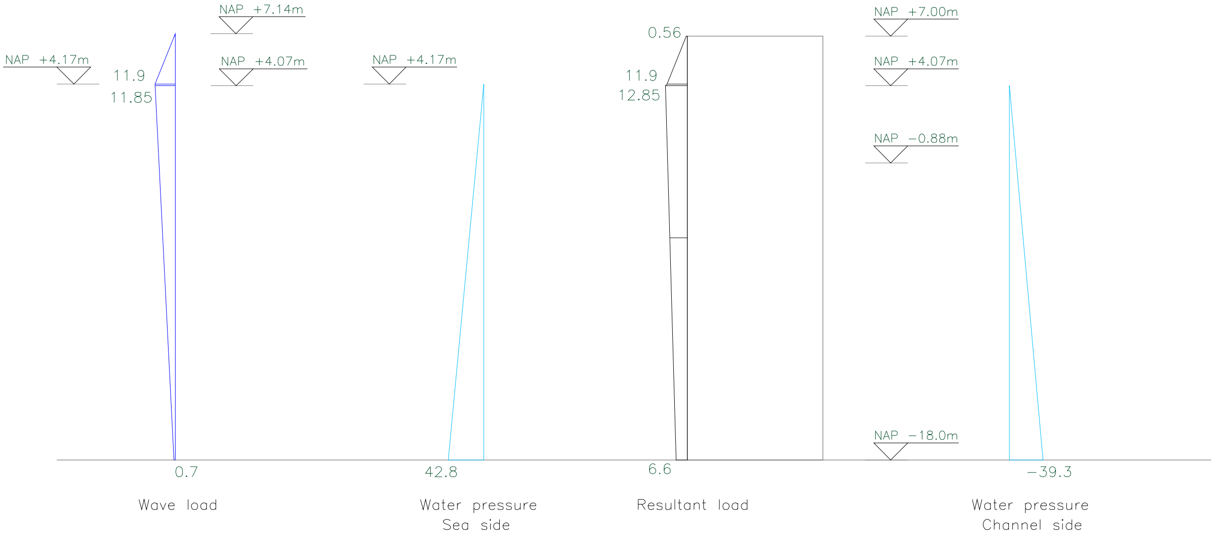


Figure A 3: Load schematization for hydraulic loads during operation

B Wave loads on hydraulic structures during operation

Wave load can be calculated by different methods such as linear wave theory, Sainflou, Rundgren, Minikin and Goda. In this part, 3 of these methods are used to calculate the wave loads in daily operations and in order to make a comparison.

Wave characteristics

These are the characteristics of the significant wave height in normal daily operations.

$H_s = 0.90m$ $\quad$ $Significant\ wave\ height$
$T_p = 2.60s$ $\quad$ $Wave\ (peak) period$
$L = 10.55m$ $\quad$ $Wave\ length\ behind\ the\ structure$
$d = 18 + 4.17 = 22.17\ m$ $\quad$ $Water\ depth$
$k = 2\pi/L = 0.596\ m^{-1}$ $\quad$ $Wave\ number$

Linear wave theory

Linear wave theory, calculates the non-breaking wave force against a vertical wall by considering the pressure distribution in a vertical, taken by the wave theory (for a single propagating wave). The wave height *H* in front of the wall is double the incoming wave height H_i, in case of total reflection.

$$H = 2H_i \qquad and\ since\ H = 2a: \qquad a = H_i = H_s$$

The maximum pressure against a wall is:

$$p = \rho g H_i \frac{\cosh(k(d+z))}{\cosh(kd)} \qquad for\ \ -d < z < 0$$
$$p = (1 - \frac{z}{H_i})\rho g H_i \qquad for\ \ 0 < z < H_i$$
$$H_i = wave\ height\ of\ an\ incoming\ wave [m]$$
$$k = the\ wave\ number\ of\ the\ incoming\ wave\ [m^{-1}]$$

Therefore the force per linear meter under the wave crest can be derived from the following integral:

$$F_c = \int_{-d}^{0} \rho g H_i \frac{\cosh(k(d+z))}{\cosh(kd)} dz + \int_{0}^{H_i} \rho g H_i \left(1 - \frac{z}{H_i}\right) dz = \rho g H_i \left(\frac{(\exp(kd) - \exp(-kd))}{2k\cosh(kd)} + \frac{H_i}{2}\right)$$
$$\Rightarrow F_c = 1022 \times 9.82 \times 0.90 \left(\frac{(\exp(0.596 \times 22.17) - \exp(-0.596 \times 22.17))}{2 \times 0.596 \times \cosh(0.596 \times 22.17)} + \frac{0.90}{2}\right)$$
$$= 19230N = 19\ kN$$

The wave pressure distribution under the wave crest will be according to Figure A 4:

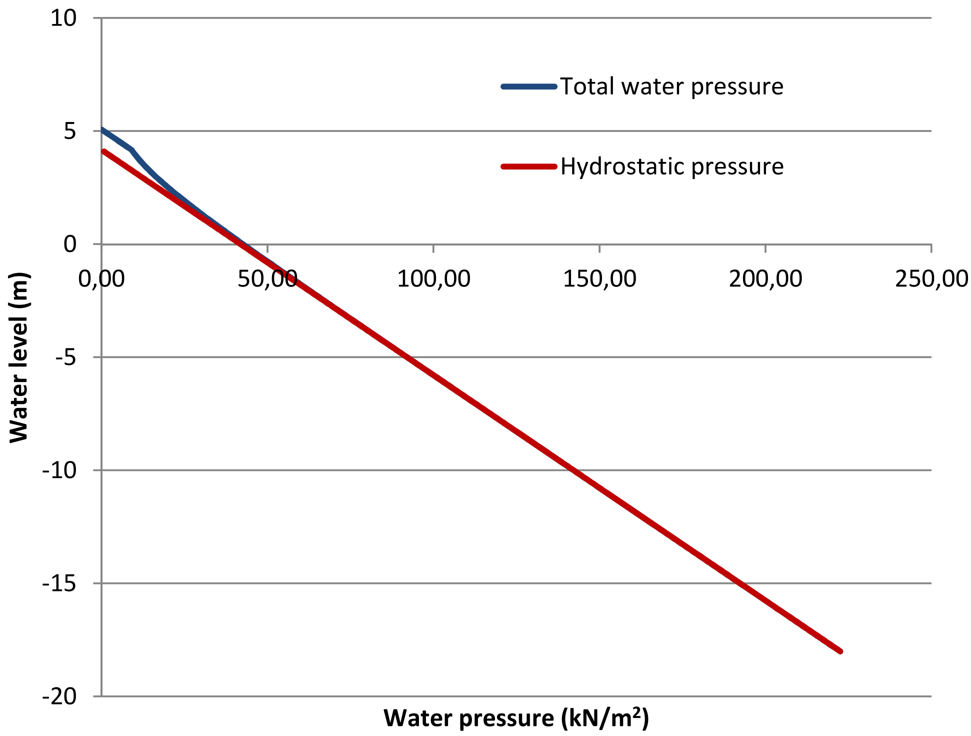


Figure A 4: Water pressure distribution under wave crest (linear wave theory). Notice that this figure shows wave pressure distribution against the actual levels, while in the linear wave formula, "0" means the water surface elevation

force per linear meter under the wave trough can be derived from the following integral:

$$F_t = \int_{-d}^{-H_i} \rho g H_i \frac{\cosh\big(k(d+z)\big)}{\cosh(kd)} dz + \int_{-H_i}^{0} \rho g H_i \left(1 - \frac{z}{H_i}\right) dz$$

$$= \rho g H_i \left(\frac{(\exp(k(d - H_i)) - \exp(-k(d - H_i)))}{2k \cosh(kd)} - \frac{H_i}{2}\right)$$

$$\Rightarrow F_t = 1022 \times 9.82 \times -0.90 \left(\frac{(\exp(0.596 \times 21.27) - \exp(-0.596 \times 21.27))}{2 \times 0.596 \times \cosh(0.596 \times 22.17)} + \frac{0.90}{2}\right)$$

$$= -12940N = -13\ kN$$

The wave pressure distribution under the wave trough will be according to Figure A 5:

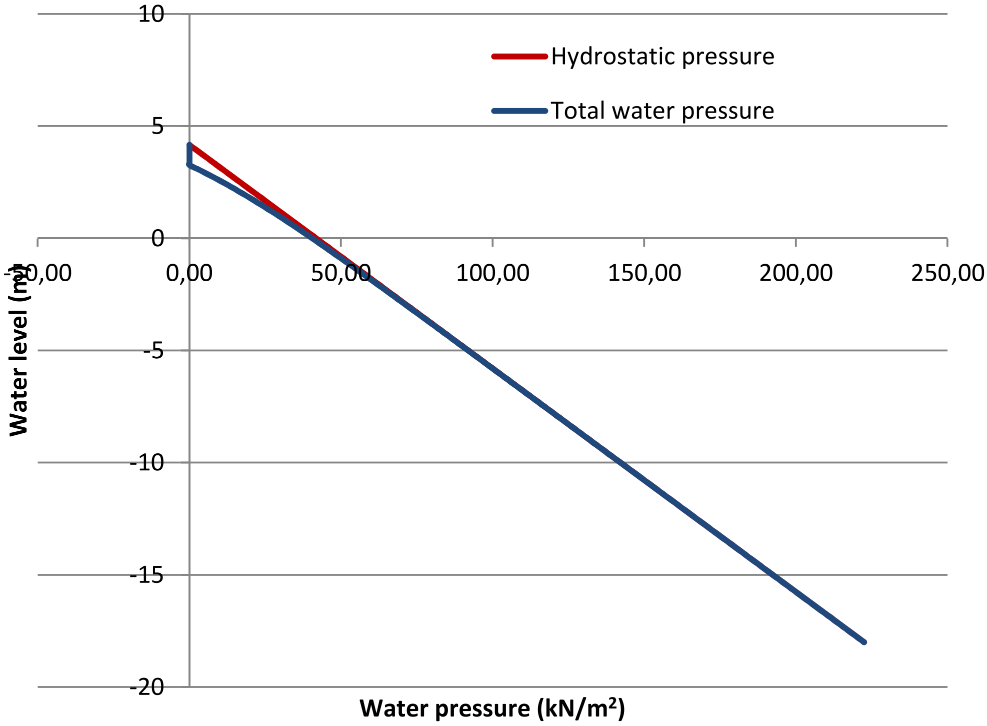


Figure A 5: Water pressure distribution under wave trough (linear wave theory). Notice that this figure shows wave pressure distribution against the actual levels, while in the linear wave formula, "0" means the water surface elevation

As it can be seen, the negative wave pressure under the trough has a lower magnitude than the positive wave pressure under the crest. This fact becomes important because, due to the curved shape of the gate, waves do not hit the skin plate at the same phase. Therefore, the wave pressure is estimated as below:

$$p_{wave} = \begin{cases} 19\sin(\omega t - kx) & sin(\omega t - kx) > 0 \\ 13\sin(\omega t - kx) & sin(\omega t - kx) < 0 \end{cases}$$

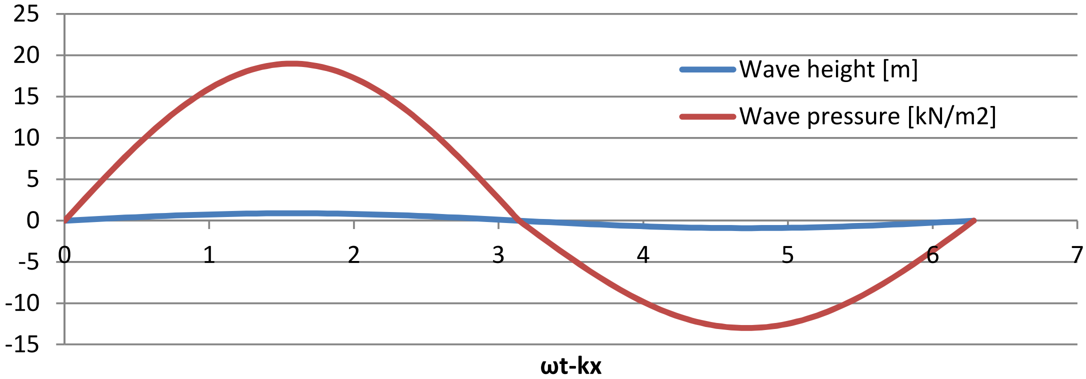


Figure A 6: Wave pressure against wave propagation (linear wave theory)

Sainflou

Sainflou's method gives a rather simple approximation of the total force on the wall. This approach is based on Stokes' second order wave theory, the waves have the shape of a trochoid and complete reflection is considered. A mean water level increase of h_0 is taken into account.

$$h_0 = \frac{1}{2} k H_i^2 \coth(kd) = \frac{1}{2} \times 0.596 \times 0.9^2 \coth(0.596 \times 22.17) = 0.24m$$

In this case, the maximum pressures under crest at middle water level and near the bed are as below:

$$p_1 = \rho g H_i = 9.0\ kN/m^2$$

$$p_0 = \frac{\rho g H_i}{\cosh(kd)} = 0.033\ kN/m^2$$

The pressure between p_0 and p_1 is assumed to be linear. Therefore Sainflou leads to an overestimation of the load for steep waves.

The force per linear meter under the wave crest can be calculated from the following expression:

$$F_c = \frac{1}{2} \times (p_0 + p_1) \times \left(d + \frac{h_0}{2}\right) + \frac{1}{2} \times p_1 \times \left(\frac{h_0}{2} + H_i\right) = 105\ \mathrm{kN/m}$$

The wave pressure distribution under the wave crest will be according to Figure A 7:

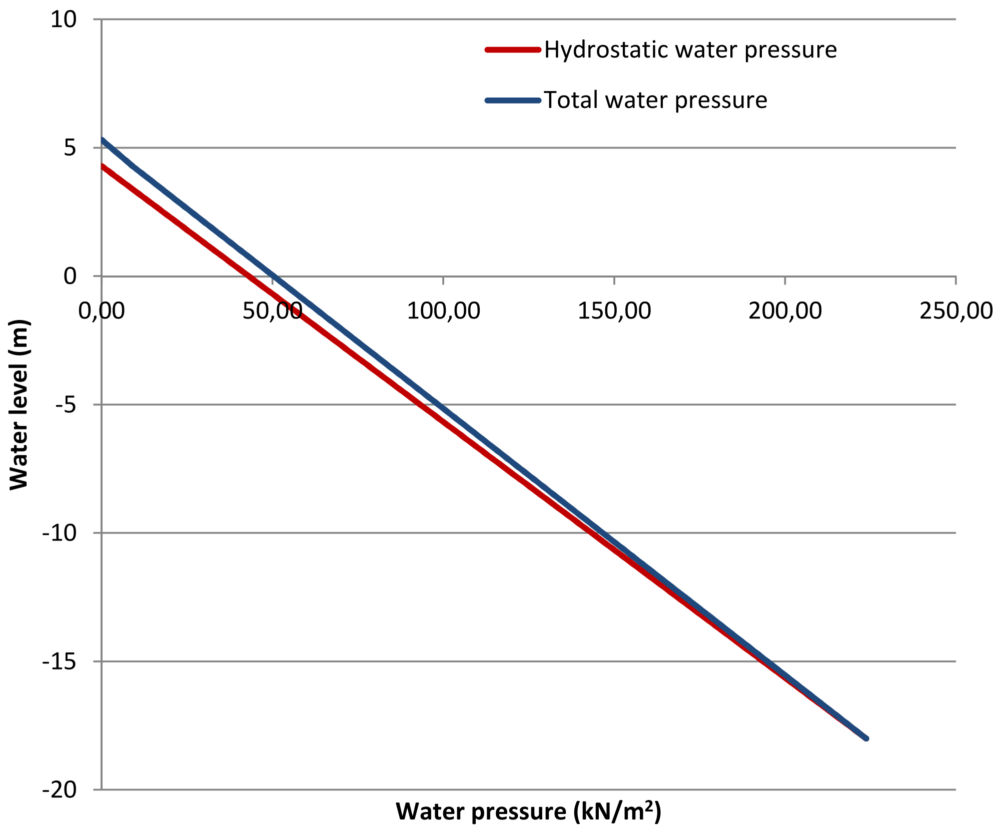


Figure A 7: Water pressure distribution under wave crest (Sainflou)

Wave pressures under trough at level "0 - H_i + h_0" and near the bed are as below:

$$p_1 = -\rho g(H_i - h_0) = -6.6\ kN/m^2$$
$$p_0 = \frac{-\rho g H_i}{\cosh(kd)} = -0.033\ kN/m^2$$

The force per linear meter under the wave trough can be calculated from the following expression:

$$F_t = \frac{1}{2} \times (p_0 + p_1) \times (d + h_0 - H_i) + \frac{1}{2} \times p_1 \times (H_i - h_0) = -73\ \mathrm{kN/m}$$

The wave pressure distribution under the wave crest will be according to Figure A 8:

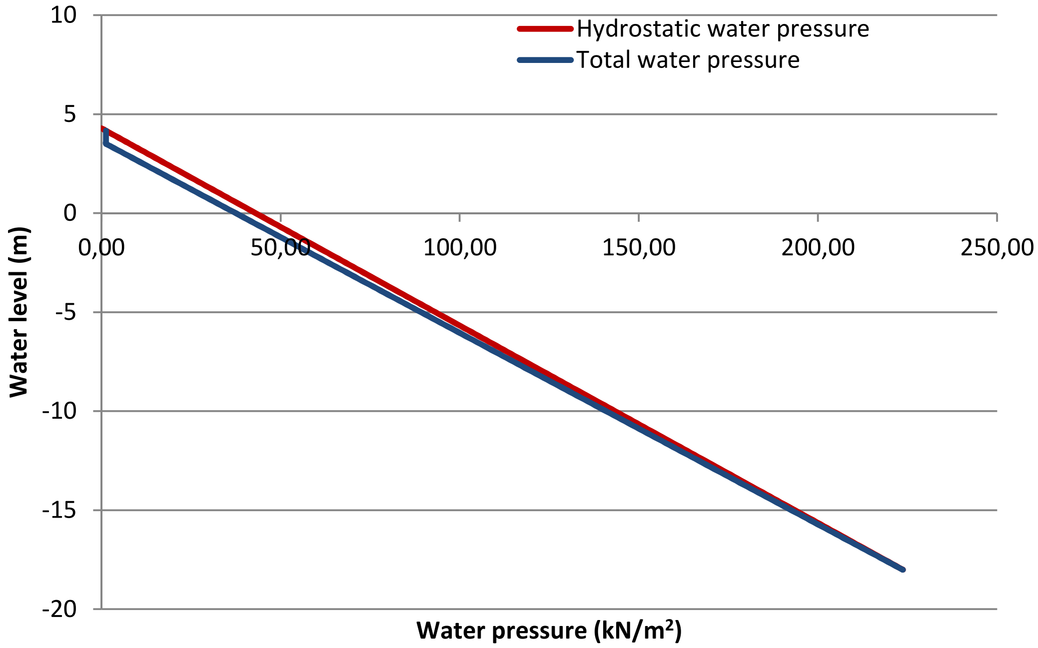


Figure A 8: Water pressure distribution under wave trough (Sainflou)

As stated in the previous method, the wave pressure on the gate, versus its propagation phase can be described as below:

$$p_{wave} = \begin{cases} 105\sin(\omega t - kx) & sin(\omega t - kx) > 0 \\ 73\sin(\omega t - kx) & sin(\omega t - kx) < 0 \end{cases}$$

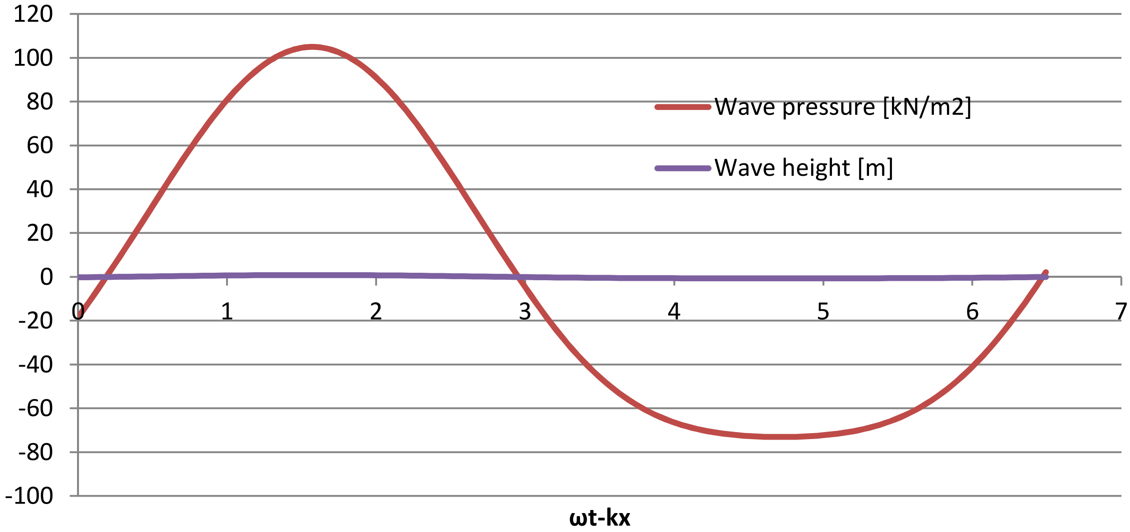


Figure A 9: Wave pressure against wave propagation (Sainflou)

Goda

Goda method, gives a general expression for the wave pressure on a caisson on a rock-fill sill. It assumes a maximum wave pressure at the SWL that decreases linearly above and below the SWL. Wave pressure vanishes at the top of the wave run-up η*. This expression has been also used for broken and breaking waves, but mostly, Goda's equations are used often for the design of vertical breakwaters. These equations don't have an analytical base but rather an empirical foundation.

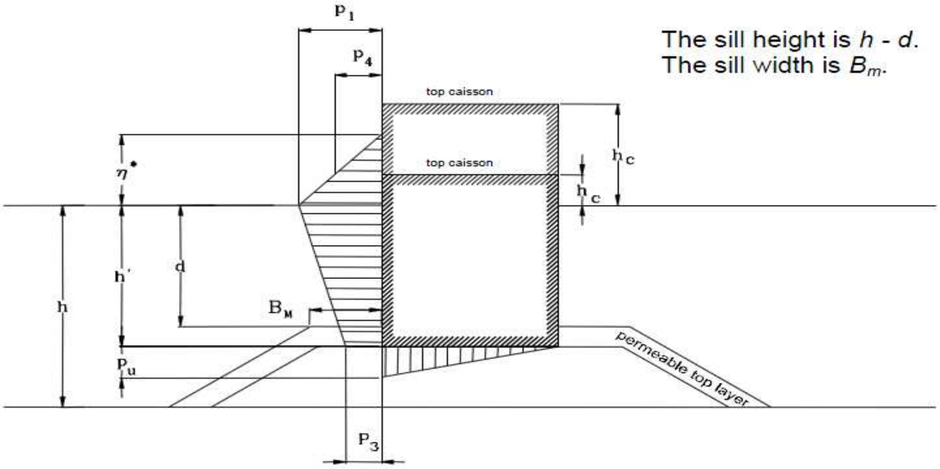


Figure A 10: Wave pressure distribution (Goda method)

The maximum wave pressures are:

$$p_1 = 0.5(1+\cos(\beta))(\lambda_1\alpha_1 + \lambda_2\alpha_2\cos^2(\beta))\rho g H_D$$
$$p_3 = \alpha_3 p_1$$
$$p_4 = \alpha_4 p_1$$
$$p_u = 0.5(1+\cos(\beta))\lambda_3\alpha_1\alpha_3\rho g H_D$$

$$\beta = The\ angle\ of\ the\ incoming\ wave$$
$$\eta^* = 0.75(1+\cos(\beta))\lambda_1 H_D$$
$$\alpha_1 = 0.6 + 0.5\left(\frac{4\pi h/L_D}{\sinh(4\pi h/L_D)}\right)^2$$
$$\alpha_2 = \min\left(\frac{(1-d/h_b)\,(H_D/d)^2}{3}, \frac{2d}{H_D}\right)$$
$$\alpha_3 = 1-(h'/h)\left(1-\frac{1}{\cosh(2\pi h/L_D)}\right)$$
$$\alpha_4 = 1-\frac{h^*{}_c}{\eta^*}$$
$$h^*{}_c = \min(\eta^*, h_c)$$

g =	9,82
β =	0
h =	22,17
h' =	22,17
d =	22,17
h_c =	2,83
H_s =	0,9
H_D =	1,98
T =	2,6
L_D =	10,6
η* =	2,97
α_1 =	0,60
α_2 =	0,00
α_3 =	0,00
α_4 =	0,05

p_1 =	11.92	KN/m^2
p_3 =	0.56	KN/m^2

The maximum force per linear meter can be calculated from the following expression:

$$F_c = \frac{1}{2} \times p_1 \times \eta^* + \frac{1}{2} \times (p_1 + p_3) \times h' = 156 \text{ kN/m}$$

The maximum wave pressure distribution will be according to Figure A 11:

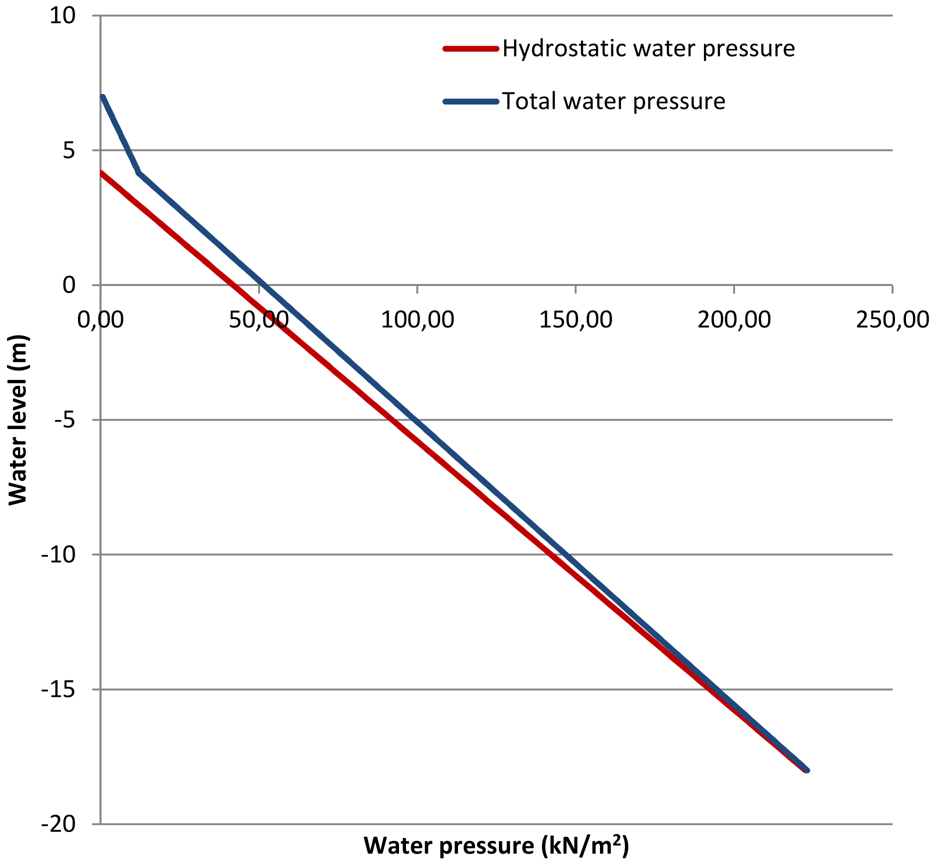


Figure A 11: Maximum water pressure distribution (Goda)

Notice that the Goda method does not provide a pattern for wave distribution under the trough or crest, but it suggests the maximum wave pressure for breaking waves; and since this method is not based solely on theory, prediction of wave pressure distribution against the wave propagation is not possible.

Comparison

As it can be seen, in the calculation of forces by different methods, different results are achieved. The maximum wave pressure from each method at the position of crest and trough is shown in Table A 1.

Method	Wave force under crest [kN/m]	Wave force under trough [kN/m]
Linear wave theory	19	-13
Sainflou	105	-73
Goda	Maximum wave force = 156 [kN/m]	

Table A 1: Wave pressure calculation results for different methods

As it can be seen, there is a considerable difference between the linear wave theory and Sainflou or Goda method. The difference results from the pressure distribution prediction of these methods. In linear wave theory, wave pressure decreases exponentially for a single wave. Due to this fact, wave pressure reaches zero very quickly (approximately 5 meters in this case) based on linear wave theory; while in Sainflou and Goda methods, the wave pressure never become as close to zero.

Considering the wave propagation phase in the calculations

As stated before, a single wave will not hit the curved gate all at the same phase. This means that, when the wave crest is hitting the gate at position 1, the gate is being hit by wave trough at position 2 (Figure A 12).

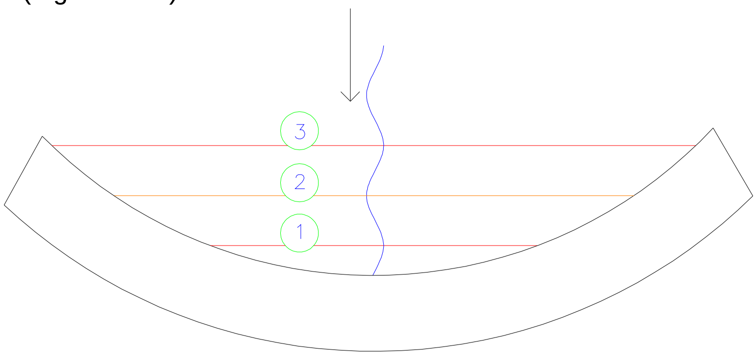


Figure A 12: Single wave hitting the gate at different phases

Since the wave pressure is varying depending on which phase the wave is in, knowing the exact phase of the wave at each point of the gate is important when considering one single wave. In that case:

$$y = \sqrt{49^2 - x^2} \qquad ; \qquad -34 < x < 34$$

$$p_{wave\ on\ gate} = \hat{p}_{wave} \sin(\omega t - ky)$$

According to linear wave theory: $\hat{p}_{wave} = \begin{cases} 19 & sin(\omega t - ky) > 0 \\ 13 & sin(\omega t - ky) < 0 \end{cases}$

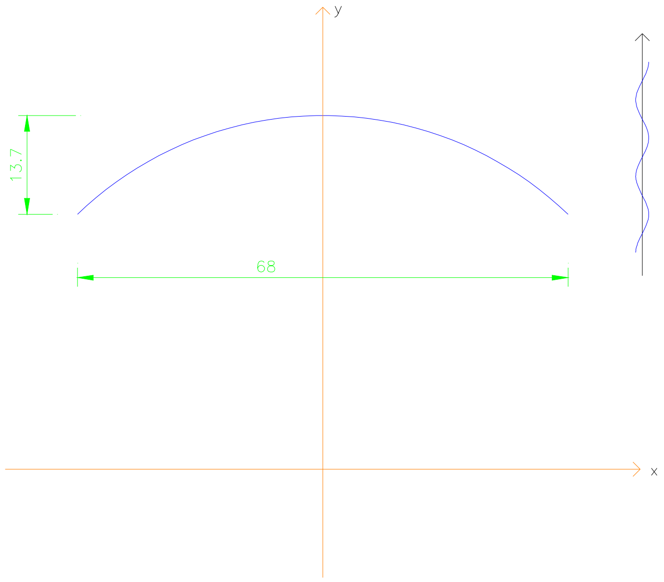


Figure A 13: Considering the curved gate in a Cartesian coordinate for wave propagation calculations

Since the maximum wave force on the gate is desired to be calculated, exact time of that maximum happening is not relevant. Therefore, instead of ωt, an initial phase of φ_0 will be considered in the calculations and it will be chosen so that the wave force becomes maximum.

$$p_{wave} = \begin{cases} 19\sin(\varphi_0 - k\sqrt{49^2 - x^2}) & sin\left(\varphi_0 - k\sqrt{49^2 - x^2}\right) > 0 \\ 13\sin(\varphi_0 - k\sqrt{49^2 - x^2}) & sin\left(\varphi_0 - k\sqrt{49^2 - x^2}\right) < 0 \end{cases}$$

Total force will be:

$$F_{wave\ on\ gate} = \int_{-34}^{+34} p_{wave} dx$$

For a certain value of φ_0 this integral becomes maximum. In this stage of design, the value of φ_0 will be chosen by iteration. To improve the iteration, we look for a value that results in containing two crests in the distance within the hollow side of the gate. Figure A 14 shows the wave pressure distribution on the gate for $\varphi_0 = -1.16$ which results in the maximum wave force on the gate.

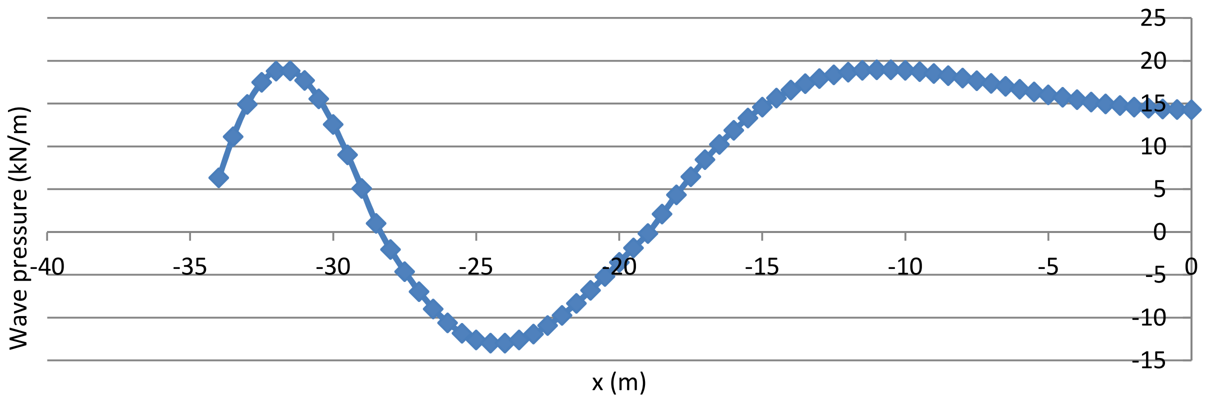


Figure A 14: Wave pressure distribution on the gate along X-direction

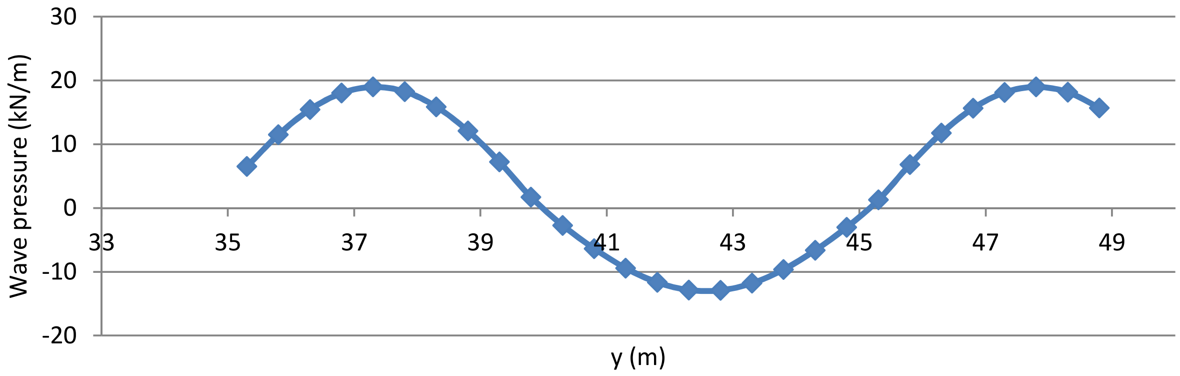


Figure A 15: Wave pressure distribution on the gate along Y-direction

$$\varphi_0 = -1.16 \quad \Rightarrow \quad F_{wave\ on\ gate} = \int_{-34}^{+34} p_{wave} dx = 562\ kN$$

For the sake of comparison, if we assume that the gate will be hit by the wave crest at all points, total force on the gate will be $19 \times 68 = 1292\ kN$ which is 2.3 times the calculated value considering the phase of the wave when hitting the curved surface of the gate.

Final Conclusion

In reality, a number of waves will hit the gate at the same time instead of one harmonic wave. Now, if we look at the Figure A 15 which depicts 3 harmonic waves with different angles, it can be seen that the gate will be hit at several points by wave crest. We know that waves in channel can have any angle between the angle of these three waves. Therefore, gate can be hit at any point by wave crest at the same time. In that case the maximum possible force could be 1292 kN; considering the situation where all the harmonic waves in the spectrum with the wave height of 0.90 m will hit the gate at the same time by their maximum force.

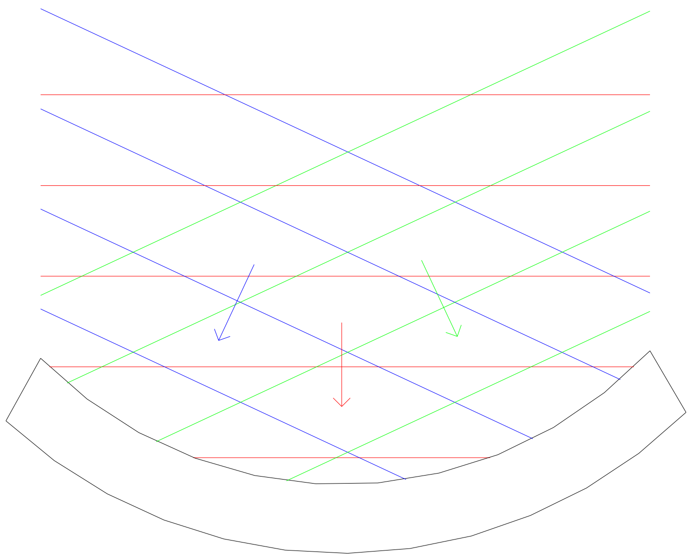


Figure A 16: propagation of 3 harmonic waves in front of the gate (lines represent the position of the crest)

Recommendation on using the methods

In order to answer the main question (applying the proper method with proper safety factors), we should first look at the assumptions and boundaries of the methods.
Linear wave theory describes the wave pressure for a single harmonic wave (here calculated with full reflection); While Sainflou describes the pressure for a single trochoidal wave with complete reflection. On the other hand, Goda method calculates the wave load for breaking waves with a certain run-up and specifically for caissons.
Calculations has been done for the operational condition waves on the gate at early stages of opening, and the waves in that stage have a much narrower spectrum than the extreme wave condition. Therefore assuming a single wave with the height equal to the significant wave height is close to reality and by considering the complete reflection, the assumption is conservative. However, the results in terms of wave forces are very low compared to the other methods. Therefore the applicability of the method should be questioned.

To apply the linear wave theory one should consider a few important aspects. The linear wave theory is based on a single regular wave with a sinusoidal shape, which only occurs in certain conditions. For example, one should take into account the wave steepness and the relative depth. The wave steepness is a translation of the shape of the wave and an important criterion is attached to the linear wave theory. The wave steepness (H/L) should be smaller than 1/40 to apply the linear theory. Mostly short waves in front of the coast are (for example due to shoaling) not sinusoidal anymore, but rather trochoidal.

Figure A 17 shows the validity of different wave theories. In the figure it is shown that according to the wave steepness the linear wave theory cannot be applied in this situation (in order to get accurate results). Furthermore, the figure shows that in this situation one can consider deep water conditions and non-breaking waves. Therefore for the accuracy of the final results the method of Sainflou will be used which is meant for trochoidal waves.

$$Wave\ steepness: \frac{H}{L} = \frac{0.90}{10.55} = 0.09 \Rightarrow \quad \frac{1}{11.7} \quad > \frac{1}{40} \longrightarrow Trochoidal\ wave$$

$$Relative\ depth: \frac{h}{L} = \frac{22.17}{10.55} = 2.10 \frac{\Rightarrow h}{L} \gg \frac{1}{2} \quad \longrightarrow Relatively\ deep\ water$$

$$\frac{h}{g.T^2} = \frac{22.17}{9.81 * 2.60^2} = 0.33$$

$$\frac{H}{g.T^2} = \frac{0.90}{9.81 * 2.60^2} = 0.014$$

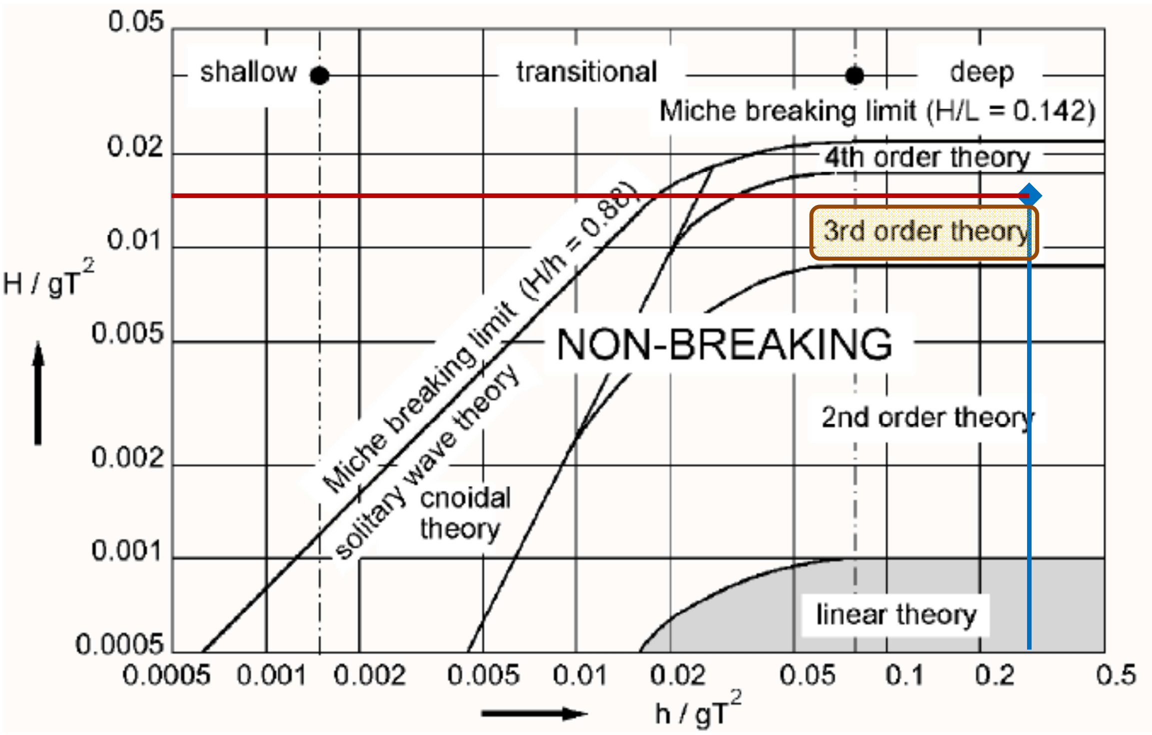


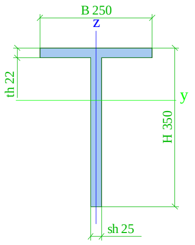
Figure A 17: Validity of wave theories (Le Méhauté, 1976 / Introduction to bed, bank and shoreline protection) (1)

C Model description and Outputs

1. Cross-sections

Name	Ver. F. Mid.	
Type	T g	
Detailed	350; 250; 22; 25	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

2.



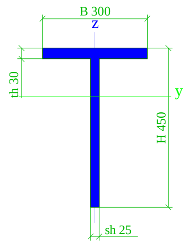
3.

A [m_2]	1,3700e-02	
A y, z [m_2]	1,3700e-02	1,3700e-02
I y, z [m_4]	1,7455e-04	2,9073e-05
I w [m_6], t [m_4]	0,0000e+00	4,9768e-06
Wel y, z [m_3]	7,4514e-04	2,3258e-04
Wpl y, z [m_3]	1,3335e-03	3,9500e-04
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	13	234
alpha [deg]	0,00	
AL [m_2/m]	1,2000e+00	

4.

Name	Ver. F. End	
Type	T g	
Detailed	450; 300; 30; 25	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

5.



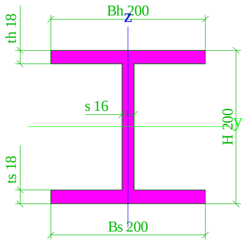
6.

A [m2]	1,9500e-02	
A y, z [m2]	1,9500e-02	1,9500e-02
I y, z [m4]	4,0036e-04	6,8047e-05
I w [m6], t [m4]	0,0000e+00	8,9011e-06
Wel y, z [m3]	1,2757e-03	4,5365e-04
Wpl y, z [m3]	2,3031e-03	7,4063e-04
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	13	314
alpha [deg]	0,00	
AL [m2/m]	1,5000e+00	

7.

Name	Lat. Br.	
Type	I ng	
Detailed	200; 200; 200; 18; 18; 16	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

8.



9.

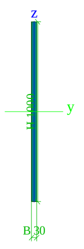
A [m2]	9,8240e-03	
A y, z [m2]	9,8240e-03	9,8240e-03
I y, z [m4]	6,5699e-05	2,4056e-05
I w [m6], t [m4]	0,0000e+00	3,3282e-06
Wel y, z [m3]	6,5699e-04	2,4056e-04
Wpl y, z [m3]	7,6278e-04	3,7050e-04

d y, z [mm]	0	0
c YLCS, ZLCS [mm]	100	100
alpha [deg]	0,00	
AL [m_2/m]	1,1680e+00	

10.

Name	End. P.	
Type	Rectangle	
Detailed	1000; 30	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

11.



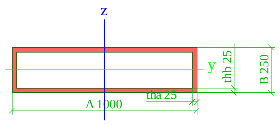
12.

A [m_2]	3,0000e-02	
A y, z [m_2]	2,5000e-02	2,5000e-02
I y, z [m_4]	2,5000e-03	2,2500e-06
I w [m_6], t [m_4]	0,0000e+00	8,4455e-06
Wel y, z [m_3]	5,0000e-03	1,5000e-04
Wpl y, z [m_3]	7,5000e-03	2,2500e-04
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	15	500
alpha [deg]	0,00	
AL [m_2/m]	2,0600e+00	

13.

Name	Sup. Beam	
Type	O	
Detailed	1000; 25; 250; 25	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

14.



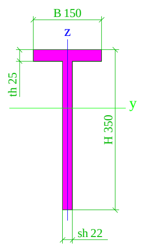
15.

A [m_2]	6,0000e-02	
A y, z [m_2]	4,8000e-02	1,2000e-02
I y, z [m_4]	6,6875e-04	6,5437e-03
I w [m_6], t [m_4]	0,0000e+00	1,9250e-03
Wel y, z [m_3]	5,3500e-03	1,3087e-02
Wpl y, z [m_3]	6,1250e-03	1,7375e-02
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	-475	100
alpha [deg]	0,00	
AL [m_2/m]	2,5000e+00	

16.

Name	Stiffenner 2	
Type	T g	
Detailed	350; 150; 25; 22	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

17.



18.

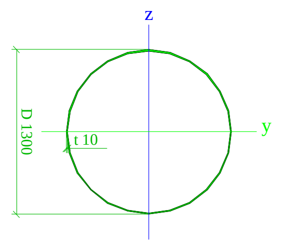
A [m_2]	1,0900e-02	
A y, z [m_2]	1,0900e-02	1,0900e-02
I y, z [m_4]	1,3846e-04	7,3196e-06
I w [m_6], t [m_4]	0,0000e+00	2,5451e-06
Wel y, z [m_3]	6,2173e-04	9,7595e-05
Wpl y, z [m_3]	1,0792e-03	1,7995e-04
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	11	223
alpha [deg]	0,00	

AL [m_2/m]	1,0000e+00	

19.

Name	Hydro- COL	
Type	Tube	
Detailed	1300; 10	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

20.



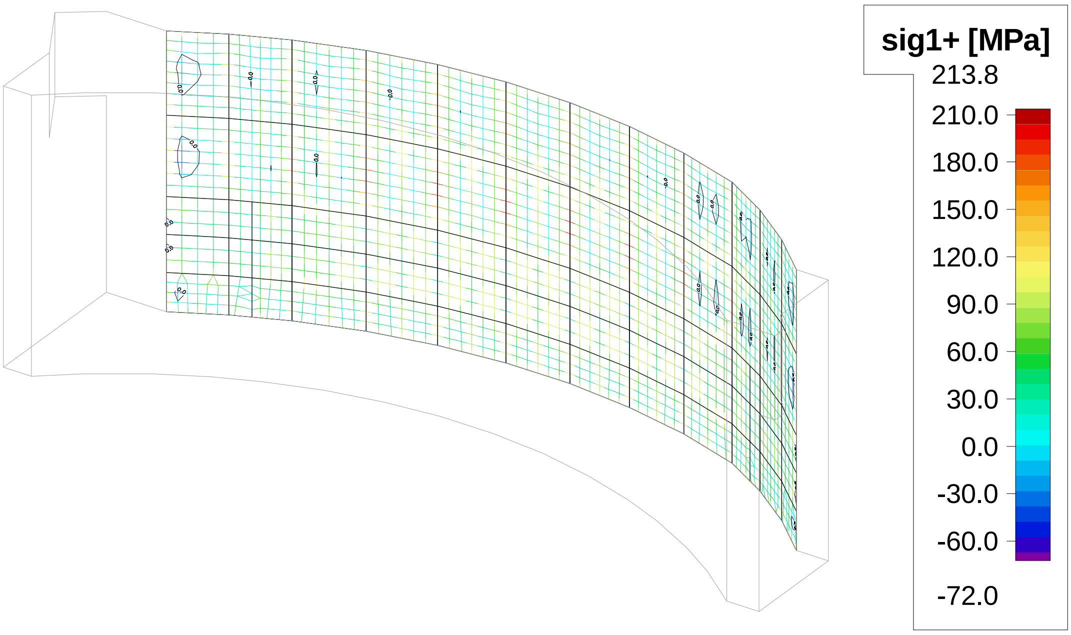
21.

A [m_2]	4,0518e-02	
A y, z [m_2]	2,5795e-02	2,5795e-02
I y, z [m_4]	8,4271e-03	8,4271e-03
I w [m_6], t [m_4]	0,0000e+00	1,6860e-02
Wel y, z [m_3]	1,2965e-02	1,2965e-02
Wpl y, z [m_3]	1,6636e-02	1,6636e-02
d y, z [mm]	0	0
c YLCS, ZLCS [mm]	0	0
alpha [deg]	0,00	
AL [m_2/m]	4,0839e+00	

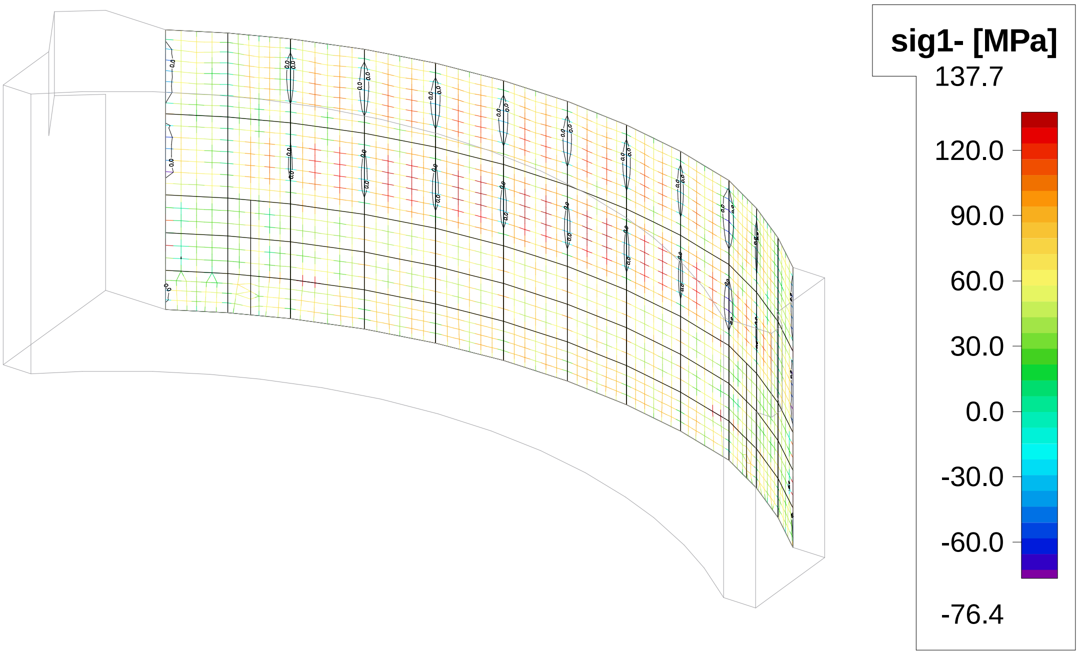
22.

Name	Guide1	
Type	Circle	
Detailed	1000	
Item material	S355	
Fabrication	general	
Buckling y-y, z-z	b	b
FEM analysis	×	

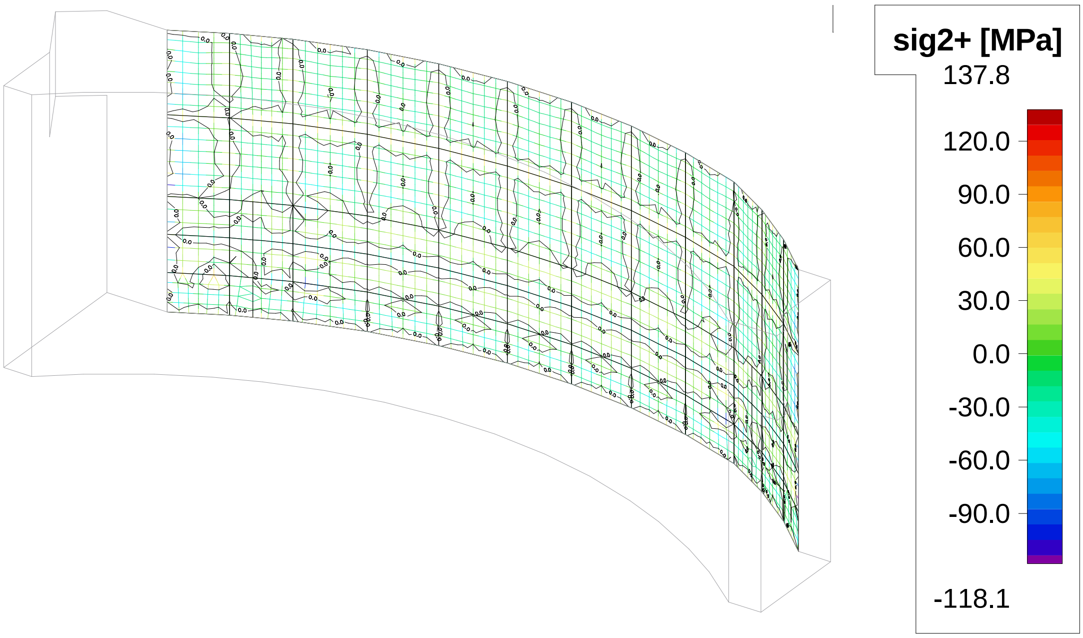
2. Stresses and internal forces in ULS for Positive head (Governing load combination for design)



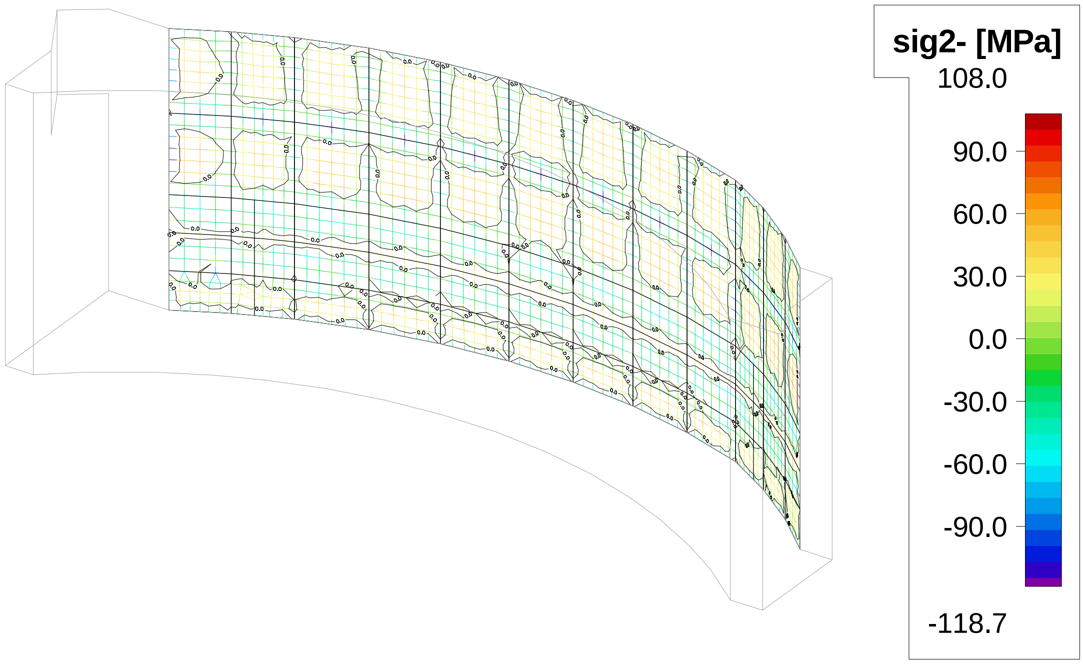
1. Skin plates at convex side - Stresses; sig1+



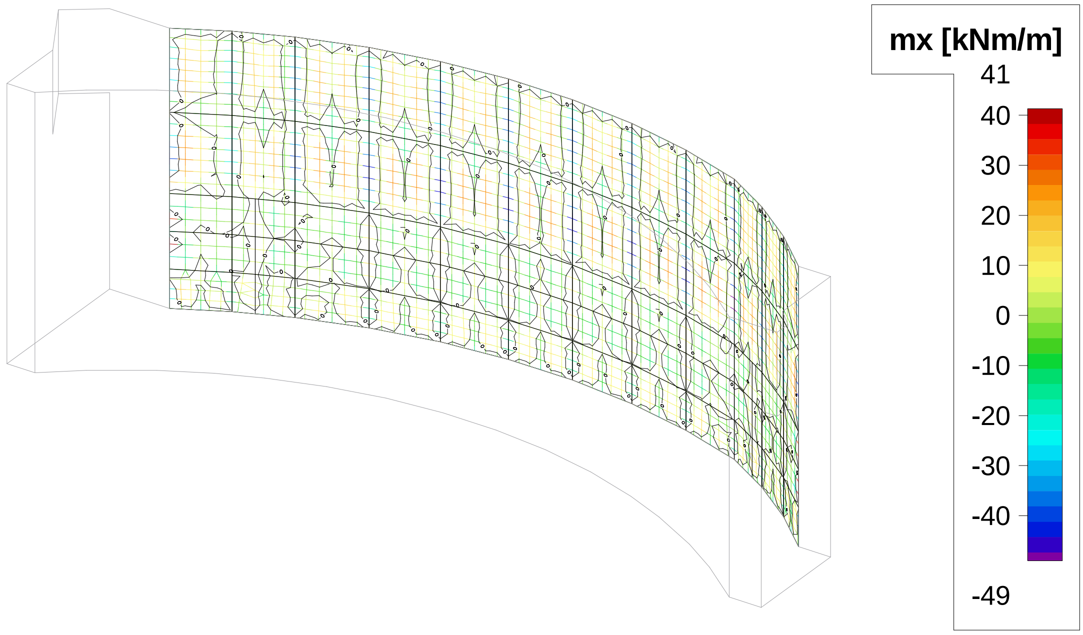
2. Skin plates at convex side - Stresses; sig1-



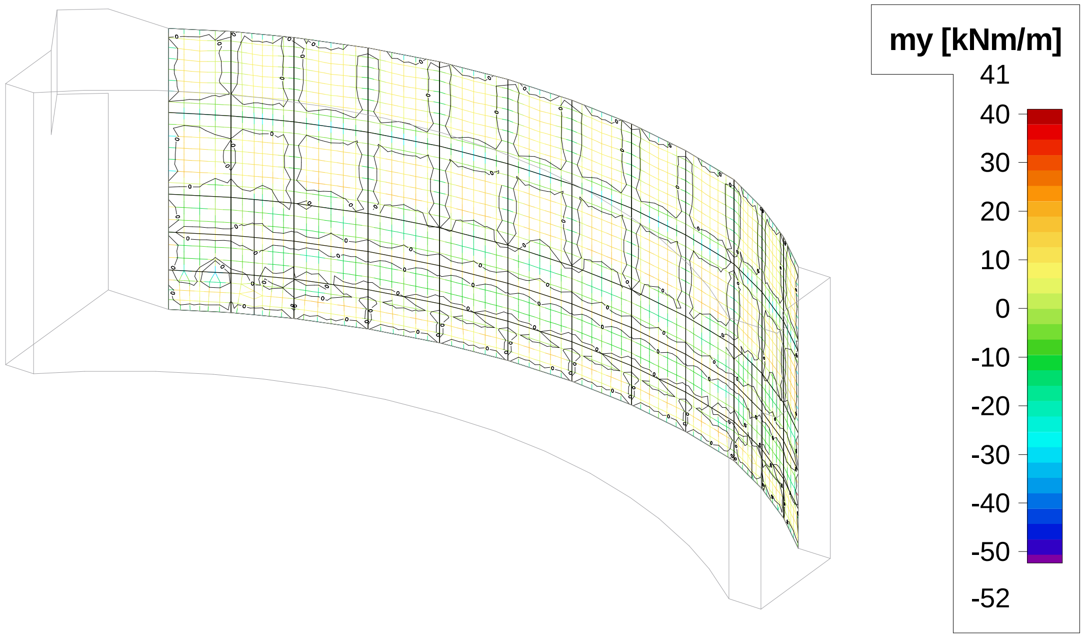
3. Skin plates at convex side - Stresses; sig2+



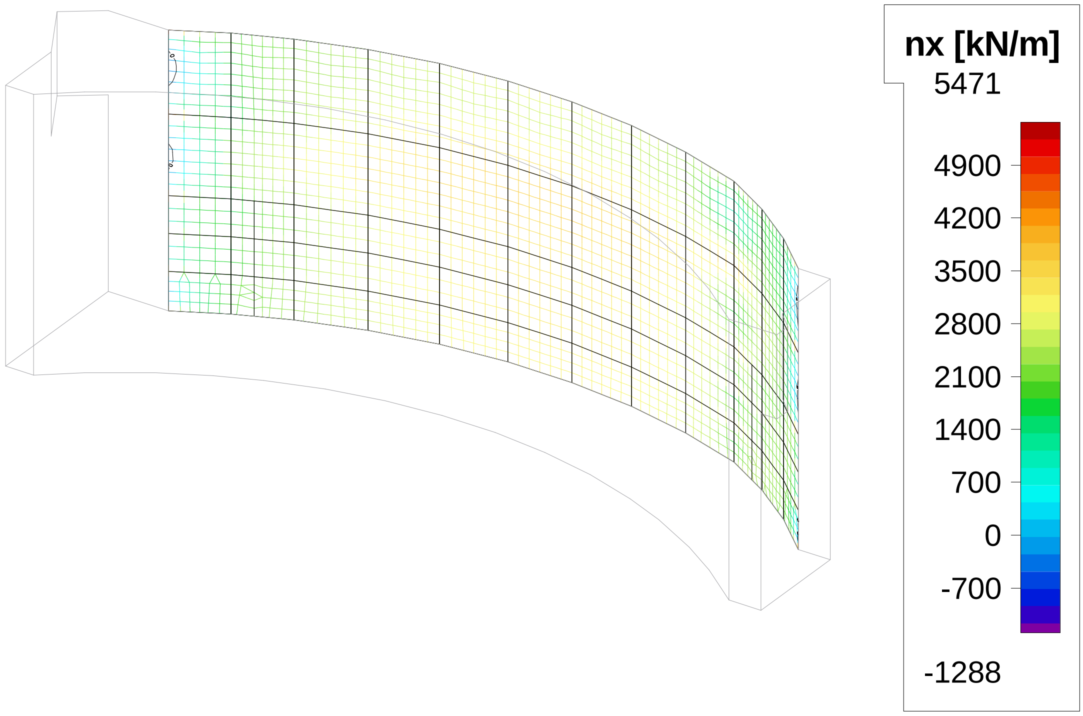
4. Skin plates at convex side - Stresses; sig2-



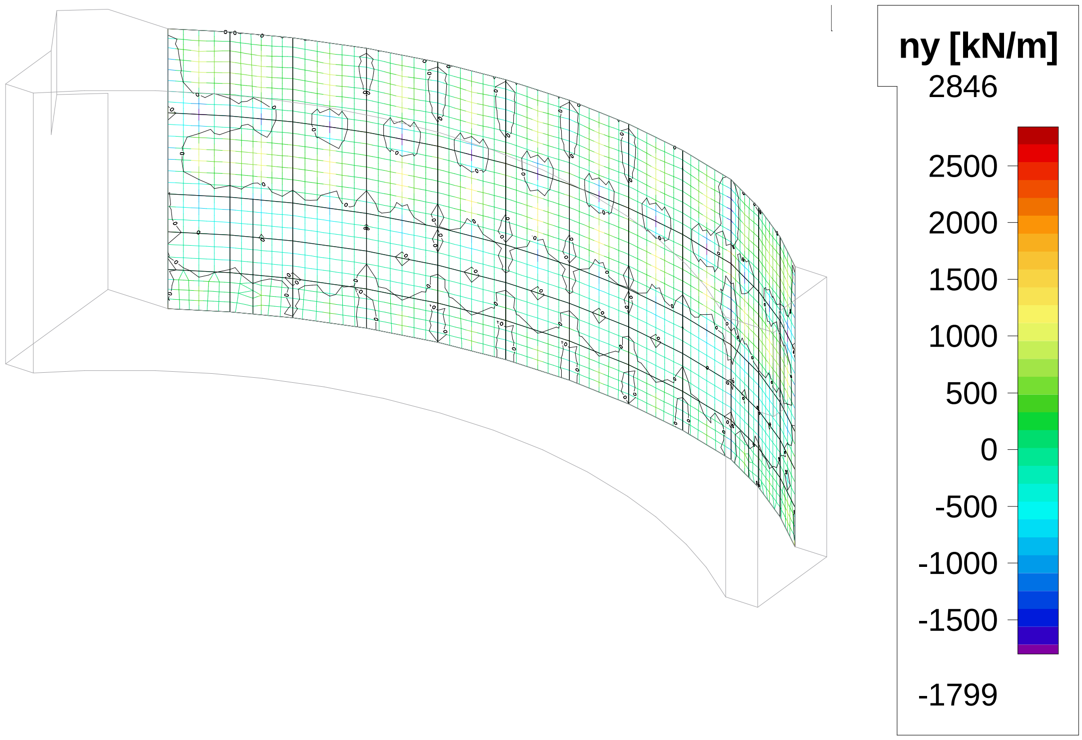
5. Skin plates at convex side - Internal forces; mx



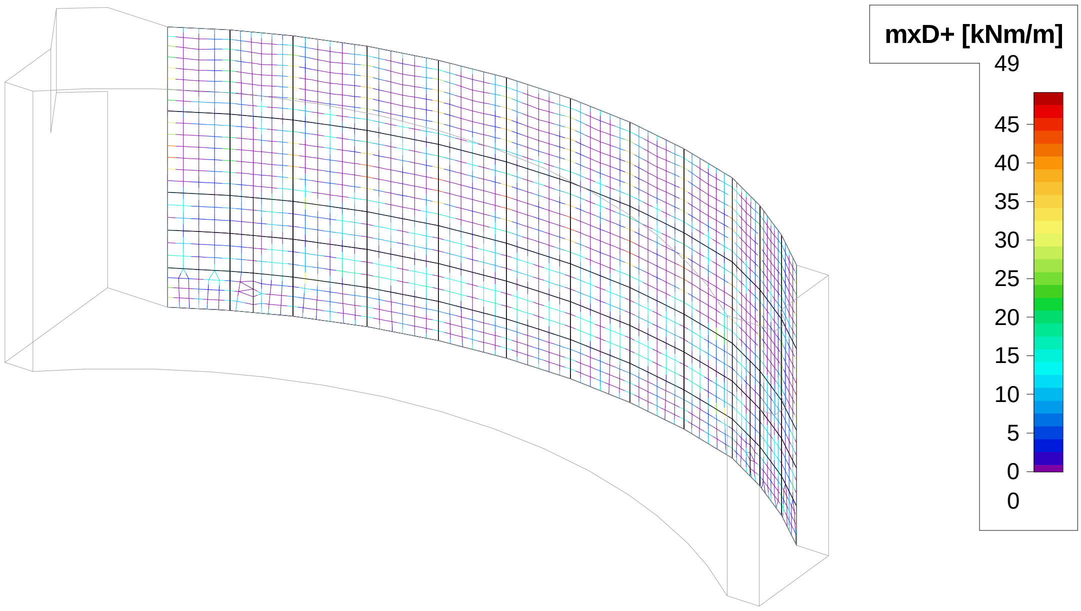
6. Skin plates at convex side - Internal forces; my



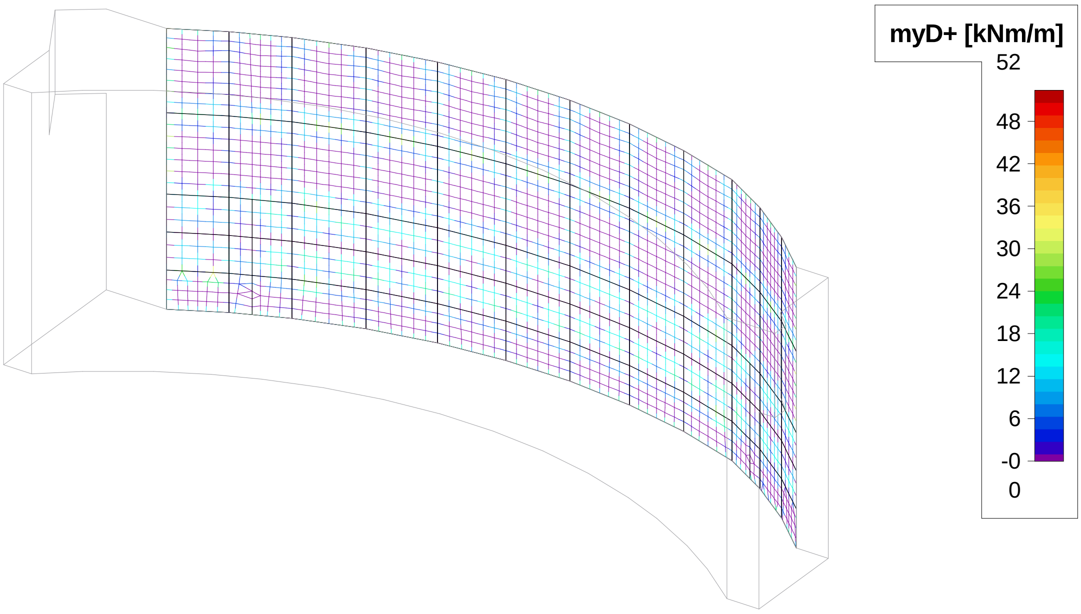
7. Skin plates at convex side - Internal forces; nx



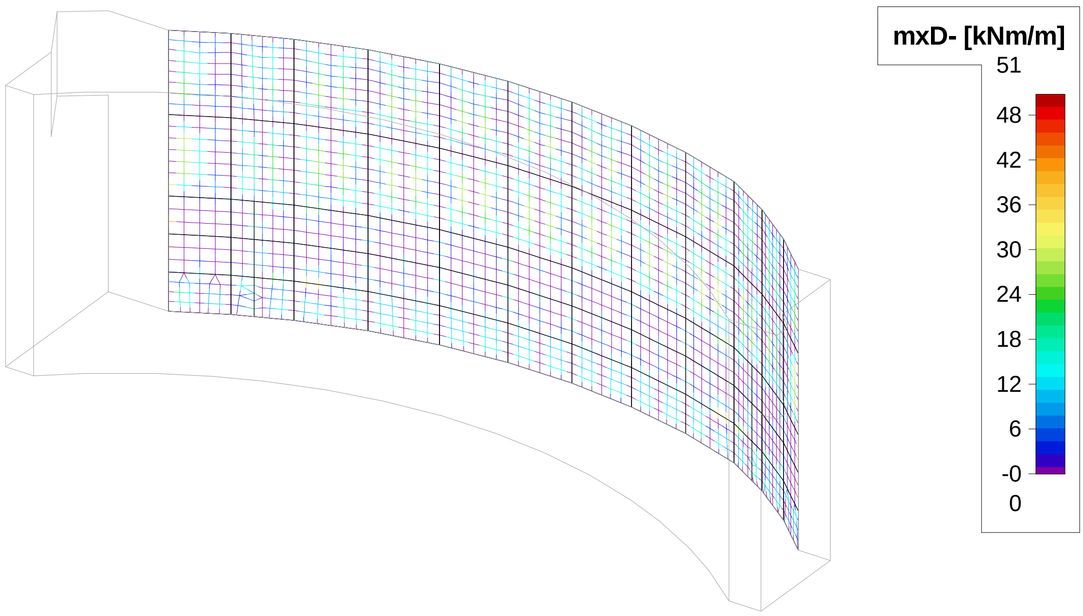
8. Skin plates at convex side - Internal forces; ny



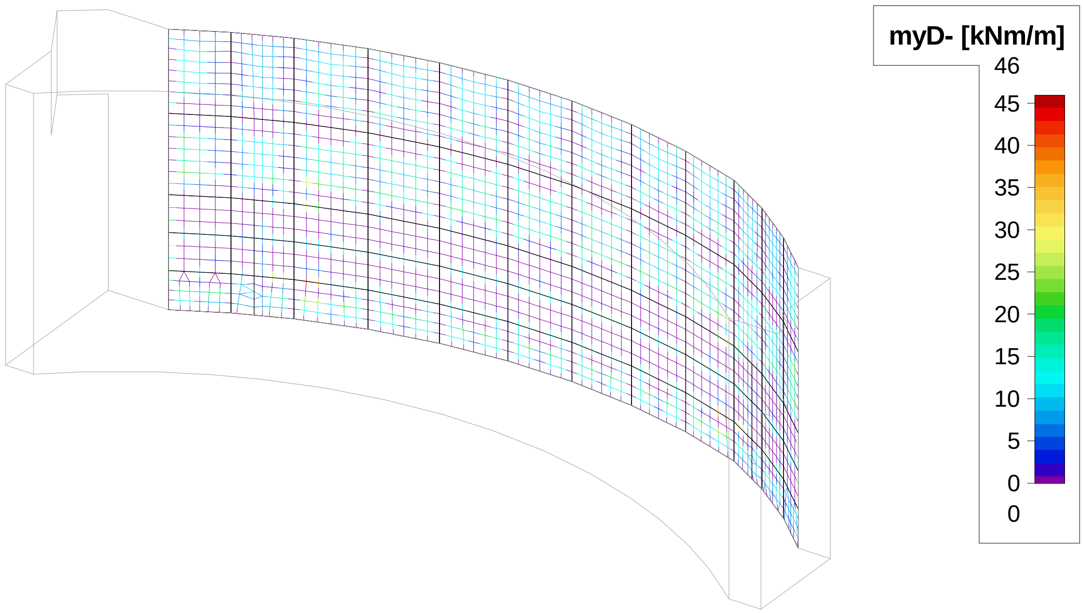
9. Skin plates at convex side - Internal forces; mxD+



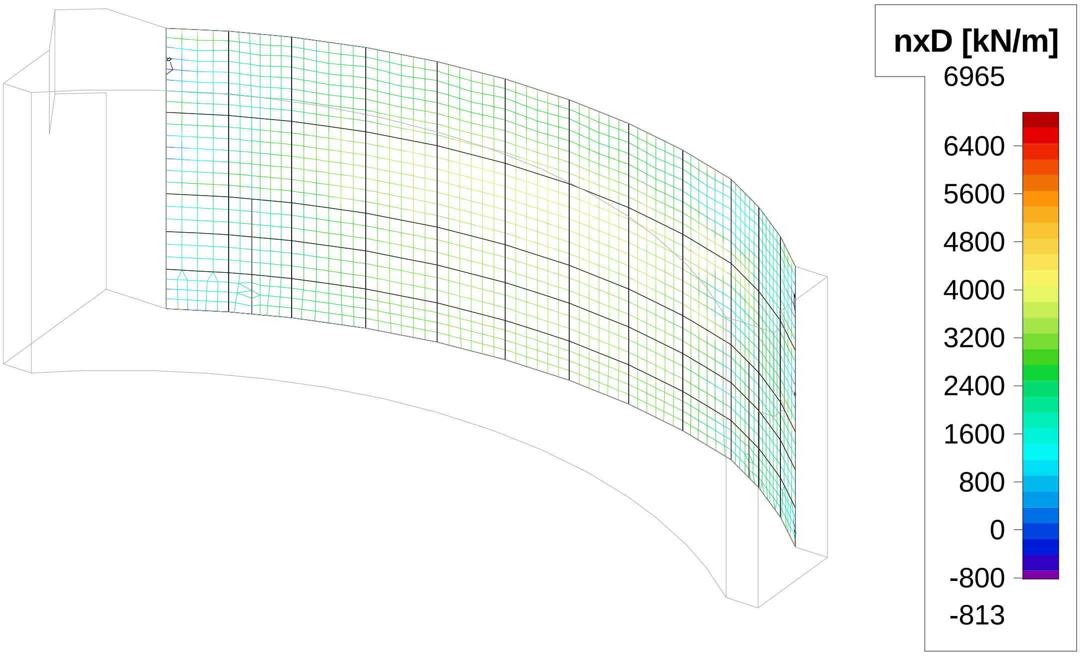
10. Skin plates at convex side - Internal forces; myD+



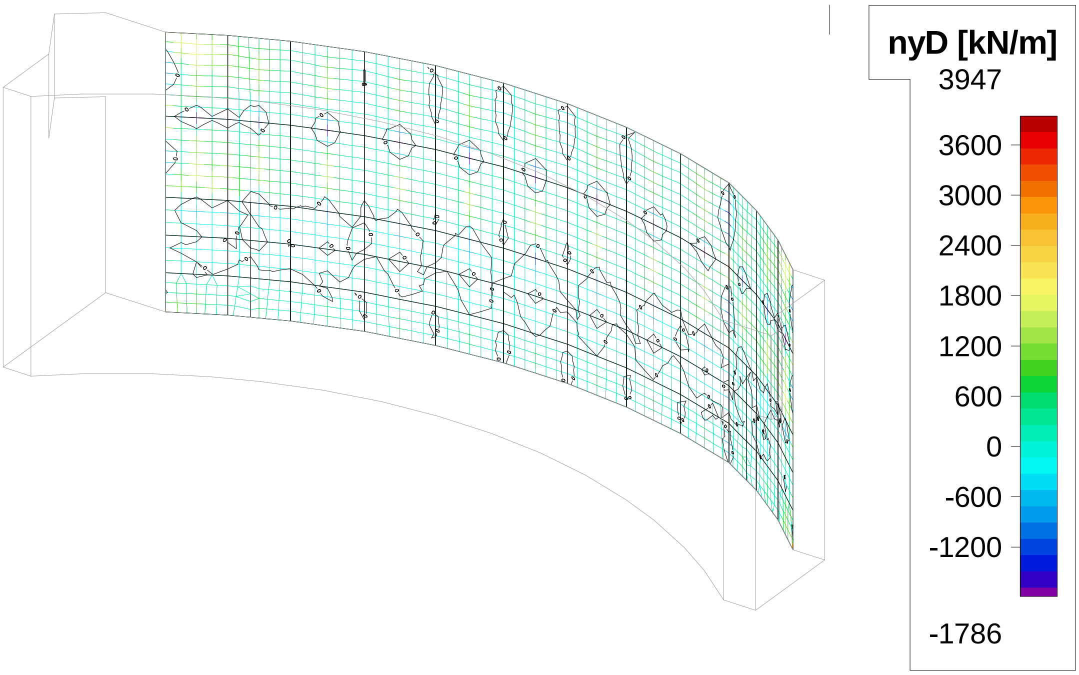
11. Skin plates at convex side - Internal forces; mxD-



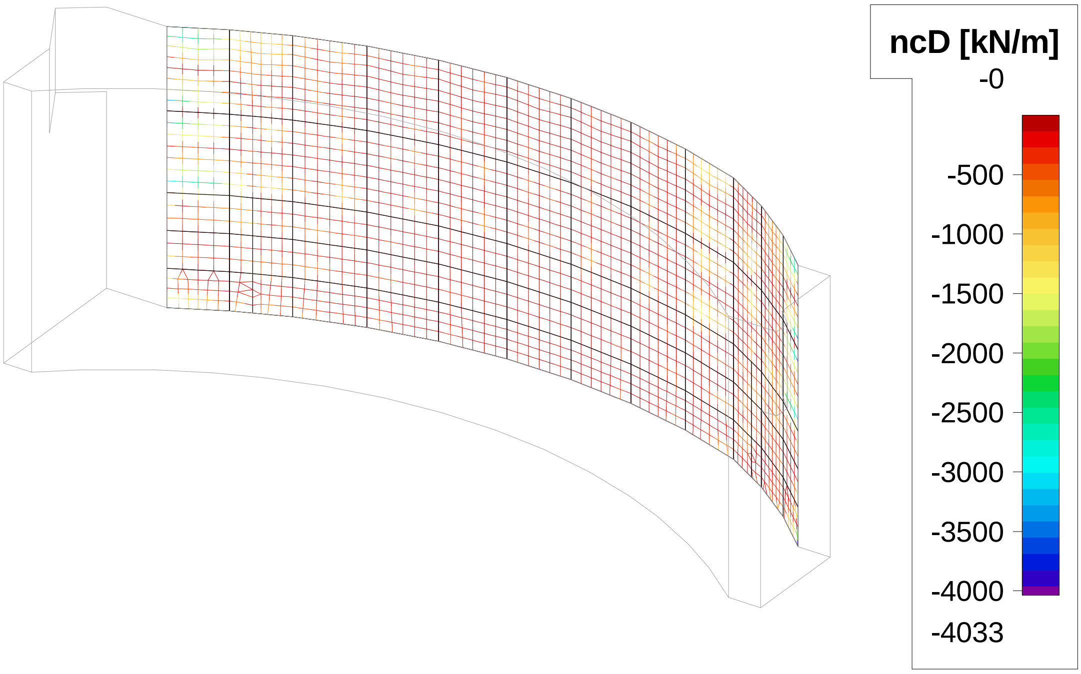
12. Skin plates at convex side - Internal forces; myD-



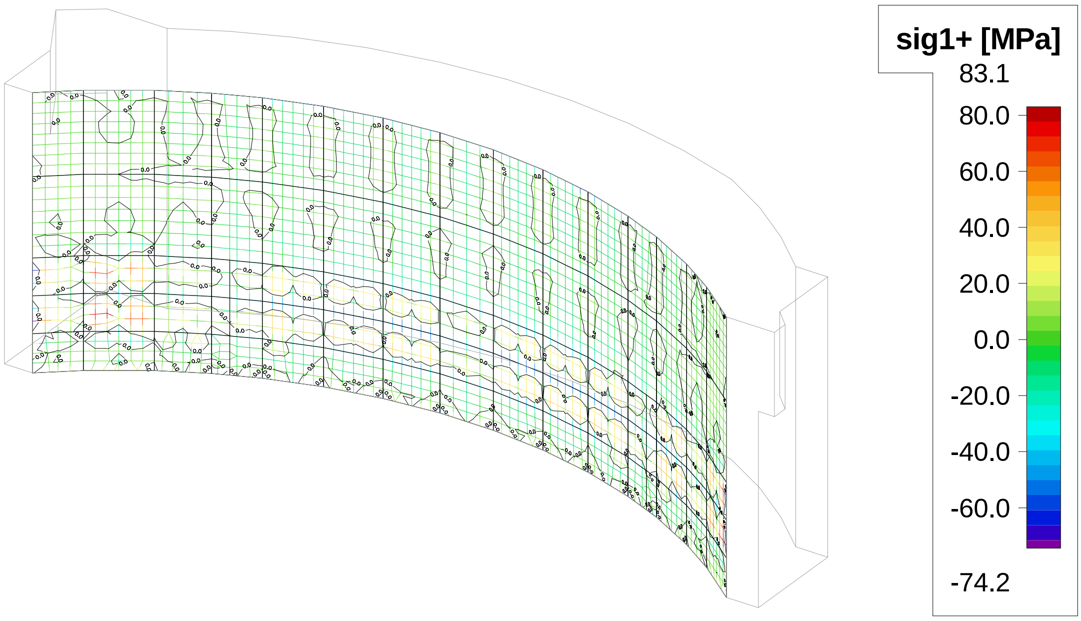
13. Skin plates at convex side - Internal forces; nxD



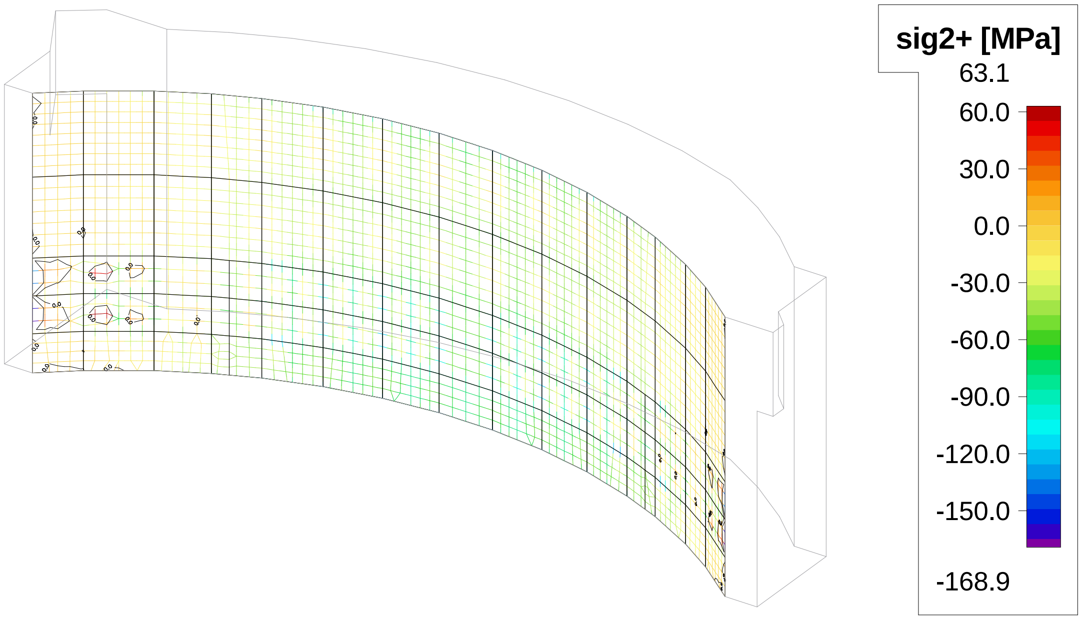
14. Skin plates at convex side - Internal forces; nyD



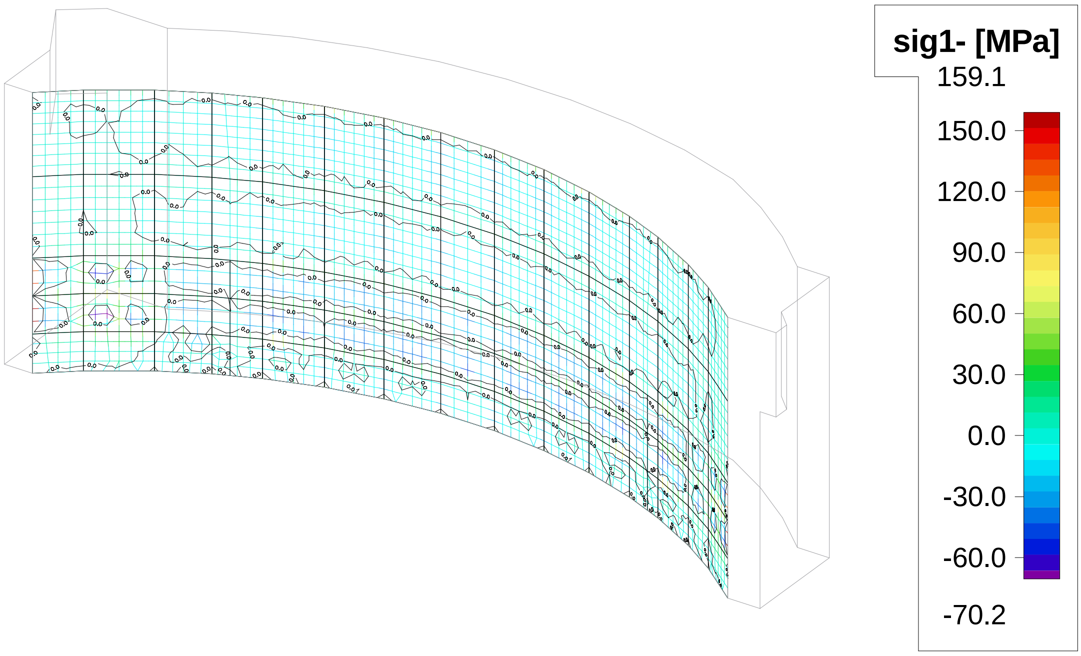
15. Skin plates at convex side - Internal forces; ncD



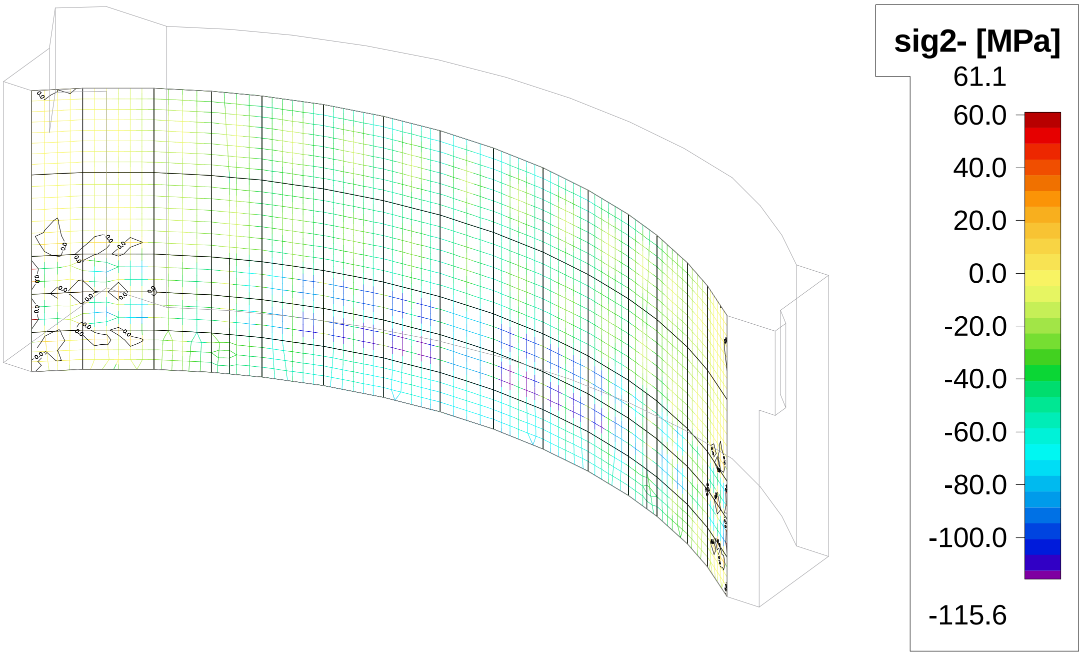
16. Skin plates at hollow side - Stresses; sig1+



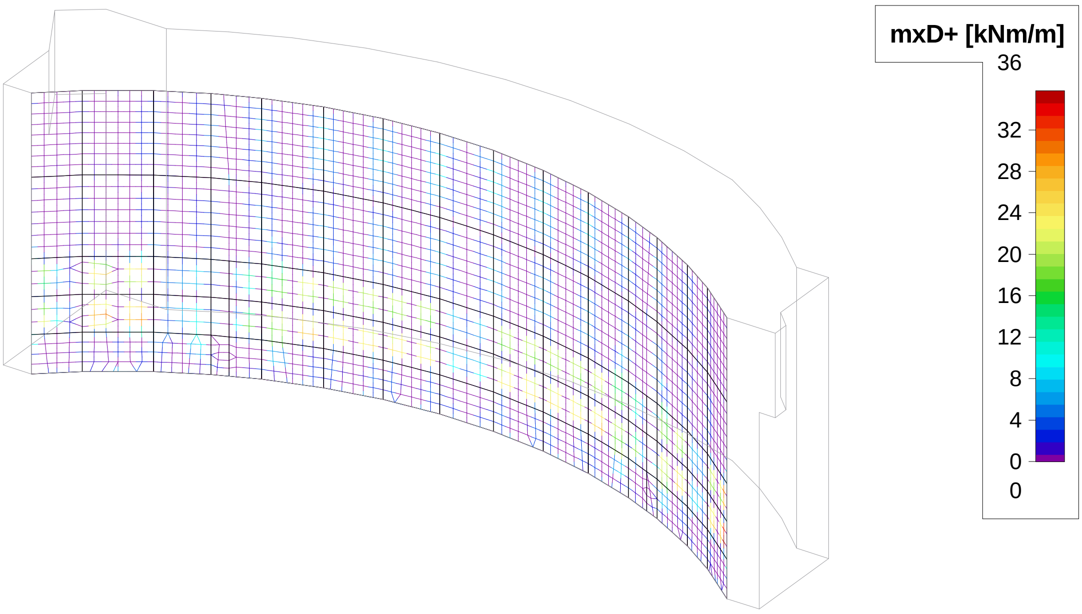
17. Skin plates at hollow side - Stresses; sig2+



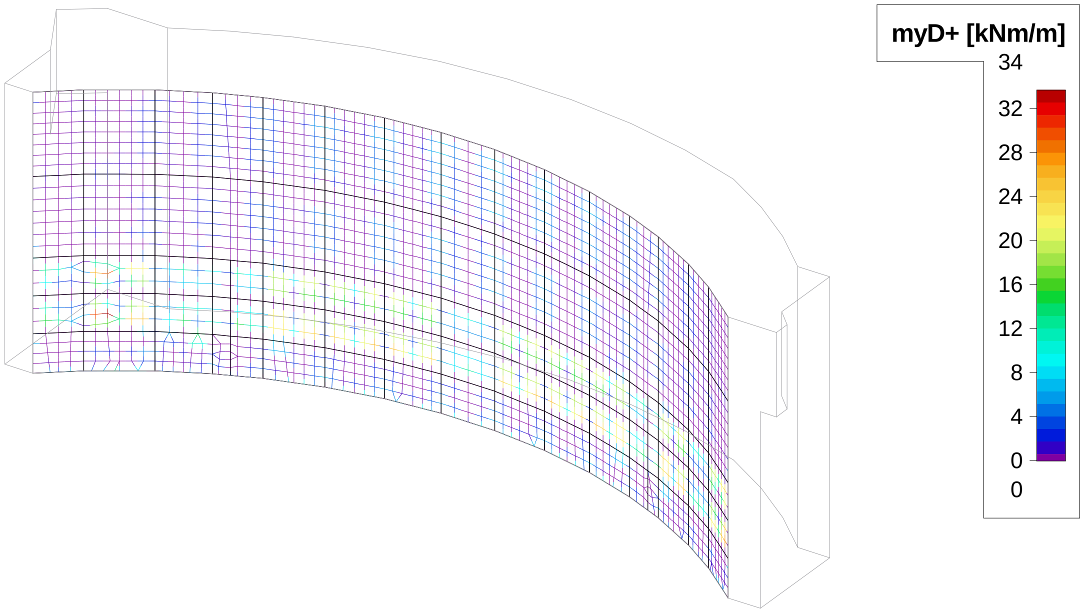
18. Skin plates at hollow side - Stresses; sig1-



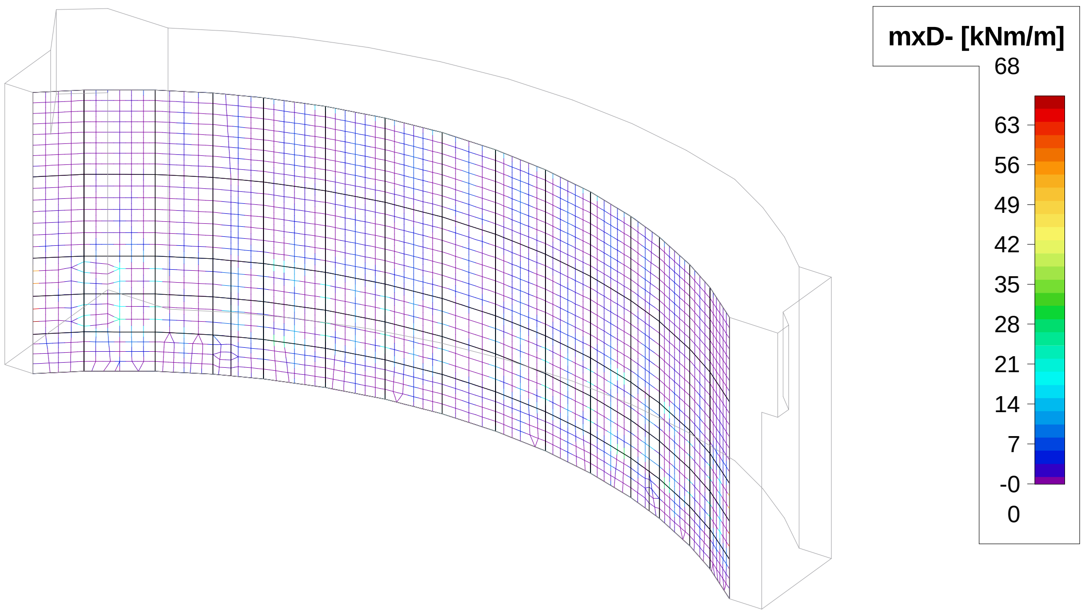
19. Skin plates at hollow side - Stresses; sig2-



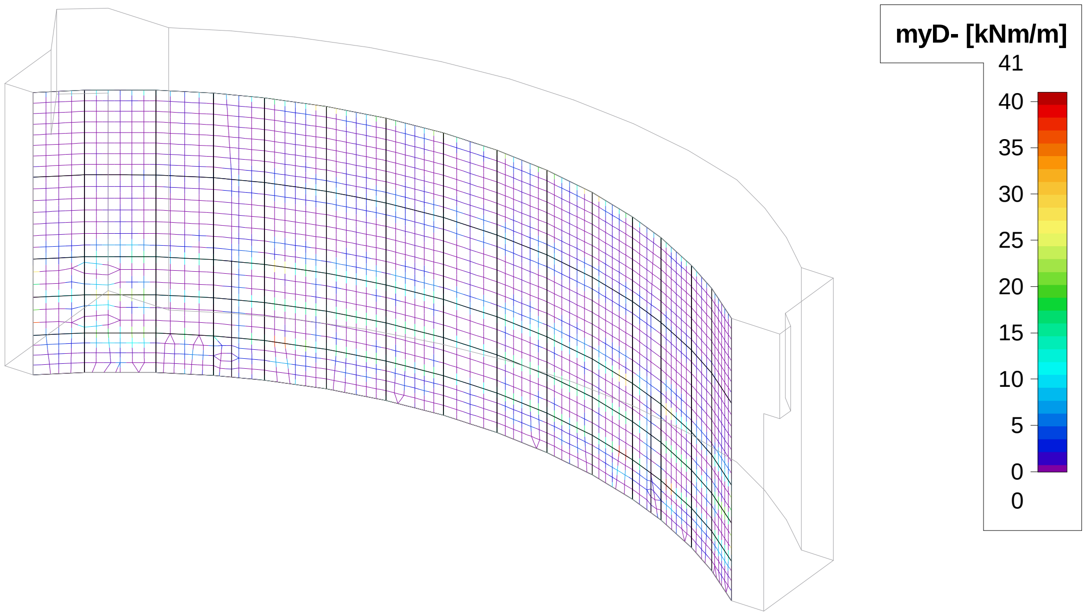
20. Skin plates at hollow side - Internal forces; mxD+



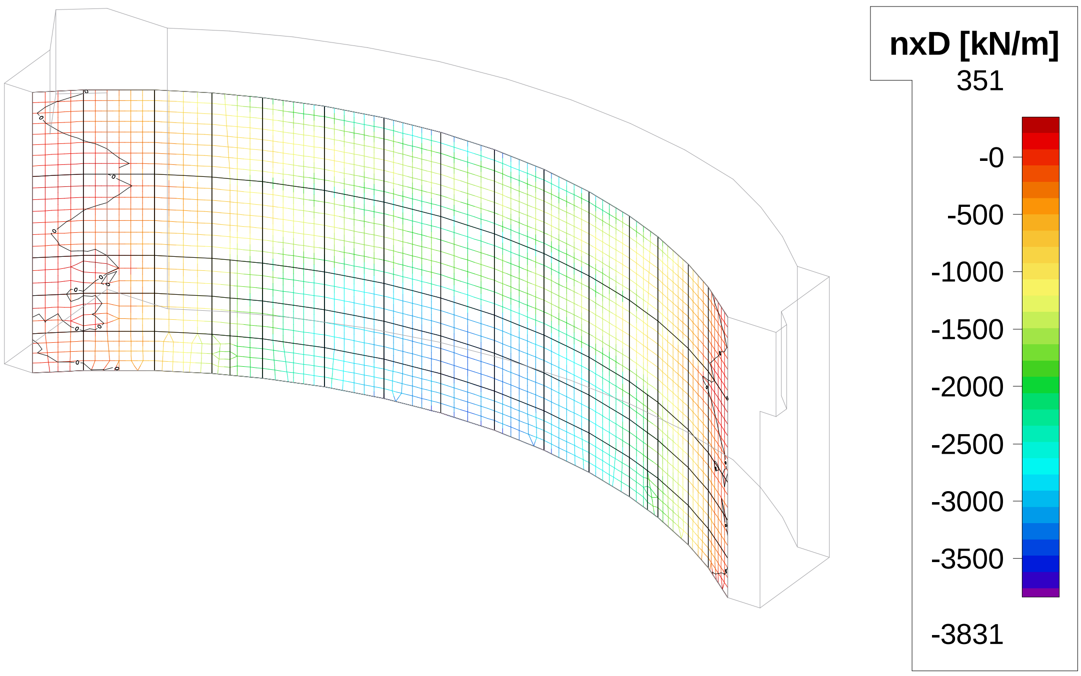
21. Skin plates at hollow side - Internal forces; myD+



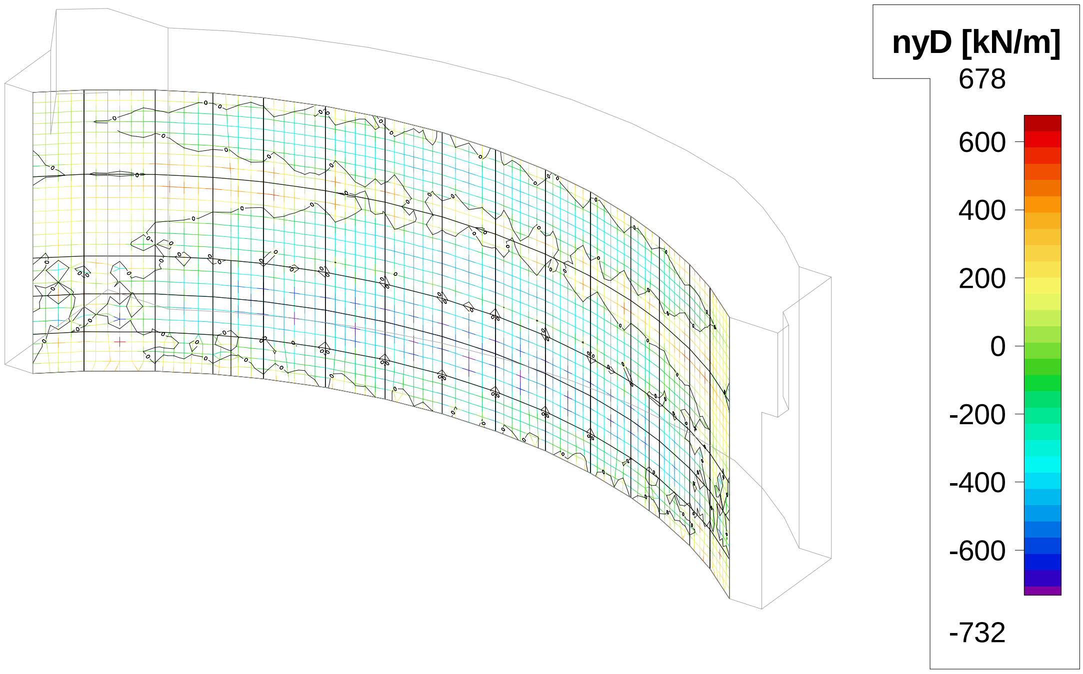
22. Skin plates at hollow side - Internal forces; mxD-



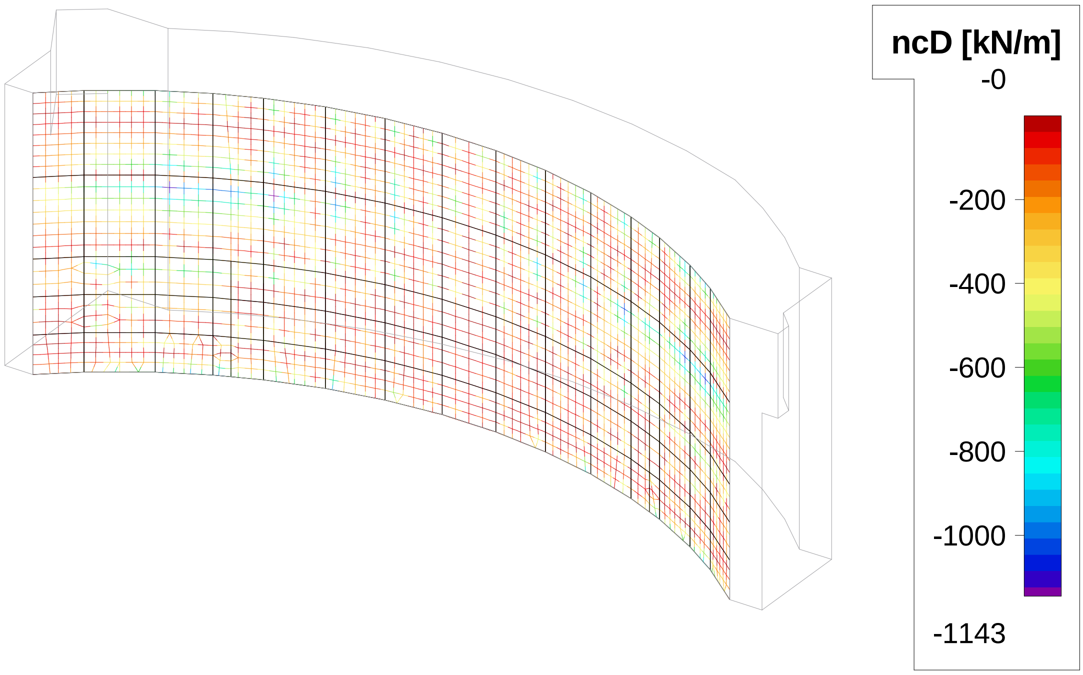
23. Skin plates at hollow side - Internal forces; myD-



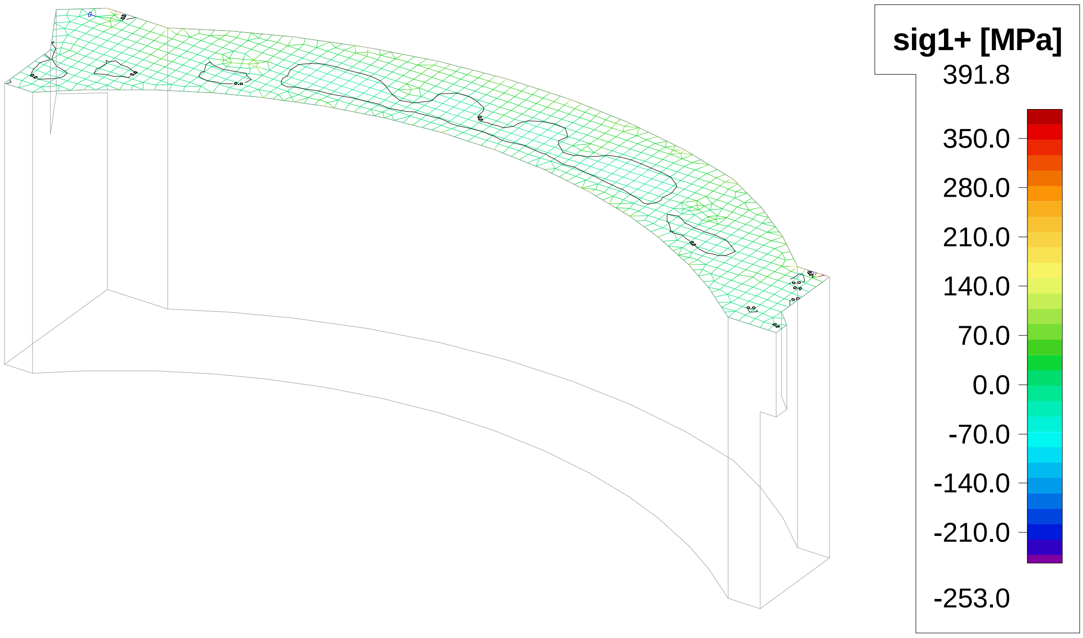
24. Skin plates at hollow side - Internal forces; nxD



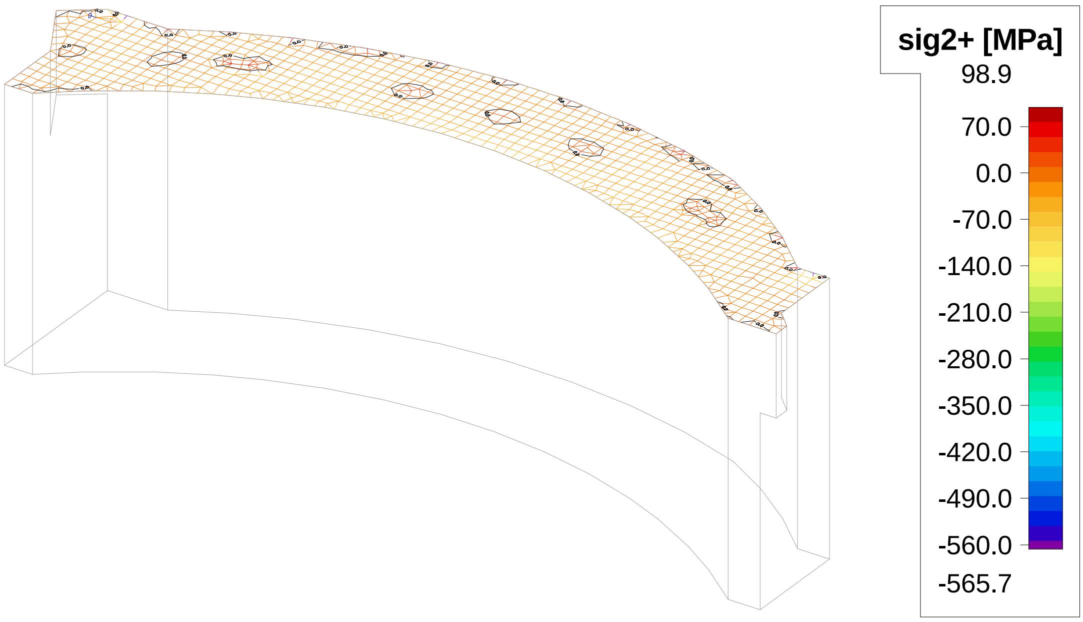
25. Skin plates at hollow side - Internal forces; nyD



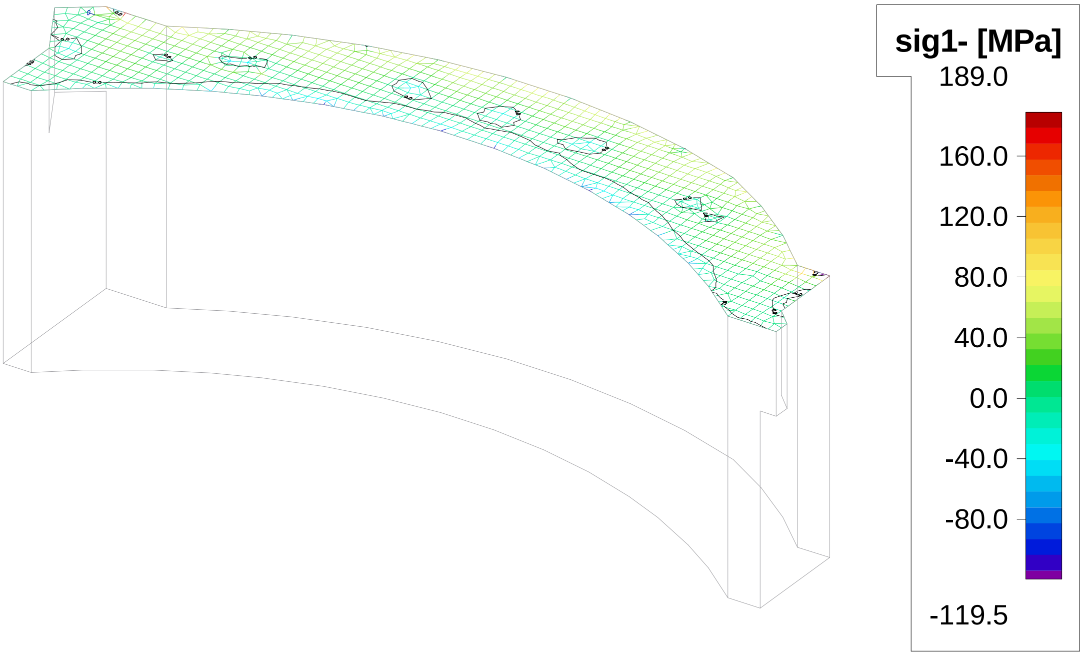
26. Skin plates at hollow side - Internal forces; ncD



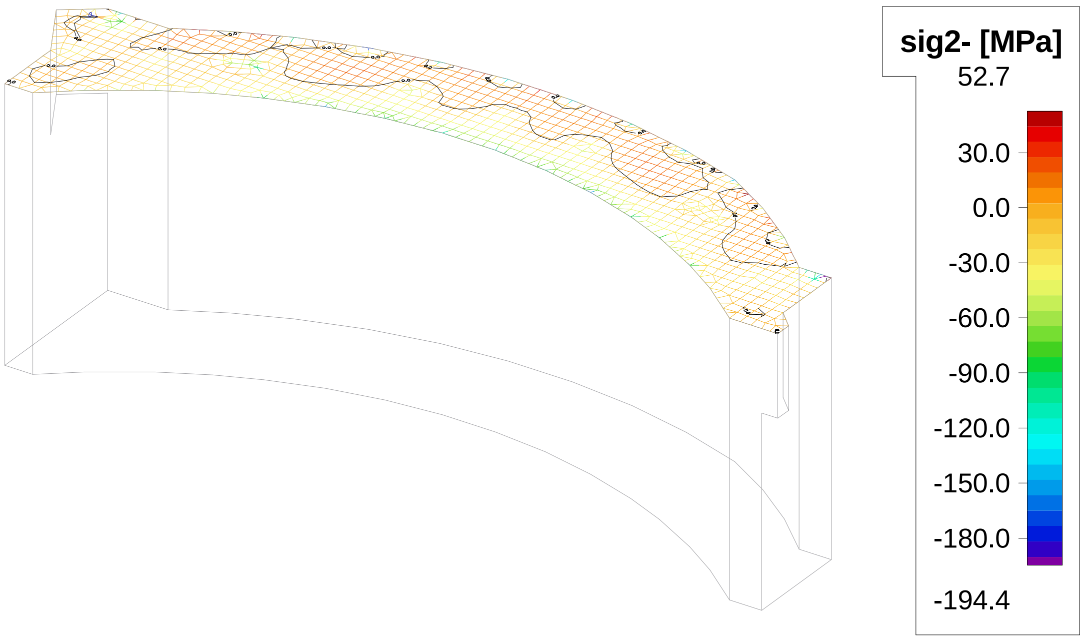
27. Top horizontal plate - Stresses; sig1+



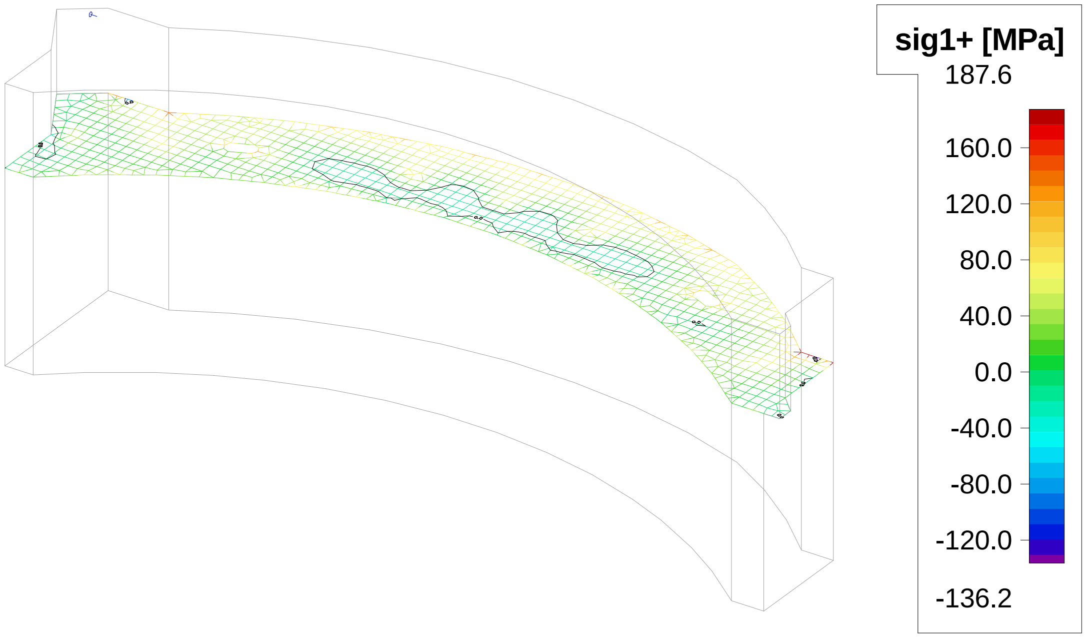
28. Top horizontal plate - Stresses; sig2+



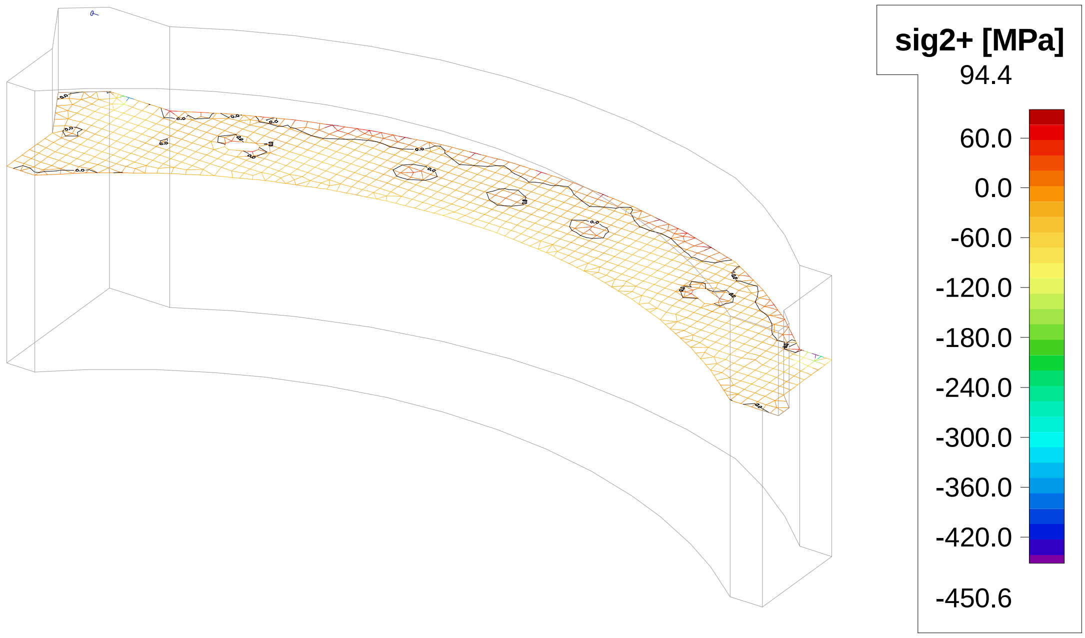
29. Top horizontal plate - Stresses; sig1-



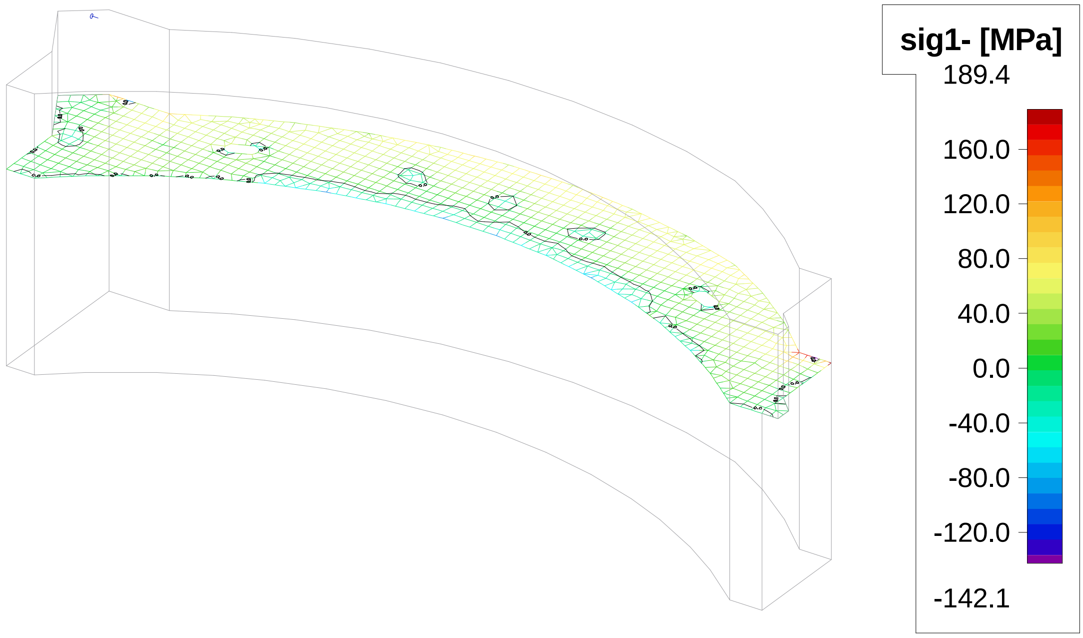
30. Top horizontal plate - Stresses; sig2-



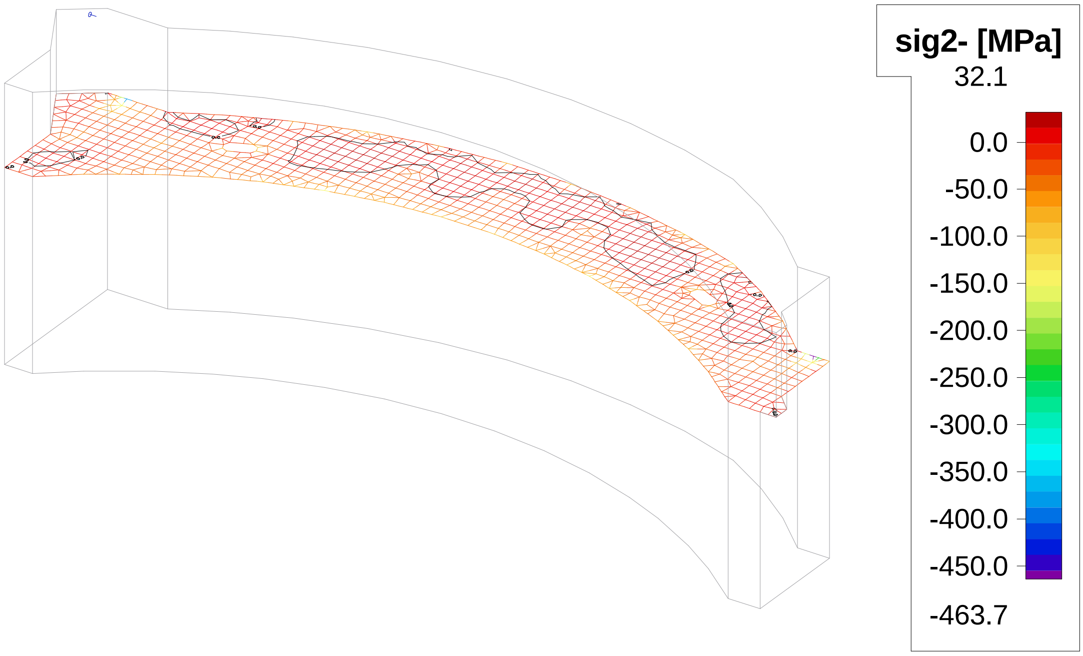
31. Middle horizontal plate - Stresses; sig1+



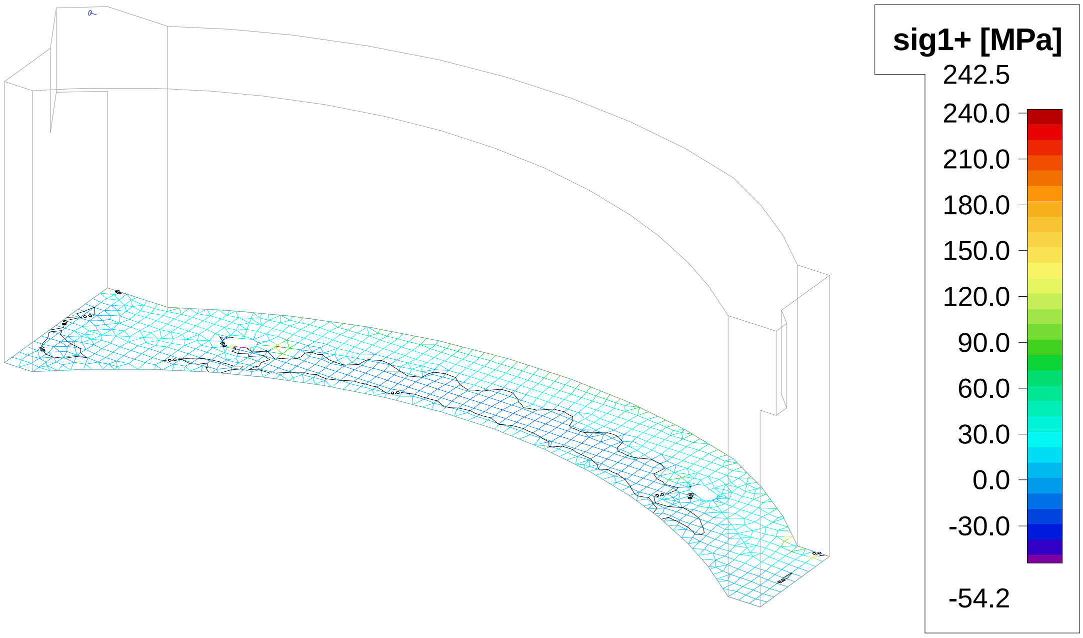
32. Middle horizontal plate - Stresses; sig2+



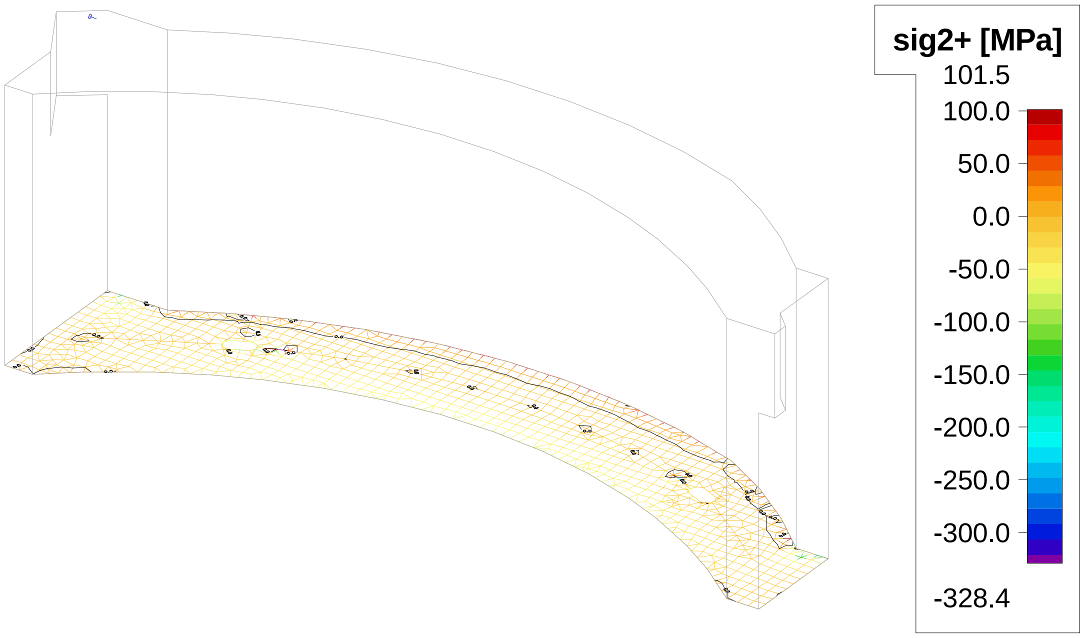
33. Middle horizontal plate - Stresses; sig1-



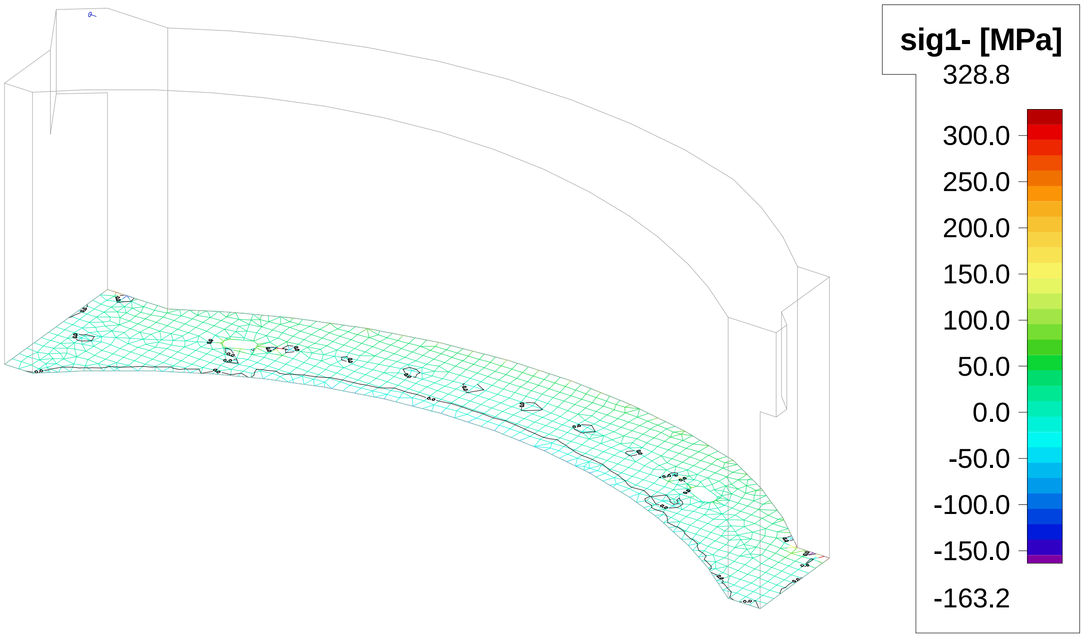
34. Middle horizontal plate - Stresses; sig2-



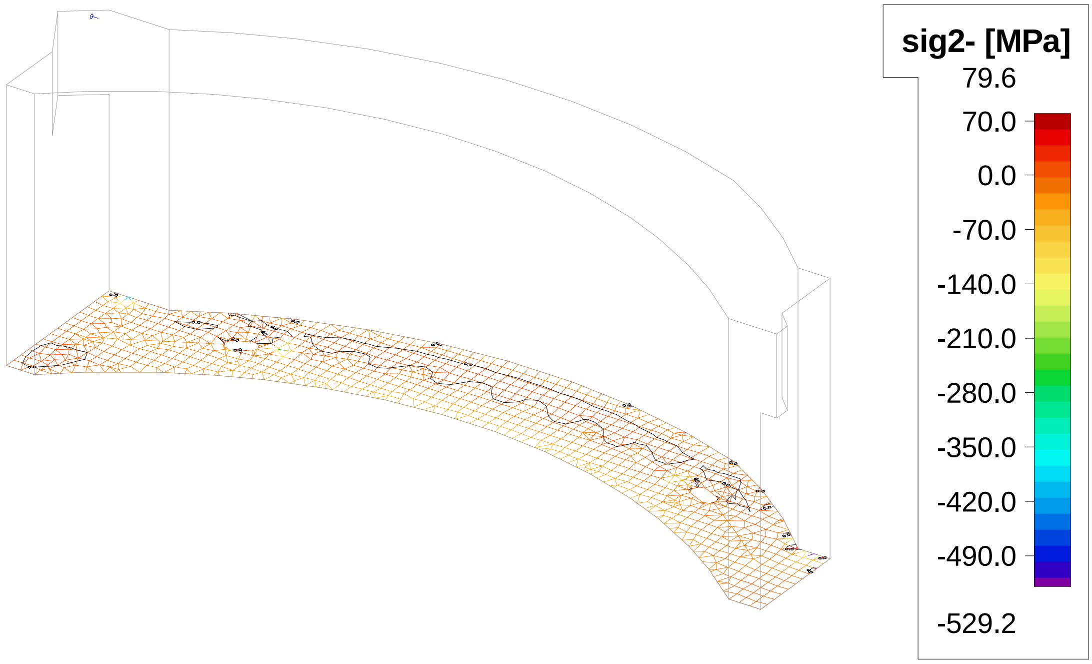
35. Bottom horizontal plate - Stresses; sig1+



36. Bottom horizontal plate - Stresses; sig2+



37. Bottom horizontal plate - Stresses; sig1-



38. Bottom horizontal plate - Stresses; sig2-

D Buoyancy chambers

Details regarding the buoyancy chambers can be seen in the following figure. The number inside each section represents the surface area of that section. Considering that the height of buoyancy tanks is 3.375 m for both two rows of tanks, the volume of each tank can be calculated separately.

The following table shows the volume of the water in the tanks in three different situations; Maximum capacity, floating during the construction or maintenance, normal operation.

Area	height	volume	Filled	max capacity	Floating		Operation	
m^2	m	m^3	No.	m^3	No.	m^3	No.	m^3
67,68	3,375	228,42	2	456,8	0	0,0	0	0,0
61,29	3,375	206,85	2	413,7	2	413,7	1	206,9
82,05	3,375	276,92	2	553,8	2	553,8	1,5	415,4
54,93	3,375	185,39	2	370,8	2	370,8	2	370,8
54,93	3,375	185,39	2	370,8	2	370,8	2	370,8
54,91	3,375	185,32	2	370,6	2	370,6	2	370,6
54,93	3,375	185,39	2	370,8	2	370,8	2	370,8
54,93	3,375	185,39	2	370,8	2	370,8	2	370,8
81,37	3,375	274,62	2	549,2	2	549,2	1,4	384,5
57,6	3,375	194,40	2	388,8	2	388,8	1	194,4
35,51	3,375	119,85	2	239,7	0	0,0	0	0,0
19,1	3,375	64,46	2	128,9	0	0,0	0	0,0
				4584,8 m^3		3759,3 m^3		3054,9 m^3

E Hydro-foot

Here the calculation for the design of hydro-feet is presented based on the formulations given by D. Ros (23) and (5).

Input:

Gravitation: $g := 9.81\frac{m}{s^2}$

Specific weight of water $\rho := 1025\frac{kg}{m^3}$

Viscosity of water $\eta := 0.001 Pa\cdot s$

Number of Hydrofoot supports $N_{sup} := 2$

Minimum water depth during operation $d := 15.8m$

Loads:

Maximum vertical force during operation $F_{vmax} := 4000kN$

Extreme load per hydro-foot $F_{max} := \frac{F_{vmax}}{2}$

$F_{max} = 2\times 10^3\cdot kN$

Mean value load per hydro-foot $F_{mean} := \frac{F_{vmax}}{N_{sup}}$

$F_{mean} = 2\times 10^3\cdot kN$

Parameters:

Outer radius $R_{0or} := 0.37m$

Inner radius $R_{1or} := 0.265m$

Minimum film thickness $h_{min} := 0.12\cdot 10^{-3}m$

Radius factor $\gamma := \frac{R_{1or}}{R_{0or}}$

$\gamma = 0.716$

Pump pressure and film pressure relation:

Assumed pump pressure $P_p := 3MPa$

Supply pressure $P_s := P_p$

Atmospheric pressure $P_a := \rho \cdot g \cdot d$

$P_a = 1.589 \times 10^5\,Pa$

Pressure factor $\beta := 0.7$

$$\beta = \frac{P_r - P_a}{P_s - P_a}$$

P_r: The average film pressure, to be defined

Determining Hydro-foot radius:

The maximum bearing load is: $F_{max} = 2 \times 10^3 \cdot kN$

The upward forces delivered by the hydro-foot is described with:

$$F(R_0) := A_{eff}(R_0) \cdot (P_r(P_s) - P_a)$$

In which A_{eff} is the effective area over which the mean film pressure P_r works:

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

The film pressure is related to the supply pressure through the factor β :

$$P_r := \beta \cdot (P_s - P_a) + P_a$$

Now R_0 can be calculated by equating $F(R_0)=F_{max}$:

$$F(R_0) := A_{eff}(R_0) \cdot (P_r - P_a)$$

Given

$F(R_0) = F_{max}$

Guess

$R_0 := 0.7m$

Solution

$R_0 := \text{Find}(R_0)$

$R_0 = 0.659m$

Calculating Flow and Restrictor Parameters:

The flow through the fluid film is described by:

$$Q_{fd} := \frac{h_{min}^{3} \cdot C_f \cdot (P_r - P_a)}{\eta}$$

$h_{min} = 0.12 \cdot mm$

Film factor

$$C_f := \frac{\pi}{12} \cdot \frac{1 + \gamma}{1 - \gamma}$$

$P_r := \beta \cdot (P_s - P_a) + P_a$

$P_r = 2.148 MPa$

The flow from the orifice is described by:

$$Q_{rd}(d_o) := C_d \cdot A_o(d_o) \cdot \sqrt{2 \cdot \frac{P_s - P_r(P_s)}{\rho}}$$

$$A_o(d_o) := \frac{\pi}{4} \cdot d_o^{2}$$

$C_d := 0.65$

$$Q_{fd} := \frac{h_{min}^{3} \cdot C_f \cdot (P_r - P_a)}{\eta}$$

$$Q_{fd} = 19.588 \frac{m^3}{hour}$$

$$Q_{op} := Q_{fd}$$

Determining restrictor dimensions from Q_r=Q_f

$$Q_r(d_o) := C_d \cdot A_o(d_o) \cdot \sqrt{2 \cdot \frac{P_s - P_r}{\rho}}$$

Guess

$$d_o := 0.02m$$

Given

$$Q_r(d_o) = Q_{fd}$$

$$d_o := \text{Find}(d_o)$$

$$d_o = 0.016m$$

Determine The flow and film thickness for F_{mean}

$$F_{mean} = 2 \times 10^{3} \cdot kN$$

$$F(R_0) := A_{eff}(R_0) \cdot (P_r - P_a) = F_{mean}$$

$$P_r := \frac{F_{mean}}{A_{eff}(R_0)} + P_a$$

$$P_r = 2.148 MPa$$

$$Q_r(P_s, d_o) := C_d \cdot A_o(d_o) \cdot \sqrt{2 \cdot \frac{P_s - P_r}{\rho}}$$

$$Q_r(P_s, d_o) = 19.588 \frac{m^3}{hour}$$

$$Q_f(h) := \frac{h^3 \cdot C_f \cdot (P_r - P_a)}{\eta}$$

Guess

$h := 0.15 mm$

Given

$Q_{op} = Q_f(h)$

Solution

$h := \text{Find}(h)$

$h = 0.12 mm$

Relation between Bearing load and the Flow / Film thickness

$$P_r(F_v) := \frac{F_v}{A_{eff}(R_0)} + P_a$$

$$Q_r(F_v) := C_d \cdot A_o(d_o) \cdot \sqrt{2 \cdot \frac{P_s - P_r(F_v)}{\rho}}$$

$$Q_f(F_v, h) := \frac{h^3 \cdot C_f \cdot (P_r(F_v) - P_a)}{\eta}$$

$$\frac{h^3 \cdot C_f \cdot (P_r(F_v) - P_a)}{\eta} = C_d \cdot A_o(d_o) \cdot \sqrt{2 \cdot \frac{P_s - P_r(F_v)}{\rho}}$$

$$h(F_v) := \frac{1}{C_f \cdot (P_r(F_v) - P_a)} \cdot \left[C_d \cdot A_o(d_o) \cdot 2^{\frac{1}{2}} \cdot \left(\frac{P_s - P_r(F_v)}{\rho} \right)^{\frac{1}{2}} \cdot \eta \cdot C_f^{\,2} \cdot (P_r(F_v) - P_a)^2 \right]^{\frac{1}{3}}$$

Relation between F_V and the flow and film thickness with a flow regulator

$Q_{reg} := Q_r(F_{max})$

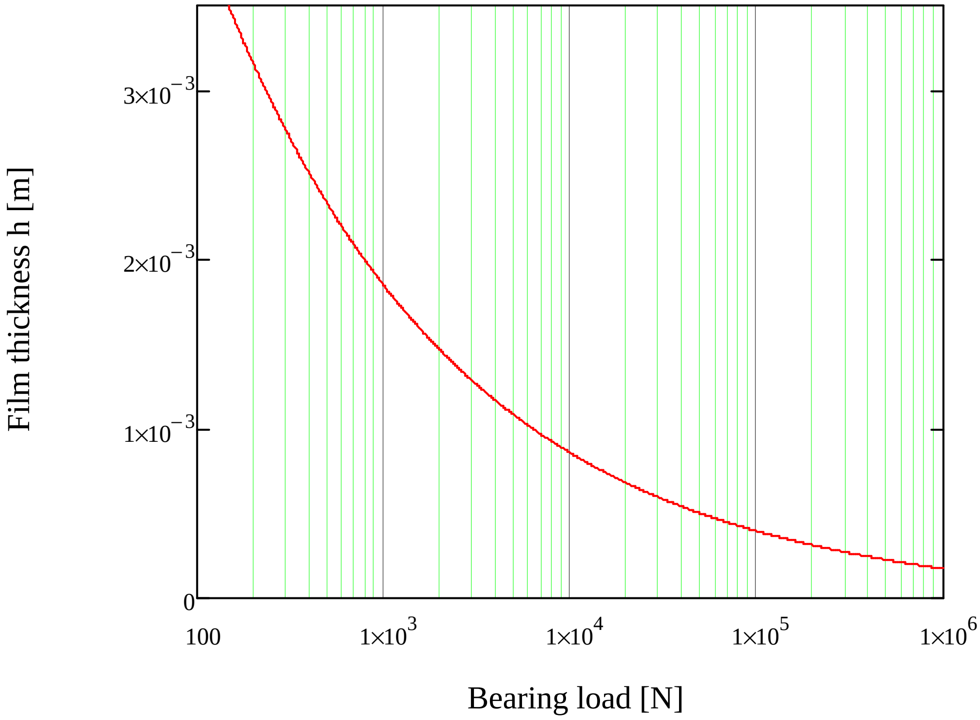
$Q_{reg} = 19.588 \frac{m^3}{hour}$

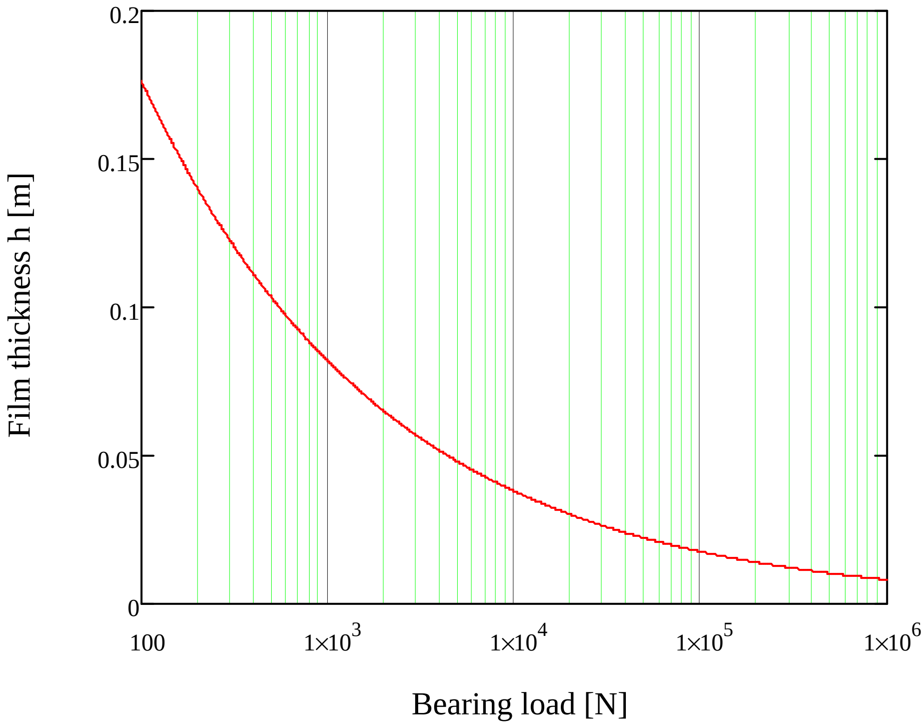
$\frac{h^3 \cdot C_f \cdot (P_r(F_v) - P_a)}{\eta} = Q_{reg}$

$$h_{reg1}(F_v) := \frac{-1}{20 \cdot C_f \cdot [(-P_r(F_v)) + P_a]} \cdot \left[(-Q_{reg}) \cdot P_a \cdot s \cdot C_f^{2} \cdot [(-P_r(F_v)) + P_a]^2\right]^{\frac{1}{3}}$$

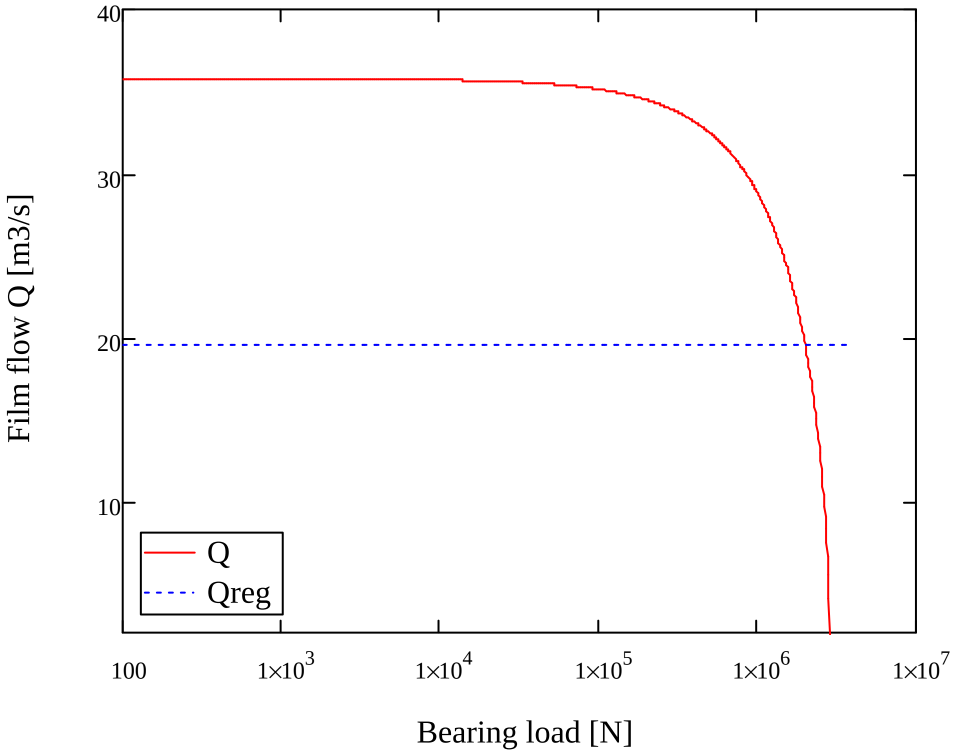
$$h_{reg2}(F_v) := \frac{1}{20} \cdot i \cdot \frac{3^{\frac{1}{2}}}{C_f \cdot [(-P_r(F_v)) + P_a]} \cdot \left[(-Q_{reg}) \cdot P_a \cdot s \cdot C_f^{2} \cdot [(-P_r(F_v)) + P_a]^2\right]^{\frac{1}{3}}$$

$h_{reg}(F_v) := h_{reg1}(F_v) + h_{reg2}(F_v)$





0.2
0.15
0.1
0.05
0
Film thickness h [m]
100
1×10^3
1×10^4
1×10^5
1×10^6
Bearing load [N]



40
30
20
10
Film flow Q [m3/s]
Q
Qreg
100
1×10^3
1×10^4
1×10^5
1×10^6
1×10^7
Bearing load [N]

Pump requirements and energy consumption

$Q_{reg} = 19.588 \frac{m^3}{hour}$

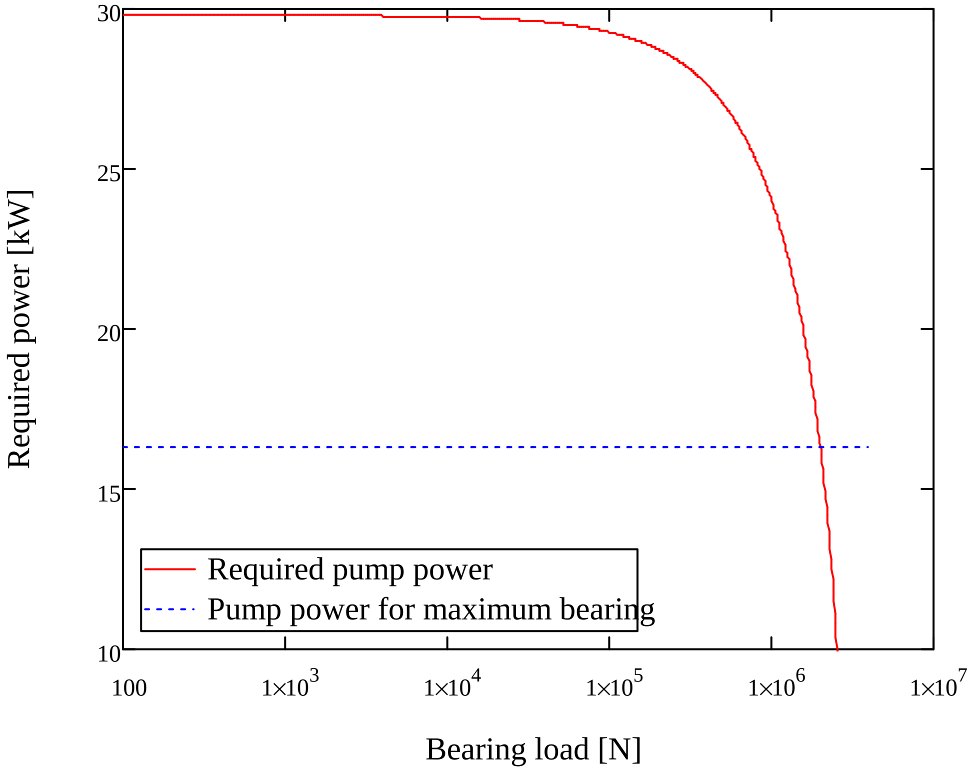
$Q_{req} := Q_{reg} \cdot N_{sup}$

$Q_{req} = 39.176 \frac{m^3}{hour}$

$P_p = 3 \cdot MPa$

$P_{pump} := Q_{req} \cdot P_p$

$P_{pump} = 32.647 kW$



Summary

$N_{sup} = 2$

$F_{max} = 2 \times 10^3 \cdot kN$

$R_0 = 0.659m$

$A_{eff}(R_0) = 1.006m^2$

$P_s = 3 \cdot MPa$

$P_r(F_{max}) = 2.148MPa$

$\beta = 0.7$

$h_{min} = 0.12 \cdot mm$

$Q_{reg} = 19.588 \frac{m^3}{hour}$

$P_{pump} = 32.647kW$

F Floating stability

Floating: Static stability

For static stability, rotation of the element should be compensated by a righting moment caused by the buoyant force and the weight of the element. This is the case where the Metacentric height (h_m) is positive. In practice, h_m > 0.50 m is recommended. (1)

$F_w := 40000 \cdot kN$	Weight of the gate
$KG := 11.0 \cdot m$	Position of gravity center with reference to K (bottom line of the element)
$V_b := 3760\,m^3$	Total volume of buoyancy chambers
$d_b := 6.875 m$	Distance between the center line of buoyancy chambers and the bottom line of the gate
$h_g := 25 m$	Lock gate height
$\gamma_{st} := 78.5 \cdot \frac{kN}{m^3}$	Specific weight of Steel
$\gamma_w := 10 \cdot \frac{kN}{m^3}$	Specific weight of Water

In order to calculate the draught, the following equation should be satisfied:

Resultant buoyancy force = Weight

--> $F_b = F_w$

--> $d/h_g * F_w * \gamma_w/\gamma_{st} + \gamma_w * V_b = F_w$

$$d := \frac{\left[\left(F_w - \gamma_w \cdot V_b\right) \cdot h_g \cdot \gamma_{st}\right]}{F_w \cdot \gamma_w}$$ Total buoyancy force

$d = 11.775 m$ Draught of the gate

$$F_b := \left(\frac{d}{h_g}\right) \cdot F_w \cdot \left(\frac{\gamma_w}{\gamma_{st}}\right) + \gamma_w \cdot V_b$$

$$KB := \frac{\left[1.2 \cdot \left(\frac{d}{h_g}\right) \cdot F_w \cdot \left(\frac{\gamma_w}{\gamma_{st}}\right) \cdot \left(\frac{d}{2}\right) + \gamma_w \cdot V_b \cdot d_b\right]}{F_b}$$

$KB = 6.886m$ — Position of "center of buoyancy" with reference to K (bottom line of the element)

$I_{yy} := 19198m^4$ — Moment of Inertia around Y-Axis

$$V_w := \left(\frac{d}{h_g}\right) \cdot \left(\frac{F_w}{\gamma_{st}}\right) + V_b$$

$V_w = 4 \times 10^6 L$ — Volume of displaced water

$$BM := \frac{I_{yy}}{V_w}$$

$BM = 4.8m$ — Distance between "center of Buoyancy" and Metacenter

$GM := KB + BM - KG$

$h_m := GM = 0.686m$ — Metacentric height